Can naturally ventilated office buildings cope with dusty outdoor air?

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ABSTRACT

Naturally ventilated (NV) buildings, when well designed and operated, can provide adequate indoor environmental quality (IEQ) while reducing the building energy demand. However, in dusty outdoor air, this ventilation technique may increase the penetration of outdoor particulate matter (PM) indoors, leading to adverse health effects. Given the increasing frequency of outdoor dust episodes in Mediterranean climates, an important research question is whether NV buildings can provide adequate indoor air quality (IAQ) during increased outdoor air dust episodes. We monitored indoor and outdoor concentrations of size-resolved PM for six months in an occupant-operated NV low-energy office building in Cyprus, an island with frequent episodes of airborne dust. In parallel, the building was monitored for its energy consumption, indoor air temperatures, relative humidity, and CO_2 concentrations. We also interviewed the building occupants regarding their perceived IEQ conditions. The results revealed that the NV provided adequate IAQ conditions in 4 out of 5 investigated indoor spaces for $PM_{2.5}$ and in 2 out of 5 investigated spaces for PM_{10}. The average indoor concentrations were in the range of 4.4-5.1 $\mu g/m^3$ for $PM_{2.5}$ and 13.8-19.9 $\mu g/m^3$ for PM_{10}, while the average outdoor concentrations for the same period were 7.4 $\mu g/m^3$ for $PM_{2.5}$ and 38.1 $\mu g/m^3$ for PM_{10}. Additionally, unlike the outdoor air, the indoor PM concentrations respected the WHO short-term 24-hour limits, indicating that the building addressed well the dusty days. In terms of other IEQ parameters, the CO_2 levels remained below 1000 ppm for more than 90% of the time, while more than 90% of the occupants were satisfied with the thermal comfort conditions. The final actual energy consumption was ~164 $kWh/m^2/yr$, drifting only by 7% from the predicted energy use. The results of this case study indicated that well-designed low-energy NV office buildings can provide adequate IEQ conditions, even in outdoor environments with dusty air.

KEYWORDS

passive technologies, office buildings, pollution penetration, I/O ratio, climate change

1 INTRODUCTION

Energy-efficient buildings are necessary to limit the energy demand and reduce greenhouse gas emissions globally. Natural ventilation (NV), when adequately designed and operated, can contribute to reducing the operational and grey energy demand in buildings while, in parallel, improving thermal comfort and indoor air quality (IAQ) (Flourentzou et al., 2017). Nevertheless, several studies criticize naturally ventilated buildings for not providing adequate protection to their occupants concerning outdoor air pollution, as the higher ventilation rates and the absence of filtration increase the penetration of outdoor air pollutants indoors; hence it may lead to a deterioration of the IAQ (Stabile et al., 2017).

Among the various outdoor air pollutants, particulate matter (PM) provokes the most severe health impacts at the commonly-observed exposure concentrations (Logue et al., 2012), being listed among the top 10 risk factors for human health (Gakidou et al., 2017). Additionally, due to climate change, there is an increasing trend in airborne dust levels in the Mediterranean regions (Ganor et al., 2010). As humans spend the majority of their time indoors, they could be exposed to elevated concentrations of airborne dust if no adequate measures are taken in the design and operation of buildings.

Saraga et al. (Saraga et al., 2017) and Katra and Krasnov (Katra & Krasnov, 2020) analyzed the impact of dust episodes on the IAQ of office and residential buildings in the middle east region. Their results indicated that outdoor air is the primary source of indoor PM. However, the existing literature investigating the impact of dusty outdoor environments on IAQ is limited. Specifically, we lack knowledge regarding whether NV is appropriate in such outdoor environments to provide adequate indoor environmental quality (IEQ) conditions at a minimal energy cost.

Given that arid and semi-arid dusty environments cover ~40% of the planet's surface and are the home to ~2.1 billion people (Katra & Krasnov, 2020), this study investigated whether an energy-efficient NV building can provide adequate IAQ in an environment with elevated outdoor air dust levels.

2 METHODS

2.1 Case study building

We conducted measurements in a building located in Cyprus, an island situated in the eastern Mediterranean, which has a semi-arid Mediterranean climate with very mild winters and hot summers (classified as Csa/BSh according to Köppen (Beck et al., 2018)). During the last years and due to climate change, dust episodes coming from North African and Middle Eastern regions have increased (Achilleos et al., 2014).

The examined building (building number 3, as presented in Figure 1) is one of the four buildings of the Nicosia Town Hall complex, which is classified in energy class A according to the local energy performance certificate (EPC), and it can be characterized as low-energy, as it was designed according to the bioclimatic principles. The building hosts offices for administrative employees and is occupied from 7 am to 4 pm on weekdays. The building is not equipped with a mechanical ventilation system but relies on the manual opening of the windows by the occupants to cover its ventilation needs. For heating and cooling, the building is equipped with air conditioning (AC) units in each space that condition the air by recirculating it through the heating and cooling coils without outdoor air ventilation. Additionally, each space in the building is equipped with a ceiling fan to increase thermal comfort during summertime, and there are blinds for solar protection and daylight control. The building users have full control over these elements, being able to open/close the windows, activate/deactivate the AC and adjust its thermostat setpoints, activate/deactivate the ceiling fan, turn on/off the lights, and adjust the solar shading according to their preferences.

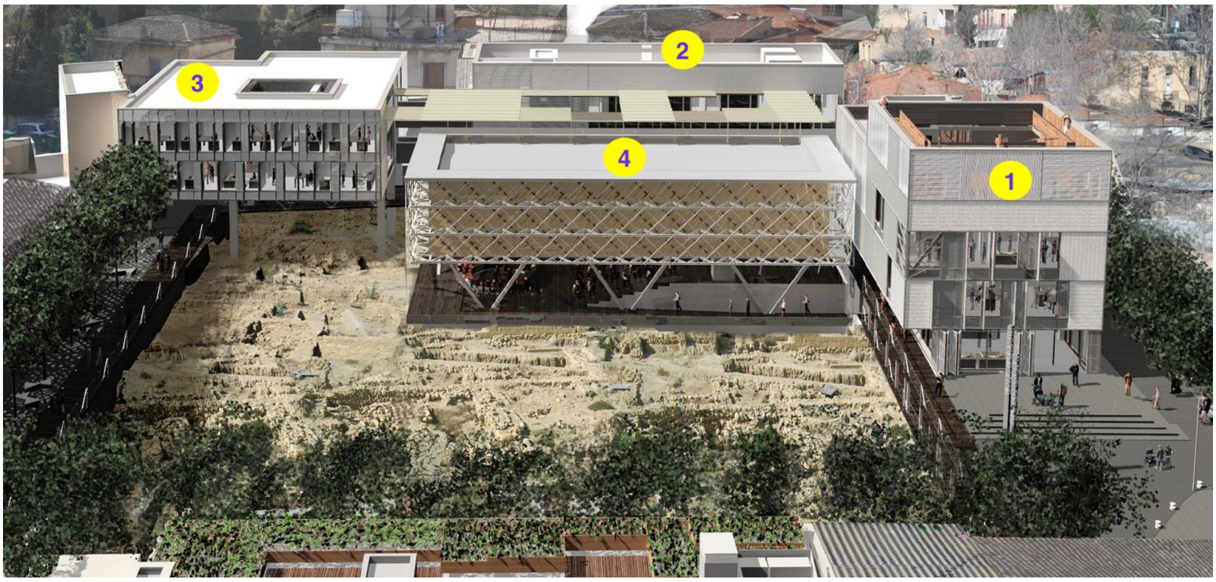

Figure 1: Nicosia Town Hall building complex. The case study building is illustrated under the number 3.

2.2 Monitoring and survey plan

Given that IEQ conditions of the passive buildings differ according to the orientation of the space, we divided the building into four different zones (North, East, South, and Center), as presented in Figure 2, where we placed the IEQ sensors. The monitored parameters were: the indoor air temperature, relative humidity (RH), CO_2, and size-resolved PM concentration. The outdoor environment of the building was also monitored for outdoor air temperatures, RH, and size-resolved PM concentrations. The positions of the sensors are equally shown in Figure 2. In parallel, the total energy consumption of the building was monitored to reveal its actual energy consumption.

The IoT-based NETATMO sensors (*Netatmo*, 2023) were utilized to measure the indoor and outdoor air temperatures and RH as well as the indoor CO_2 concentrations, as their accuracy is satisfactory compared to high-grade instruments (Demanega et al., 2021). For the PM measurements, both indoors and outdoors, it was used the Alphasense OPC-R2 sensors ("Alphasense," 2023), which were tested in a controlled environment and presented satisfactory accuracy for the $PM_{2.5}$ and PM_{10} concentration measurements compared to high-grade instruments.

To ensure that the sensors monitored the representative IEQ conditions of occupied zones, they were placed between 1.1-1.7 m above the floor and at least 1 m away from doors, windows, and air supply/exhaust of the recirculated air of the AC unit. A pair of indoor PM sensors was placed in the inlet and outlet of an AC unit, which was recirculating the air to condition it in order to monitor the particle arrestance efficiency of its filter. The outdoor PM sensors were placed close to the operable windows to monitor the PM concentration of the air outside the building. The outdoor T and RH sensors were placed under shade on the roof of the building and in the atrium to probe the outdoor weather conditions around the building.

The monitoring of T, RH, and CO_2 took place between April 2021 and December 2022 with a five minutes time step, while the monitoring of indoor and outdoor PM took place between July and December 2022 with a one-minute time step. This period was selected in order to capture how the building operates in the different outdoor environmental conditions of the hot, mid, and cold seasons. All data were post-processed to exclude the non-occupied hours, as our focus was on the IEQ conditions to which the occupants were exposed.

In order to collect feedback from the building users regarding their perception of the IEQ, we interviewed the users by asking them predefined questions, following the procedure described in (Flourentzou, 2022). The interviews included questions about thermal comfort satisfaction during the different seasons, air quality and ventilation satisfaction, as well as acoustic and visual comfort satisfaction to cover the whole spectrum of the IEQ and identify potential problems. Additionally, at the end of the interview, the users were asked about their global satisfaction with the building in order to record how they overall evaluate their IEQ. In total, 16 users working in 6 different spaces were interviewed and provided their feedback.

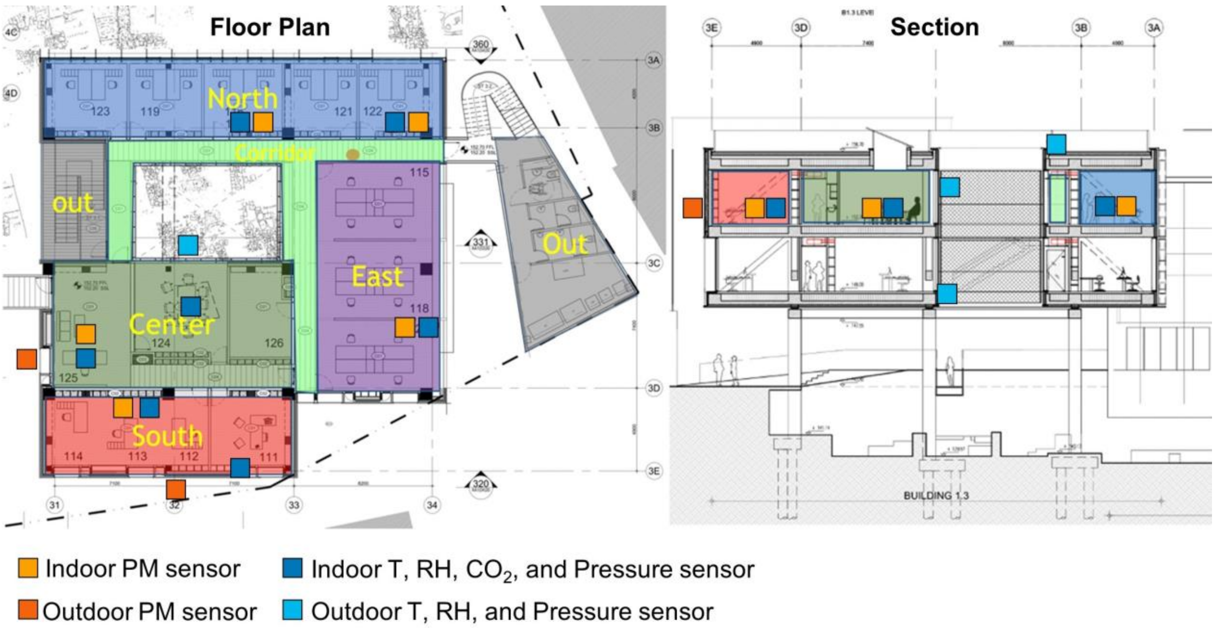

Figure 2: Sensor positions according to the buildings' zones.

3 RESULTS AND DISCUSSION

3.1 Indoor and outdoor PM levels

As presented in **Error! Reference source not found.**, the 6-month average indoor $PM_{2.5}$ c oncentrations during working hours were between 4.4 and 5.1 μg/m^3 across different office spaces. $PM_{2.5}$ concentrations were in compliance with the WHO air quality guidelines (World Health Organization, 2021) in 4 out of 5 monitored spaces. In the one space where the WHO guideline limit (5 μg/m^3) was not respected, the indoor average $PM_{2.5}$ concentration was slightly above the threshold (5.1 μg/m^3). The average outdoor $PM_{2.5}$ concentration was 7.4 μg/m^3.

The 6-month average indoor PM_{10} concentrations during working hours were between 13.8 and 19.9 μg/m^3; they presented thus a significant disparity across the different spaces. The PM_{10} levels complied with the WHO guidelines in 2 out of 5 monitored spaces, as only two spaces respected the annual average concertation limit of 15 μg/m^3. However, the average levels remained below 20 μg/m^3 in all spaces, which was the limit of the previous WHO air quality guideline, indicating generally acceptable PM_{10} levels. The outdoor average PM_{10} concentration for the same period was 38.1μg/m^3.

The higher indoor PM_{10} that did not respect the limits could be explained by the composition of the outdoor PM, which had high concentrations of coarse particles compared to the fine ones ($PM_{2.5}/PM_{10}$ ratio ~ 0.2). Additionally, the high indoor PM_{10} concentrations can be explained by the resuspension provoked by the activities of the occupants, as no other significant indoor PM source was located in the building.

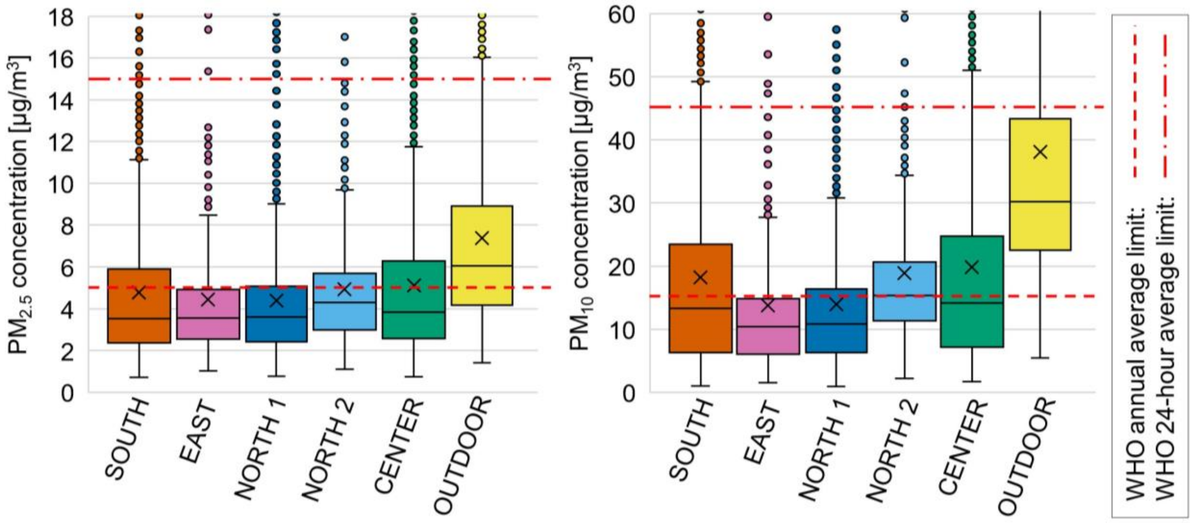

Figure 3: Indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations during working hours. Note: Box plots indicate the minimum, 1st quartile, mean (black cross), median and 3rd quartile, maximum and outlier values.

Regarding the short-term exposure limits, as presented in Table 1, during the 183 days of monitoring, the outdoor concentrations overpassed the average daily exposure limit of $PM_{2.5}$ (15 µg/m^3) for 14 days and of PM_{10} (45 µg/m^3) for 26 days. Additionally, one severe dust episode was observed during the monitored period (daily average PM_{10} concentration > 100 µg/m^3). For the same period, the indoor daily average concentrations of $PM_{2.5}$ overpassed the limit of 15 µg/m^3 only three times, while those of PM_{10} never overpassed the limit of 45 µg/m^3. These observations indicate that the building provided satisfactory protection against short-term PM exposures for its occupants even during the days with high outdoor PM levels, as WHO air quality guidelines permit up to three exceedances of the short-term threshold limits per year (World Health Organization, 2021).

Table 1: Number of exceedance of the short-term exposure limits of the WHO guidelines during the 183 days monitoring period.

	Indoor		**Outdoor**	
	$PM_{2.5}$	**PM_{10}**	**$PM_{2.5}$**	**PM_{10}**
# of times exceeded the 24h limit:	3	0	14	26

The recirculation of the air through the filters of the AC units had a minor effect in reducing indoor PM, as our measurements revealed that the filters in the AC units had an arrestance efficiency of ~19% for PM_{10}, while the arrestance efficiency for $PM_{2.5}$ was close to 0.

3.2 Hourly PM variation

As presented in Figure 4, the PM levels were not stable during the day. Regarding indoor $PM_{2.5}$ and PM_{10} concentrations, higher concentrations were observed during working hours (7-16h) compared to non-working hours. These higher concentrations can be explained by two mechanisms: (1) the infiltration of PM from outdoors via the NV, which was only applied during the occupied hours, and (2) the particle resuspension from the occupant activities.

The outdoor PM levels equally presented high variability through the different hours of the day. Outdoor $PM_{2.5}$ and PM_{10} concentrations were higher during commuting hours (7-9h and 18-21h), indicating a relationship between outdoor PM levels and traffic. The morning $PM_{2.5}$ and

PM$_{10}$ concentration peaks are also visible in the indoor concentrations. These higher indoor PM concentrations can also be explained by two observations made *in situ*: (1) the occupants' habit of opening the window as soon as they arrive at the office, a time when the outdoor PM$_{2.5}$ and PM$_{10}$ were high, leading to an increased outdoor PM penetration indoors and (2) the increased resuspension of particles due to occupants' movements during the first working hour. More efficient ventilation that can economize energy without deteriorating IAQ could be achieved by continuously monitoring outdoor air pollution and activating ventilation when indoor and outdoor environmental conditions are favorable (Belias & Licina, 2022, 2023).

The indoor-to-outdoor ratio (I/O) of PM$_{2.5}$ was ~0.4 during unoccupied hours and ~0.7 during occupied hours, while the I/O of PM$_{10}$ was ~0.2 during unoccupied hours and ~0.5 during occupied. The low I/O ratios indicate that the primary PM source in the building was the outdoor air.

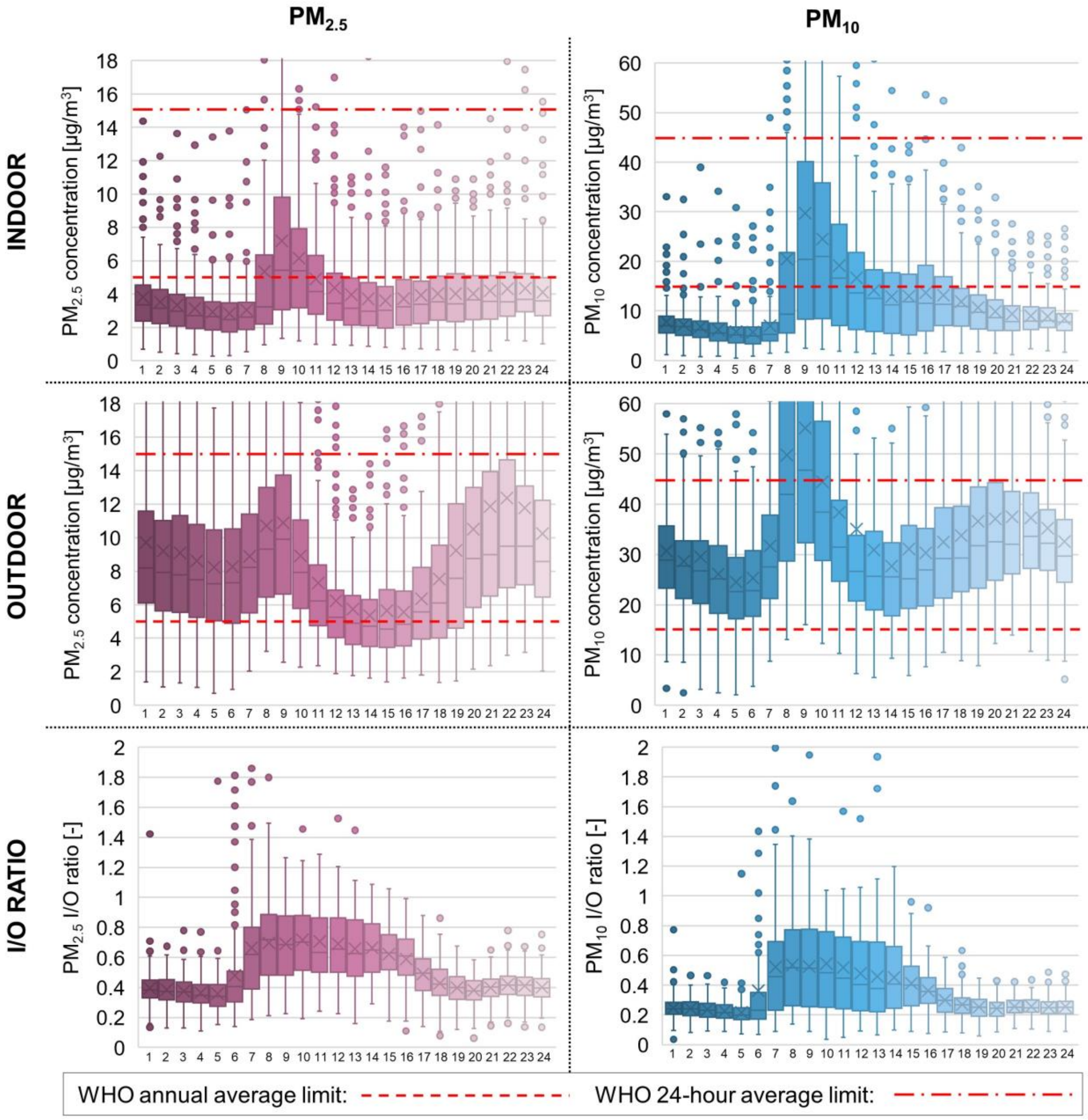

Figure 4: Hourly indoor and outdoor PM$_{2.5}$ and PM$_{10}$ concentrations as well as hourly indoor to outdoor PM$_{2.5}$ and PM$_{10}$ ratios.

3.3 Indoor CO2 levels

The continuous indoor CO_2 monitoring revealed that its concentrations remained below 1000 ppm for more than 90% of the occupied time. Figure 5 presents the CO_2 levels of a typical office, where it can be observed that during the occupied hours, the CO_2 concentrations were between 450 and 1000 ppm for the majority of the time, while on some days, they overpassed the 1000 ppm, but never the 1700 ppm. When the building was unoccupied, CO_2 levels dropped below 450 ppm. These values indicate that the occupant-controlled NV performed as designed, providing sufficient ventilation for the occupants.

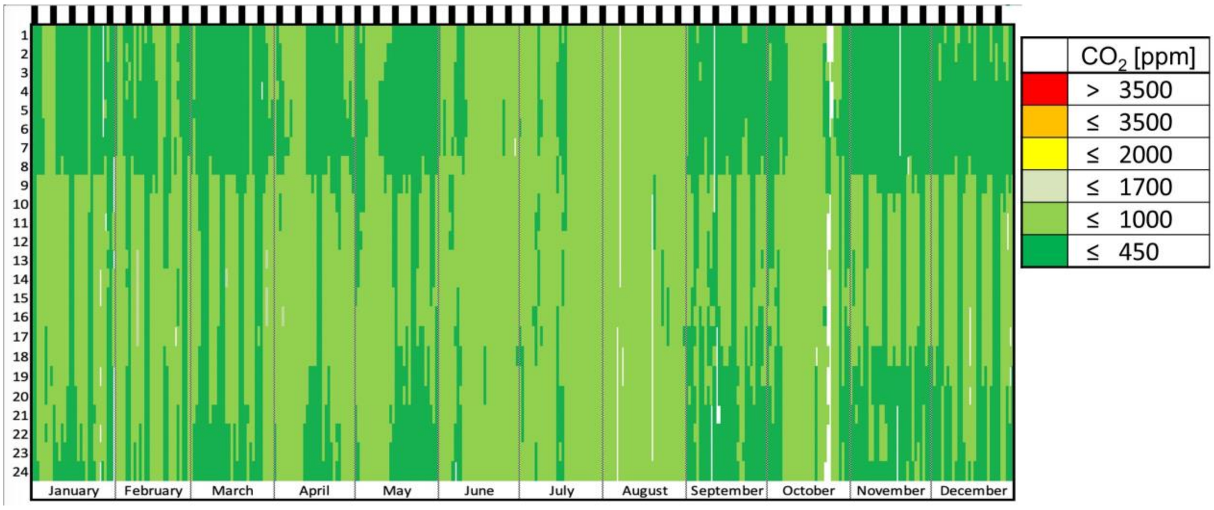

Figure 5: Indoor CO_2 levels in the south zone office. Note: weekends are represented with black on the top of the chart, hours of the day on the y-axis, and the days (grouped by months) on the x-axis.

3.4 Perceived IEQ

The feedback from the users indicated high satisfaction with the thermal environment except for one space, which was located in the northeast corner of the building, where the users reported high thermal discomfort during wintertime. This perception of thermal comfort by the users was in accordance with the measurements, as the temperatures were between the adaptive thermal comfort limits as defined by EN 16798-1 (EN 16798-1, 2019) in all the spaces except for the above-mentioned office space.

All users expressed high satisfaction regarding air quality perception, which is also in accordance with CO_2 measurements, as CO_2 concentrations remained below 1000 ppm for 90% of the occupied time. Additionally, the users reported that they found the indoor air much cleaner than the outdoor concerning the dust.

Additionally, users reported high satisfaction with the visual comfort due to the daylight from the large openings. However, the perceived acoustic quality was average, as the users reported that the sound privacy between the spaces was ineffective. Overall, more than 90% of the interviewed occupants evaluated the IEQ as exceptional and very good.

3.5 Energy consumption

Figure 6 presents the monthly expected energy consumption according to the EPC and the actual measured energy consumption for 2020-2022. The results revealed that in 2020, the building presented a significant performance gap, as it consumed more energy than predicted for several months due to the inadequate maintenance of the AC units, where the unchanged dusty filters led to malfunction and overconsumption (Siegel, 2002). Once the problem was identified and solved, the actual energy consumption was at the same levels as the predicted one, 153 kWh/m^{2}y ±10%, indicating a class A, energy-efficient building for the Cyprus climate.

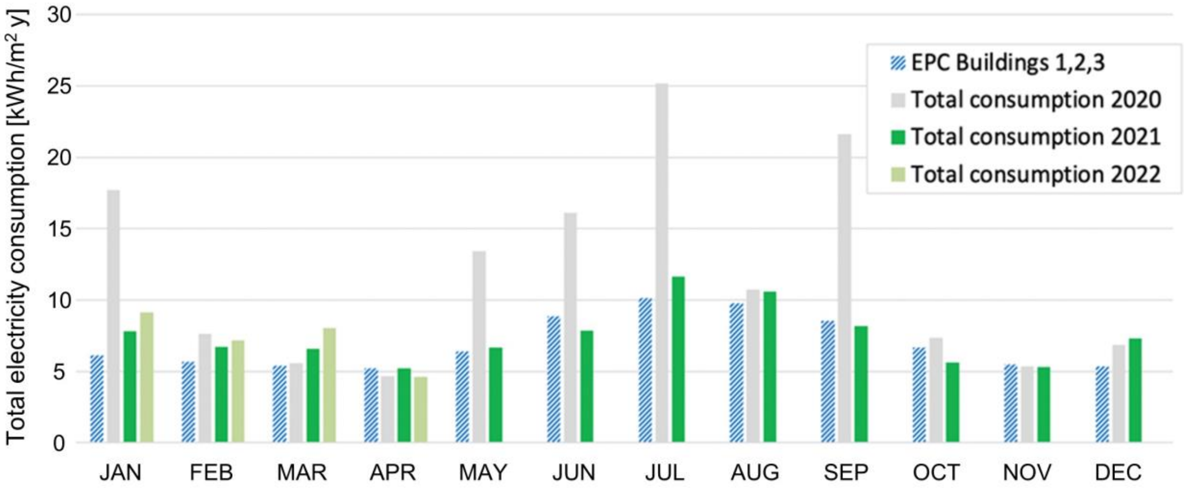

Figure 6: Monthly expected energy consumption according to the energy performance certificate (EPC) compared to the actual energy consumption during 2020-2022 years.

4 CONCLUSIONS

This study conducted measurements and occupant surveys to reveal if a low-energy, naturally ventilated (NV) office building can provide adequate indoor environmental quality (IEQ) conditions in a dusty environment characterized by a semi-arid Mediterranean climate with very mild winters and hot summers.

The results revealed average indoor concentrations during working hours in the range of 4.4-5.1 μg/m^3 for $PM_{2.5}$, while the outdoor average $PM_{2.5}$ concentration was at 7.4 μg/m^3. Indoor PM_{10} concentrations ranged from 13.8 to 19.9 μg/m^3 for an average outdoor concentration of 38.1μg/m^3. The indoor $PM_{2.5}$ levels complied with the WHO air quality guideline in 4 out of 5 monitored spaces, while PM_{10} levels respected these limits in 2 out of 5 monitored spaces, indicating that the indoor PM levels were generally acceptable. Additionally, the indoor CO_2 concentrations remained below the 1000 ppm limit for more than 90% of the time, indicating acceptable IAQ. User-perceived IEQ was aligned with the measurements, as more than 90% of the interviewed occupants evaluated the IEQ as exceptional or very good, while the building's energy use was low, being an energy class A building. These results support that well-designed and operated energy-efficient NV buildings can provide high IEQ conditions, even in environments with dusty outdoor air.

Further studies are necessary to investigate the impact of different ventilation techniques on the IEQ and energy consumption of offices as well as other building types in environments with dusty outdoor air. These efforts will generate knowledge that will enable more sustainable building design that saves energy while providing high IEQ conditions.

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