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Compliance of indoor air quality during sleep with legislation and guidelines – A case study of Lisbon dwellings

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Credit Author Statement

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"Compliance of indoor air quality during sleep with legislation and guidelines – a case study of Lisbon dwellings"

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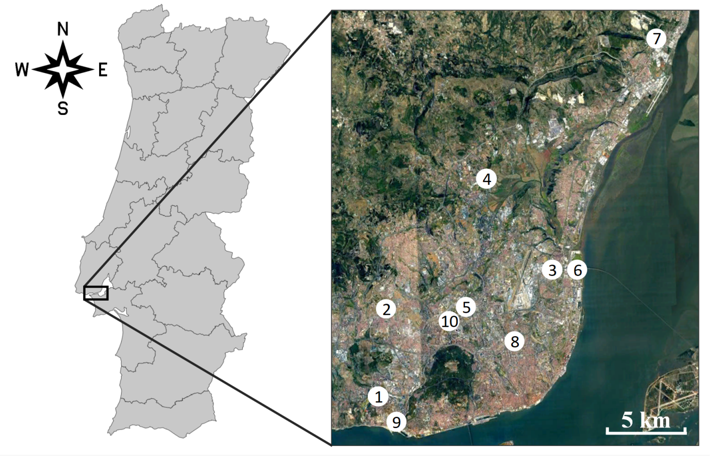
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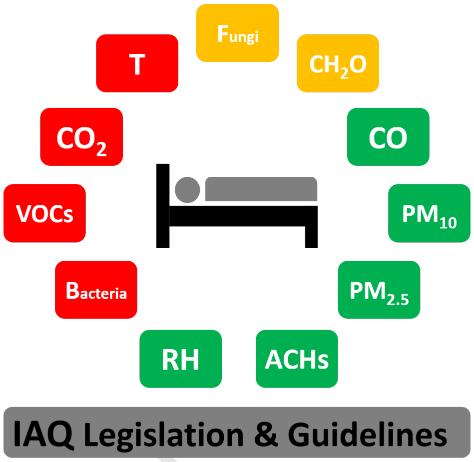
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IAQ Legislation & Guidelines

Compliance of indoor air quality during sleep with legislation and guidelines – a case study of Lisbon dwellings

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Abstract

This study aimed to provide a comprehensive characterisation of the indoor air quality during the sleeping period of 10 couples at Lisbon dwellings, using a multi-pollutant approach, and to understand how the compliance with legislation and guidelines was to assure a good indoor air quality. The assessment of indoor air quality was conducted in the cold season using real time monitors during the sleeping period for comfort parameters (temperature and relative humidity) and air pollutants (carbon dioxide – CO_2, carbon monoxide – CO, formaldehyde – CH_2O, total volatile organic compounds – VOCs, and particulate matter – $PM_{2.5}$ and PM_{10}), together with active sampling of bioaerosols (fungi and bacteria) before and after the sleeping period. Lower compliance (less than 50% of the cases) with the Portuguese legislation was found for temperature, CO_2 (3440 ± 1610 $mg.m^{-3}$), VOCs (1.79 ± 0.99 $mg.m^{-3}$) and both bioaerosol types. In 70% of the cases, $PM_{2.5}$ (15.3 ± 9.1 $\mu g.m^{-3}$) exceeded the WHO guideline of 10 $\mu g.m^{-3}$. All bedrooms presented air change rates above the recommended minimum value of 0.7 h^{-1}, highlighting that a good indoor air quality during sleep is not guaranteed.

KEYWORDS

Indoor air quality; sleep; exposure; particulate matter; bedroom; ventilation

HIGHLIGHTS

- $PM_{2.5}$ levels during sleep exceeded the WHO guideline of 10 $\mu g.m^{-3}$ in 70% of bedrooms
- Temperature, CO_2, VOCs and bacteria were above thresholds in 70% of bedrooms
- Ventilation guidelines are not enough to promote compliance with IAQ legislation

1. Introduction

Nowadays, indoor air quality (IAQ) is considered as a major factor that influences human health and the welfare of citizens (Sundell, 2004). This awareness is the result of years of research efforts, especially over the last two decades, focused on exposure levels in different microenvironments and daily activity patterns. One of the main reasons for this shift in the exposure assessment studies, namely from outdoor to indoor environments, was the awareness that, in developed countries, people spend around 90% of their time indoors (Almeida-Silva et al., 2014; Faria et al., 2020).

Taking into account that people spend one third of their life sleeping (Canha et al., 2017) and that sleep is essential for human welfare, performance and health (Krueger et al., 2016; Strøm-Tejsen et al., 2016), sleeping environments have started to gather some interest from the scientific community in recent years (Boor et al., 2017; Katsoyiannis and Cincinelli, 2019; Lan and Lian, 2016) aiming at understanding the exposure levels during sleep and how they can affect sleep quality.

The vital role of sleep in the human life is unquestionable. Multiple studies have shown its importance in many different spheres of the daily life. For instance, a study conducted with university students in the United States of America (Becker et al., 2018) found that anxiety and depressive symptoms were consistently associated with poorer sleep quality, with the former being linked with more sleep disturbances and sleep medication use, and the latter with increased daytime dysfunction. Moreover, sleep difficulties led to lower academic results, increased daytime sleepiness and emotion dysregulation.

Sleep duration also has been shown to have an impact on wellbeing, where short and long sleep duration was found to increase the risk of health outcomes (Jike et al., 2018; Lubetkin and Jia, 2018), ranging from depression, poor cognition, and obesity, to cardiovascular disease, including hypertension, coronary heart disease and stroke. A greater negative impact on morbidity and mortality was also associated with short and long sleep duration (Jike et al., 2018; Lubetkin and Jia, 2018). The lowest mortality was experienced by participants reporting a usual sleep duration of 7 hours (6.5-7.4 hours) per night (Kripke et al., 2002), which also corresponded to the lowest burden of disease in elderly people

(Lubetkin and Jia, 2018). However, the mortality hazard increased proportionately with sleeping duration, leading to an added mortality risk of 15% and an elevated hazard rate of cerebrovascular death of about 50% compared to people sleeping between 6 to 8 hours, both in men and women (Alvarez and Ayas, 2004), when reported sleep exceeded 8.5 hours, or was below 3.5 hours for women and 4.5 hours for men (Kripke et al., 2002). Sleep deprivation was also associated with the activation of the sympathetic nervous system, impairment of glucose control, increased inflammation, higher cortisol levels, and reduced levels of leptin, an appetite-suppressing hormone, which may lead to weight gain and eventually diabetes (Alvarez and Ayas, 2004). Moreover, sleep loss was also found to affect emotion regulation (Tempesta et al., 2018), lowering emotional competence and empathy.

Several studies have already found that some environmental factors of the sleeping environments have a direct impact on the sleep quality of the occupants, from comfort parameters (Lan et al., 2016; Pan et al., 2012; Zhang et al., 2018) and noise levels (Halperin, 2014) to ventilation conditions, which are related to concentrations of pollutants, such as carbon dioxide (Strøm-Tejsen et al., 2016). However, sleeping environments are still not fully characterised, considering the complexity of parameters that constitute indoor air, since most studies only focus on single pollutants, such as CO_2 (Katsoyiannis and Cincinelli, 2019). The characterisation of IAQ in these specific micro-environments faces several challenges, such as sleep disturbance due to noisy monitoring equipment (Canha et al., 2019). An IAQ overview during the sleeping period was provided in a very few studies, in which it has been shown, for instance, that several pollutants (e.g. particulate matter, carbon dioxide, formaldehyde and volatile organic compounds) can exceed the established guidelines (Almeida-Silva et al., 2014; Canha et al., 2017, 2019). A wider knowledge about the air quality that people breathe during sleep is needed in order to understand which parameters can influence sleep quality and how it can be improved by decreasing individuals' exposure.

The aim of the present study is to contribute to a comprehensive characterisation of indoor air quality of sleeping environments, based on a multi-pollutant approach (comfort parameters, chemical and biological contaminants), which is essential for future calculation of exposure levels and identifying the most critical parameters for the occupants. Therefore, this study characterised IAQ during sleep, in real conditions, of bedrooms of ten couples from Lisbon (Portugal), using a real time monitoring strategy, assessing its compliance with legislation and guidelines.

2. Materials/Methods

2.1. Study site and individual’s characterisation

Ten volunteer couples participated in an IAQ monitoring programme during the 2016/2017 cold season in the urban area of Lisbon, Portugal. Figure 1 presents the location of the dwellings where the study was conducted. All dwellings were apartments, located in different floors (varying from second to eleventh floor). Table S 1 and

Table S *2* (both in "Supplementary Information" section) present details about the studied dwellings and bedrooms, respectively.

The volunteers were selected to minimise confounders/external factors that could influence the results. Therefore, the following selection criteria were applied: couples (male-female) with ages between 25 and 45, without children with ages below 5 years, healthy (no consumption of medication), no sleep disorders history and non-smokers. Table S 3 gives details about the volunteers that participated in this study. The volunteers were requested to sleep in usual conditions, namely regarding the ventilation patterns. All of them always slept with the bedroom window closed, but some kept the door open while others closed it (only couples 5 and 8 usually slept with the bedroom door closed).

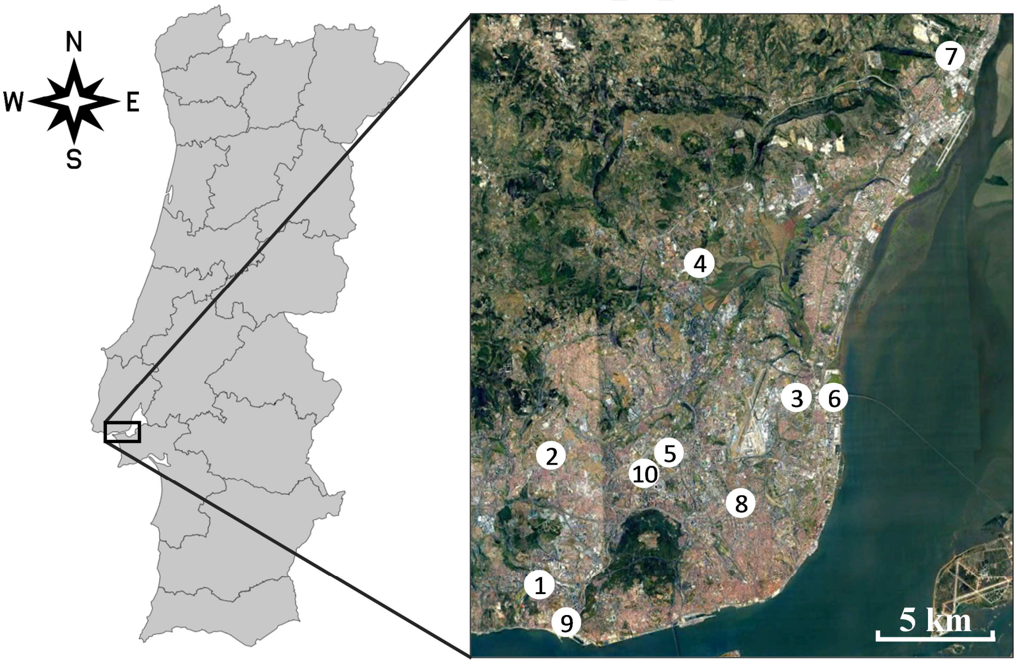

Figure 1. Location of the studied dwellings in the Lisbon district, Portugal.

2.2. Indoor air quality monitoring

The monitoring programme was based on a comprehensive multi-pollutant assessment where physical (temperature and relative humidity), chemical (carbon dioxide, carbon monoxide, formaldehyde, volatile organic compounds, particulate matter – PM_{10} and $PM_{2.5}$) and microbiological (fungi and bacteria) parameters were quantified. The IAQ monitoring was conducted during three nights relying on typical real-time instruments (Canha et al., 2017, 2019):

1) Carbon monoxide (CO_2), temperature (T), relative humidity (RH) and total volatile organic compounds (VOCs), by using a Graywolf (IQ-610 probe, WolfSense Solutions, USA);
2) Formaldehyde (CH_2O), by using a Formaldemeter (htV-M, PPM Technology, UK);
3) Particulate matter of aerodynamic diameter lower than 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}), by using a DustTrak DRX monitor (8533 model, TSI, USA).

All the devices were calibrated according to the manufacturers' specifications and the sampling frequency was set to 60 seconds. Due to the noise emitted by the pump of the DustTrak DRX monitor and in order to avoid interference with the sleep quality of the volunteers, a soundproofed wooden box was created to place this equipment in it. Figure S 1 ("Supplementary Information" section) shows the apparatus of IAQ monitoring in the bedrooms. The monitoring devices were placed at the centre of the bedroom, at approximately one meter from the bed and at about 80 cm from the floor, since this height corresponds reasonably to the breathing level of a person lying in bed.

Despite the factory calibration of the DustTraks used in our study, the response of optical instruments may vary for different types of aerosols (Moosmüller et al., 2001), which makes the calibration process of the utmost importance for accurate measurements. Therefore, $PM_{2.5}$ and PM_{10} readings of the used DustTrak instruments were rectified using correction factors obtained from an inter-comparison study using these instruments and reference gravimetric equipment from Leckel (Berlin, Germany). The Leckel samplers are certified by the European Committee for Standardisation as a reference instrument for PM_{10} and $PM_{2.5}$ measurements according to CEN EN 12341 and CEN EN 14907. This inter-comparison study was done in an office with low occupancy. Figure S 2 provides the inter-comparison results for both PM fractions, using the two different measurement methods. Reasonable to good correlations were obtained between the DustTrak and Leckel data (with R^2 ranging from 0.56 to 0.78). $PM_{2.5}$ and PM_{10} concentrations measured by DustTrak were corrected based on the linear regression equations shown in Figure S 2. One of the real time instruments over-reports the PM_{10} and $PM_{2.5}$ mass concentrations by a factor up to 1.7. This value is in line with previous studies comparing gravimetric or filter-based methods with DustTrak measurements. A study in an indoor environment impacted by biofuel combustion reported a factor of 1.65 for $PM_{2.5}$ measurements with DustTraks (McNamara et al., 2011), while in a wood smoke ambient airshed, DustTraks over-recorded PM_{10} by a factor of 2.73 (Kingham et al., 2006). Likewise, DustTraks measured concentrations that were 1.94 – 2.57 times higher than filter-based and federal reference method measurements in occupied and test homes (Ramachandran et al., 2000; Wallace et al., 2011; Yanosky et al., 2002).

Microbiological counts were also assessed in each bedroom, before and after the sleeping period (within a time frame of 30 minutes after the volunteers woke up). The sampling procedure was based on active sampling using a MAS-100^{TM} air sampler device. Colony forming units (CFU.m^{-3}) of bacteria and fungi were counted after an incubation period of 7 days at the typical temperature for each microorganism type. The methodology was already fully described elsewhere (Canha et al., 2015).

The IAQ monitoring took place from December 2016 to March 2017 in each bedroom during 3 consecutive weeknights (from Tuesday to Thursday), during the usual sleeping period of the volunteers. The monitoring period in each bedroom varied according to the usual sleeping patterns of the volunteers, with a mean sleep night of 450 minutes per bedroom and the sleeping period ranging from 22:00 to 09:20.

The mean results of the chemical and microbiological parameters for each bedroom were evaluated taking into account the Portuguese legislation (*Ordinance no. 353-A/2013*) that establishes 8-h limit values specifically for indoor air.

2.2.1. Calculation of air changes per hour

In order to characterise the ventilation of the bedrooms during the sleeping period, air changes per hour (ACHs, h^{-1}) were calculated using the tracer gas method, i.e. the CO_2 emitted by the occupants during the sleeping period and focusing on its build-up phase, through the application of a computerised tool already described elsewhere (Hänninen, 2013). Examples of its application can be found in the literature for different micro-environments, such as classrooms (Canha et al., 2016; Hänninen et al., 2017), gyms (Ramos et al., 2014) and bedrooms (Almeida-Silva et al., 2014; Canha et al., 2017).

2.3. Statistical analysis

The statistical analyses were conducted using Excel and XLSTAT 2014.1.09 software programmes. Non-parametric statistics were applied to the environmental monitored data, namely, Spearman correlations to analyse potential associations between parameters. Origin version 7.5 (OriginLab Corporation) was used to plot the results.

3. Results and Discussion

3.1. Comfort Parameters

3.1.1. Temperature

Figure 2 presents the temperature values registered during the sleeping period in the 10 bedrooms, with a mean value of 18.8 ± 2.8 ºC, ranging from 15.3 ± 0.4 (bedroom 1) to 24.8 ± 0.3 (bedroom 5). Considering the international guideline ISO 7730:2005 (ISO, 2005) that establishes a temperature range for the occupants' comfort for the colder period between 20 and 24ºC, only two bedrooms provided mean temperatures within that range (bedrooms 7 and 8). Most of the bedrooms (7 out of 10) presented mean values below the recommended range for thermal comfort, ranging from 15.3 ± 0.4 (bedroom 1) to 19.2 ± 0.4 (bedroom 9). Only bedroom 5 registered a mean temperature during sleep above the recommended guideline (24.8 ± 0.3 ºC). Overall, only 20% of the cases were within the recommended range of temperature, which is below the 58% of cases found in a previous study conducted in 12 bedrooms with single occupancy (Canha et al., 2019) in Portugal (as shown by **Error! Reference source not found.** in the Supplementary Information section).

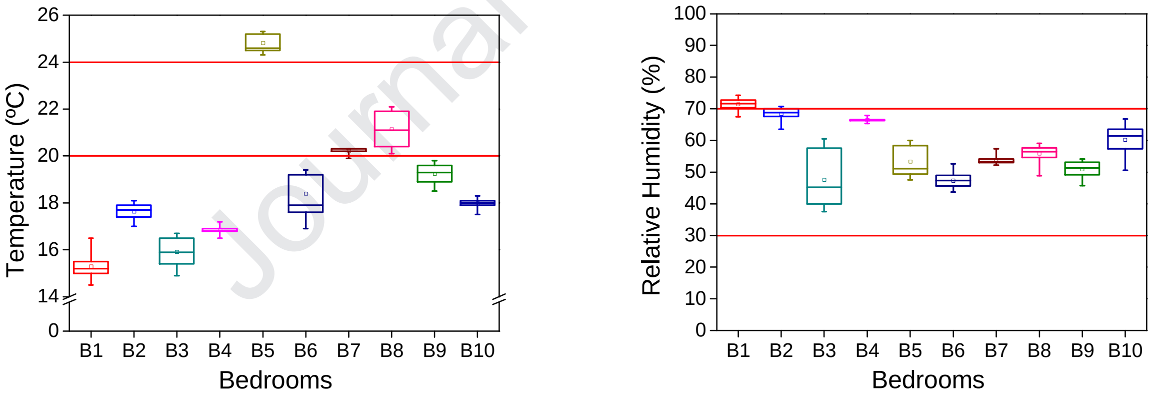

Figure 2. Temperature (left) and relative humidity (right) during the sleeping period in the 10 bedrooms. Red lines represent the recommended range of values and the box plots show the 25, 50 and 75 percentiles, with minimum, average (square) and maximum values.

Most of the bedrooms presented colder temperatures than the comfortable range for sleep, which highlights the lack of heating during the colder period and a typical type of construction in Southern European countries that is not capable to deal with the extreme temperatures that can happen in winter and in summer. These results are in agreement with a study conducted in bedrooms of 141 dwellings in the North of Portugal, where a mean temperature of 14.9 ± 3.1 ºC was found, with only 4% of the dwellings with temperatures during sleep above 20ºC (Magalhães et al., 2016).

3.1.2. Relative Humidity

An overall mean of 57.6 ± 8.7% was registered for the 10 bedrooms (Figure 2). Taking into consideration the recommended range for the occupants' comfort in indoor environments (ISO, 2005), which was set at 30-70% in colder periods, only 1 bedroom presented a mean value above the upper limit (bedroom 1, with a mean value of 71.4 ± 1.6%), while all other bedrooms have met the requirements. Similar results were found in the previous study mentioned above that assessed IAQ in 12 bedrooms with single occupancy, in which relative humidity mean values were within the recommended range. The high levels of relative humidity in bedroom 1 during sleep may be due to the outdoor conditions, since there was heavy rain during the monitoring period of that specific bedroom.

3.2. Air Changes per Hour

Figure 3 depicts the mean values of ACHs in each bedroom during the sleeping period and Table S 4 ("Supplementary Information" section) provides details about their calculation and a statistical summary. All bedrooms presented mean ACHs higher than the minimum value of 0.7 h^{-1} established for bedrooms by EN 16798-1:2019 (CEN, 2019). The global average was 2.15 ± 1.24 h^{-1}, ranging from 0.72 ± 0.19 h^{-1} (bedroom 5) to 3.75 ± 1.06 h^{-1} (bedroom 6). Bedroom 6 was the only one with mechanical ventilation, which explains the higher value of ACHs. Despite having natural ventilation, bedrooms 3 and 4 also had ACHs above 3 h^{-1}. The range of ACHs registered in the present study is similar to those obtained in previous works conducted in single occupancy bedrooms (Canha et al., 2017, 2019), which concluded that opening the bedroom door is the main factor influencing ACHs during sleep.

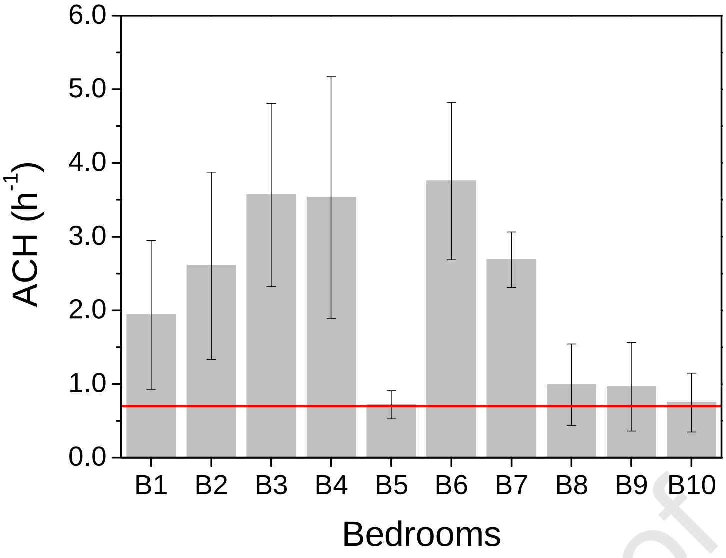

Figure 3. Air change rates for each bedroom during the sleeping period. Red line stands for the minimum value of 0.7 h^{-1} established for bedrooms by EN 16798-1:2019 (CEN, 2019).

3.3. Carbon Dioxide

Only 30% of bedrooms were below the limit value of 2250 mg.m^{-3} defined by the Portuguese legislation (*Ordinance no. 353-A/2013*) set to CO_2 concentration (Figure 4). Overall, the mean CO_2 level during sleep registered in this study was 3440 ± 1610 mg.m^{-3}, ranging from 1200 ± 210 mg.m^{-3} (bedroom 6) to 6810 ± 660 mg.m^{-3} (bedroom 1). The bedroom with the lowest CO_2 levels was the same that had the highest ACHs, i.e. the one with mechanical ventilation, showing the importance of this system in diluting air contaminants.

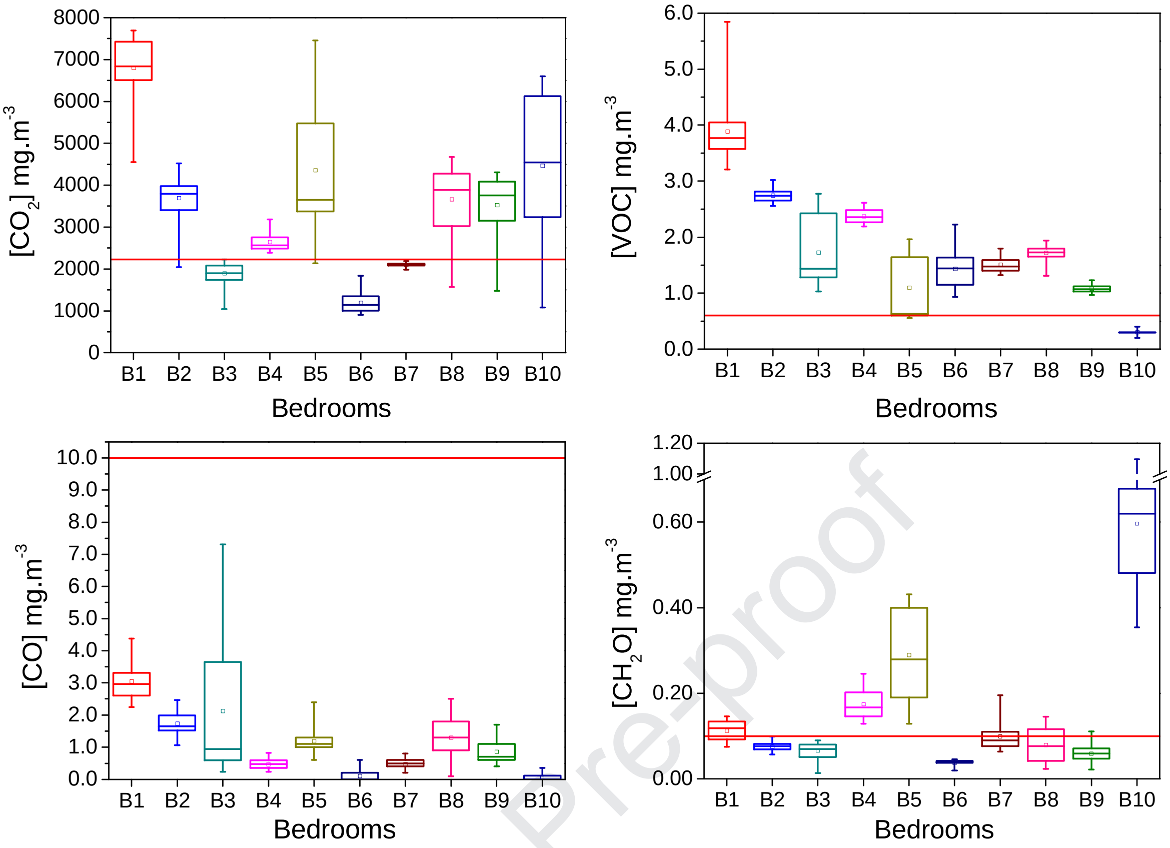

Figure 4. Levels of CO_2 (top, left), CO (bottom, left), VOC (top, right) and CH_2O (bottom, right) during the sleeping period in each bedroom. Red lines represent the limit value established by the Portuguese Ordinance no. 353-A/2013 for each parameter. Box plots present 25, 50 and 75 percentiles, with minimum, average (square) and maximum values.

Carbon dioxide levels clearly indicates that the air change rates are not enough to promote its dilution (concurrently with other pollutants) during sleep, which can lead to a lower quality of sleep. As already described in the literature, high levels of carbon dioxide during sleep promote a lower sleep quality and next day performance (Strøm-Tejsen et al., 2016). A CO_2 level of around 1500 mg.m^{-3} (835 ppm) was considered the threshold above which several parameters would be negatively affected, such as, sleep quality and next-day performance (Strøm-Tejsen et al., 2016), in a study with university's students in Denmark. In the present study, only one bedroom (bedroom 6) presented a mean CO_2 level during the sleeping period lower than this threshold. It is important to highlight that all bedrooms were occupied by two adults, which may explain the higher CO_2 levels found in the present study, when comparing to single occupancy studies, such as the ones previously conducted in Portugal. In single-unit dwellings, mean CO_2 levels were always below the limit value of 2225 mg.m^{-3} (Canha et al., 2017), while other study registered 67% of the cases (8 out of 12 bedrooms with single occupancy) with mean values above the limit value and a peak mean CO_2 level of 4808 ± 1139 $mg.m^{-3}$ (Canha et al., 2019). A study in Portuguese elderly care centres found that 40% of the cases (4 in 10 bedrooms with single occupancy) had mean levels of CO_2 above the limit value, peaking at 3000 $mg.m^{-3}$ (Almeida-Silva et al., 2014). During the sleeping period, the occupants are the only source of CO_2 and its generation rate per person depends of several factors, such as the age, gender and other physiological parameters like the mean body mass (Persily and de Jonge, 2017). On average, the CO_2 generation rate by a couple (one male and one female) during sleep is 0.0036 $L.s^{-1}$.person (Persily and de Jonge, 2017).

A study conducted in Poland during the sleeping period of one female teenager (Mainka and Zajusz-Zubek, 2019) showed that CO_2 levels of 6000 $mg.m^{-3}$ were reached several times, when the bedroom's door was closed. Another study carried out in Chinese student dormitories reported a mean CO_2 steady value of 3150 $mg.m^{-3}$ during sleep and associated levels above 3384 $mg.m^{-3}$ with worse IAQ satisfaction (Zhang et al., 2018).

3.4. Carbon Monoxide

The mean CO level was 1.14 ± 0.96 $mg.m^{-3}$, ranging from 0.05 ± 0.07 $mg.m^{-3}$ (bedroom 10) to 3.05 ± 0.52 $mg.m^{-3}$ (bedroom 1) (Figure 4). All bedrooms presented mean CO levels always below the limit value of 10 $mg.m^{-3}$ established by the Portuguese legislation (*Ordinance no. 353-A/2013*). Bedroom 1 was the one where CO levels were higher during sleep. This is likely related to the location of the kitchen, which was next to the bedroom, and, therefore, some CO infiltration may have occurred due to the emissions of the appliances that existed in there.

Carbon monoxide is typically a product of incomplete combustion processes that, in indoor environments, can be originated by cooking appliances, water heating systems or fireplaces (Canha et al., 2018; Mullen et al., 2016), or by infiltration from outdoor sources, such as traffic exhaust emissions (Ramos et al., 2016).

3.5. Formaldehyde

Overall, the mean CH_2O level was 0.16 ± 0.17 $mg.m^{-3}$, ranging from 0.04 ± 0.17 $mg.m^{-3}$ (bedroom 6) to 0.60 ± 0.14 $mg.m^{-3}$ (bedroom 10). Four bedrooms showed mean CH_2O levels during the sleeping period above the limit value of 0.1 $mg.m^{-3}$ established by the Portuguese legislation (Figure 4). High levels of CH_2O indoors may be originated from emissions from household materials and consumer products (Canha et al., 2017).

The results of the present study showed a high variability between the studied bedrooms but are, in some way, in agreement with other results documented in the literature. A previous study conducted in bedrooms of smokers and non-smokers in Portugal showed a significant difference between the CH_2O levels in each type of bedroom during the sleeping period (Canha et al., 2019): 0.11 ± 0.03 $mg.m^{-3}$ (smokers) and 0.05 ± 0.14 $mg.m^{-3}$ (non-smokers). Another study that evaluated different ventilation conditions in a single room reported CH_2O levels ranging from 0.090 ± 0.034 $mg.m^{-3}$ (bedroom with closed door and open window) to 0.205 ± 0.082 $mg.m^{-3}$ (both door and window opened) (Canha et al., 2017). A study in 10 bedrooms of elderly care centres in Lisbon (Portugal) revealed mean CH_2O levels ranging from 0.03 to 0.15 $mg.m^{-3}$ (Almeida-Silva et al., 2014). In the USA a mean value of 0.017 $mg.m^{-3}$ was found in 340 bedrooms (Mullen et al., 2016), in Spain a mean value of 0.027 $mg.m^{-3}$ was monitored in 10 bedrooms (Rovira et al., 2016), in Gonabad (Iran) a mean level of 0.149 $mg.m^{-3}$ was registered in 20 bedrooms of new houses (Dehghani et al., 2018) and in Shanghai (China) a mean level of 0.029 $mg.m^{-3}$ was found in 20 bedrooms of asthmatic children (Fang et al., 2019). Overall, the values of the studies conducted in Portugal are slightly higher than the ones reported for other countries. In addition to possible variations in sources and physical parameters that affect emissions (e.g. temperature), the use of different measurement techniques can affect the comparability of results. In the present study, a real monitoring device (Formaldemeter htV-M) was used. Its lower specificity for lower concentrations (<0.120 $mg.m^{-3}$) and potential interferences on the electrochemical sensor from other VOCs (Hirst et al., 2011) may contribute to some inaccuracy of the results. Despite the potential overestimation of CH_2O levels, this type of methodology has the advantage of allowing the temporal variability of the pollutant during the sleeping period. Instead, standard methods based on liquid impingers, coated-solid cartridges, or sorbent tubes, only provide a value over the exposure time.

3.6. Volatile Organic Compounds (VOCs)

Only one bedroom (B10) presented a mean VOC level (0.33 ± 0.05 $mg.m^{-3}$) below the limit value of 0.1 $mg.m^{-3}$ established by the Portuguese Ordinance no. 353-A/2013 (Figure 4), namely. The overall mean was 1.79 ± 0.99 $mg.m^{-3}$, which is around 18 times higher than the threshold, with the highest level being registered in bedroom 1 (3.89 ± 0.50 $mg.m^{-3}$). Similar VOC patterns have already been found in previous studies, although of a lower magnitude, with concentrations exceeding 5 times the recommended value (Canha et al., 2019). This group of pollutants is emitted by common household products and building materials, such as paints and varnishes, as well as by cleaning and consumer products (Chin et al., 2014).

3.7. Particulate Matter (PM)

The overall $PM_{2.5}$ mean (15.3 ± 9.1 µg.m^{-3}) was below the limit value of 25 µg.m^{-3} established by the Portuguese legislation (Figure 5). $PM_{2.5}$ concentrations ranged from 4.7 ± 3.7 µg.m^{-3} (bedroom 2) to 36.6 ± 36.8 µg.m^{-3} (bedroom 1). Only bedroom 1 presented levels above the threshold during the sleeping period, although the mean value in bedroom 8 (24.4 ± 23.0 µg.m^{-3}) was also close to the legal limit.

The PM_{10} mean levels registered in all bedrooms were also below the threshold of 50 µg.m^{-3} imposed by the Portuguese legislation, with an overall mean concentration of 19.9 ± 12.0 µg.m^{-3}, ranging from 5.9 ± 5.1 µg.m^{-3} (bedroom 2) and 48.6 ± 50.4 µg.m^{-3} (bedroom 1). A high proportion of PM_{10} was composed of fine particles. $PM_{2.5}$ accounted, on average, for 77 ± 4 % of PM_{10} levels (ranging from 72% in bedroom 5 to 84% in bedroom 10).

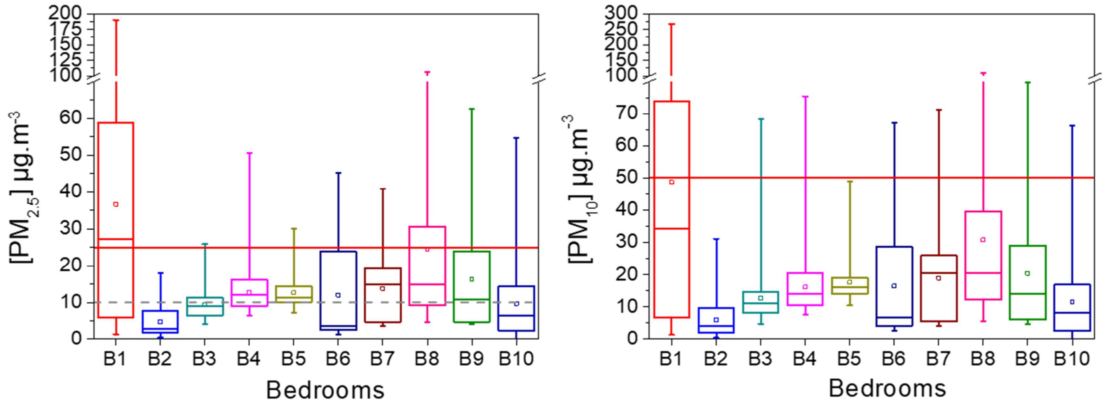

Figure 5. PM levels during the sleeping period in the 10 studied bedrooms: (left) $PM_{2.5}$ and (right) PM_{10}. Red lines represent the limit values established by the Portuguese Ordinance no. 353-A/2013, whilst the dash grey line is the guideline value recommended by the World Health Organisation. Box plots present the 25, 50 and 75 percentiles, with minimum, average (square) and maximum values.

Coarse particles are typically associated with resuspension of mineral dust (Calvo et al., 2013) but, in indoor environments, a variety of human activities, such as cleaning or ironing, and other sources, such as textiles or human skin desquamation, contribute to the PM_{10} levels (Alves, 2017; Morawska et al., 2017). Regarding the fine particles, 70% of the bedrooms showed mean levels above the guideline of 10 µg.m^{-3} recommended by the World Health Organisation (EEA, 2018). It is important to highlight that WHO states that there is no evidence of a safe level of PM exposure or a concentration value below which no adverse effects occur (WHO Regional Office for Europe, 2013) and, due to this awareness and scientific outcomes already achieved, in 2013, $PM_{2.5}$ was classified as carcinogenic to human beings by the International Agency for Research on Cancer (IARC, 2013; Loomis et al., 2013).

Moreover, even if, according to the national legislation, the mean levels of PM can be considered relatively low, their impacts on occupants' personal exposure can be significant, given the time people spend in the bedroom (typically around 8h). A study conducted in Lisbon (Portugal) to assess children's exposure to particulate matter found that, after the classroom ($PM_{2.5}$ - 42.4%; PM_{10} – 49.7%), bedrooms are the micro-environment that contribute most to exposure ($PM_{2.5}$ – 26.7%; PM_{10} – 21.5%) (Faria et al., 2020), despite being the one with the lowest concentrations (always below 20 $\mu g.m^{-3}$). The estimated exposure during the sleeping period in weekdays was 141 $\mu g.m^{-3}.h$ and 177 $\mu g.m^{-3}.h$ for $PM_{2.5}$ and PM_{10}, respectively. Higher exposures were registered on weekends: 192 $\mu g.m^{-3}.h$ for $PM_{2.5}$ and 245 $\mu g.m^{-3}.h$ for PM_{10}. As stated above, the high exposure to PM is due to the significant time spent in this micro-environment, which shows its importance to the overall human exposure.

The exposure (E) is defined by $E = C_j.t_j$, where C_j is the PM concentration measured in a specific micro-environment and t_j is the time spent in it (Faria et al., 2020; Morawska et al., 2013). The potential inhaled dose (D) can be estimated by multiplying the exposure in a specific micro-environment by the inhalation rate (IR, $m^3.h^{-1}$) of the occupants during that period. IR depends on the type of activity developed by the occupants and their age (Buonanno et al., 2011). For the volunteers of the present study, the IR for sleeping and resting can be assumed as 0.36 $m^3.h^{-1}$ (age group between 19 and 40 years old) (Buonanno et al., 2011). Table 1 presents PM exposure and potential inhaled dose assessed for the bedrooms of the present study.

Table 1. $PM_{2.5}$ and PM_{10} exposure and correspondent potential inhaled dose during the sleeping period for the studied bedrooms.

	Exposure ($\mu g.m^{-3}.h$)		Potential inhaled dose (μg)	
Bedroom	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}
1	272.8	362.1	98.2	130.3
2	41.4	43.7	14.9	15.7
3	67.2	93.9	24.2	33.8

4	86.3	120.0	31.1	43.2
5	85.3	131.2	30.7	47.2
6	95.8	122.4	34.5	44.1
7	100.4	140.5	36.1	50.6
8	177.9	229.2	64.1	82.5
9	142.6	152.0	51.3	54.7
10	66.5	86.0	23.9	30.9
Mean ± SD	113.6 ± 64.8	148.1 ± 84.8	40.9 ± 23.3	53.3 ± 15.7
[Min-Max]	[41.4 - 272.8]	[43.7 - 362.1]	[14.9 - 98.2]	[15.7 - 130.3]

Exposures to $PM_{2.5}$ and PM_{10} were estimated to be 113.6 ± 64.8 µg.m^{-3}.h and 148.1 ± 84.8 µg.m^{-3}.h, respectively. These values are lower than the ones previously assessed for children in Lisbon (Faria et al., 2020): 141.4 µg.m^{-3}.h for $PM_{2.5}$ and 177.4 µg.m^{-3}.h for PM_{10}. The mean potential inhaled doses during the sleeping period in the present study was 40.9 ± 23.3 µg for $PM_{2.5}$ and 53.3 ± 15.7 µg for PM_{10}, which were close to the assessed potential inhaled doses by children (43.8 µg for $PM_{2.5}$ and 55.0 µg for PM_{10}) (Faria et al., 2020).

3.8. Bioaerosols

Levels of bioaerosols (bacteria and fungi) were quantified before (night) and after the sleeping (morning) period in the 10 bedrooms (Figure 6). For fungi, due to operational and logistical constraints, it was not possible to assess the loads in bedroom 10). The Portuguese legislation establishes that the indoor bacteria levels should be lower than the sum of the outdoor level and 350 CFU.m^{-3}, while for fungi the indoor levels should be simply lower than the outdoor levels (*Ordinance no. 353-A/2013*). For bacteria, in 80% of the cases, the morning levels were above the limit value established by the national legislation. This is likely related to the fact that humans are a source of bacteria (Canha et al., 2015). Regarding fungi, only 44% of the bedrooms presented morning values below the corresponding outdoor loads. A morning/night ratio of 1.12 ± 0.57 was registered for fungi, while the corresponding value for bacteria was 2.21 ± 2.10, highlighting the role of human occupancy as a driver of bacterial contamination in the indoor air. The present study only quantified the colony forming units. However, further work should be conducted in order to perform the identification of the different species of fungi and bacteria in sleeping environments.

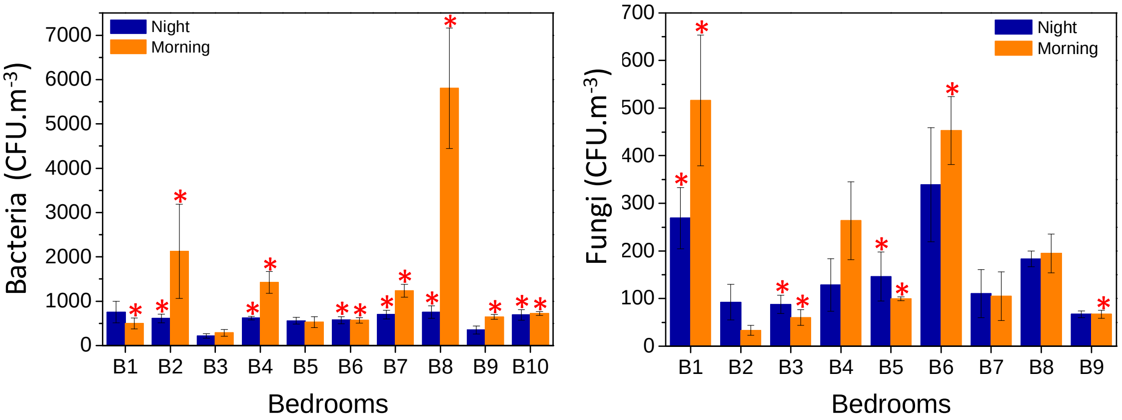

Figure 6. Bioaerosols levels before (night) and after sleep (morning): (left) bacteria and (right) fungi. Red asterisks stand for cases above the limit values established by the Portuguese legislation (*Ordinance no. 353-A/2013*).

3.9. Spearman Correlations

Table S 5 (in the "Supplementary Information" section) shows the spearman correlations between the monitored parameters of indoor air during the sleeping period. The relative humidity was positively correlated with both CO_2 and bacterial loads. These two last parameters are both associated with the human presence, since CO_2 released through breathing (Strøm-Tejsen et al., 2016), while several bacterial communities are shed by occupants (Hospodsky et al., 2012). A negative association between ACHs and CO_2 was found, as expected, since higher ACHs promote higher CO_2 dilution (Canha et al., 2016). Moreover, ACHs were calculated from CO_2 levels, which highlights this association.

A positive relationship between CO_2 and CH_2O, already described in other studies (Canha et al., 2016), was also observed, indicating that formaldehyde is emitted by indoor sources, such as building materials and consumer products (WHO, 2010).

A positive association between CO and VOCs was also found, highlighting their common source, such as infiltration of traffic emissions (von Schneidemesser et al., 2010). $PM_{2.5}$ and PM_{10} correlate well between each other, which is not surprising, as it was found that a significant part of PM_{10} is composed of fine particles. As expected, the fungi levels before and after the sleeping period also presented a positive association, since no local source of fungi is present in the bedroom during the sleeping period. This is line with the morning/night ratio of 1.12 ± 0.57, previously mentioned.

3.10. Considerations

The use of real time monitors to assess temporal variability of pollutants during sleep is a good strategy to overcome some problems that can arise from reference methods, such as the gravimetric method for particulate matter, due to the noise of the sampling pumps and its potential interference in the sleep of the volunteers. However, despite all precautions on the use of such equipment (such as calibrations), results should be critically evaluated since potential under and over-estimation may be found, as already discussed and described elsewhere (Canha et al., 2019, 2017). Anyway, this multi-pollutant strategy allows a comprehensive assessment of the indoor air quality during sleep, with minimum impact on the volunteers' sleep, and provides meaningful insights about the compliance with guideline values, information that is scarce in the literature (Lan and Lian, 2016). The present work, as summarised in Table 2, shows that the indoor air quality during sleep in couples' bedrooms during winter time presents non-conformities for different parameters. On average, indoor air quality during sleep was within acceptable ranges only for 61% of the parameters, highlighting the need to focus on such type of environments and the need to apply preventive and remedial measures to breathe healthier air.

Table 2. Compliance of IAQ for 11 parameters in the studied bedrooms with Portuguese legislation and other guidelines (*). "Yes" when the parameter is within the acceptable range or "No" if otherwise.

	IAQ Parameters											
Bedroom	**T***	**RH***	**ACHs***	**CO$_2$**	**CO**	**CH$_2$O**	**VOCs**	**PM$_{2.5}$**	**PM$_{10}$**	**Bacteria**	**Fungi**	**% Yes**
B1	No	No	Yes	No	Yes	No	No	No	Yes	No	No	27%
B2	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	Yes	64%
B3	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	73%
B4	No	Yes	Yes	No	Yes	No	No	Yes	Yes	No	Yes	55%
B5	No	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	No	55%
B6	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	64%
B7	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	82%
B8	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	Yes	73%
B9	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	No	55%
B10	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	n/a	60%
% Yes	20%	90%	100%	30%	100%	60%	10%	90%	100%	20%	44%	

Some other limitations of the present study include the limited number of bedrooms (10) and the reduced monitoring period (only 3 nights per bedroom). However, the information gathered allows a first understanding of how IAQ can vary during the sleeping period of a couple in a typical bedroom of a dwelling in Lisbon. To have a more robust characterisation of this type of micro-environment, future efforts should be conducted to increase the number of bedrooms. Moreover, further work should also be carry out to understand which environmental factors may have impact on sleep quality, taking into account the importance of nigh rest in the quality of human life.

4. Conclusions

The bedrooms under study presented an overall compliance of 61 ± 15 % with the guidelines, ranging from 27% (bedroom 1) to 82% (bedroom 7). The parameters that fully met the mandatory requirements in all bedrooms were only ACHs, CO and PM_{10}. The parameters that showed a lower compliance (less than 50% of the cases) were temperature (30%), CO_2 (30%), VOCs (10%), and bioaerosols, namely, bacteria (20%) and fungi (44%), together with $PM_{2.5}$ (30%), when considering the WHO guideline.

Air change rates, despite always being above the established guideline (0.7 h^{-1}), are clearly not enough to provide a good indoor air quality during sleep by promoting the dilution of the pollutants emitted. Therefore, a clear evidence from this work is that air change rates are not enough to ensure compliance of pollutant levels with legal standards and guidelines. Lower air quality may lead to lower sleep quality, as already described in the literature for CO_2 levels and comfort parameters, which, in turn, will promote a degradation of the human welfare and performance during daytime.

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7. Supplementary Information

Table S 1. Details of the studied dwellings located in the district of Lisbon, Portugal.

	Location													**Window**	
Dwelling	**Parish**	**Municipality**	**Construction Year (recent renovation)**	**Area (m^2)**	**Heigth (m)**	**Typology, Tn***	**Type of ownership**	**Type**	**Floor level**	**Type of house heating**	**Fuel to cook**	**Type of Ventilation**	**Type of flooring**	**Type of frame**	**Type of Glass**
1	Linda-a-Velha	Oeiras	1960 (2015)	52	2.8	T1	Rented	Apartment-type	2	Electric heaters	Gas	Natural ventilation	Wood	Aluminum	Double
2	Mina de Água	Amadora	2007	115	2.1	T2	Own	Apartment-type	3	Electric heaters	Electricity	Natural ventilation	Wood	Aluminum	Double
3	Portela	Lisbon	1990 (2015)	120	2.7	T2	Own	Apartment-type	2	Electric heaters	Gas	Natural ventilation	Wood	Aluminum	Double
4	Loures	Loures	2011	110	2.5	T2	Own	Apartment-type	8	Air conditioning	Electricity	Natural ventilation	Wood	Aluminum	Double
5	Carnide	Lisbon	2005	95	2.8	T2	Rented	Apartment-type	4	Oil heaters	Gas	Natural ventilation	Wood	Aluminum	Double
6	Parque das Nações	Lisbon	2007	180	2.8	T4	Own	Apartment-type	11	Central heating	Gas	Mechanical ventilation	Wood	Aluminum	Double
7	Sobralinho	Vila Franca de Xira	2009	80	2.8	T2	Rented	Apartment-type	3	Electric heaters	Gas	Natural ventilation	Tiles	Aluminum	Double
8	Alvalade	Lisbon	1970 (2008)	100	2.87	T5	Rented	Apartment-type	2	n/a	Gas	Natural ventilation	Wood	Wood	Simple
9	Algés	Lisbon	1960 (2012)	75	2.8	T2	Rented	Apartment-type	3	Electric heaters	Gas	Natural ventilation	Wood	Aluminum	Double
10	Carnide	Lisbon	1990 (2013)	82	2.6	T1	Rented	Apartment-type	4	Electric heaters	Gas	Natural ventilation	Wood	Aluminum	Simple

* Tn where n is the number of rooms

Table S 2. Details of the studied bedrooms.

				Windows					Doors			
Dwelling	**Bedroom**	**Area (m^2)**	**Floor type**	**Nr**	**Area (m^2)**	**Type of frame**	**Glass type**	**Outdoor**	**Nr**	**Area (m^2)**	**Door facing**	**Area of carpets or rugs (m^2)**
1	B1	12.2	Wood	1	1.37	Aluminum	Double	Street	1	1.41	Hallway + bathroom + kitchen	2.78
2	B2	20.0	Wood	1	2.80	Aluminum	Double	Street	1	1.60	Hallway	n/a
3	B3	15.8	Wood	1	2.80	Aluminum	Double	Street	1	1.60	Hallway	n/a
4	B4	15.2	Wood	1	2.86	Aluminum	Double	Square in between buildings	2	1.50	Hallway + bathroom	1.32
5	B5	12.0	Wood	1	2.80	Aluminum	Double	Street	1	1.50	Hallway	n/a
6	B6	18.0	Wood	1	8.00	Aluminum	Double	Street	1	1.60	Hallway	4.50
7	B7	10.5	Wood	1	2.62	Aluminum	Double	Street	1	1.50	Hallway	1.20
8	B8	20.0	Wood	2	4.72	Wood	Simple	Street	1	1.54	Hallway	n/a
9	B9	10.5	Wood	3	4.32	Aluminum	Double	Street	1	1.60	Hallway	n/a
10	B10	10.5	Wood	1	0.99	Aluminum	Simple	parking space and leisure park	1	1.40	Hallway	0.77

Table S 3. Details of the participants in the study.

Dwelling	Gender	Age	Height (m)	Weight (kg)
1	Female	28	1.63	50
	Male	29	1.86	83
2	Female	34	1.67	69
	Male	41	1.80	82
3	Female	29	1.61	60
	Male	31	1.74	70
4	Female	31	1.60	59
	Male	36	1.83	110
5	Female	26	1.65	66
	Male	26	1.81	74
6	Female	41	1.62	69
	Male	44	1.84	75
7	Female	26	1.64	64
	Male	26	1.73	73
8	Female	27	1.61	55
	Male	27	1.75	82
9	Female	30	1.66	51
	Male	31	1.80	70
10	Female	33	1.62	70
	Male	28	1.72	88

Table S 4. Details of the calculation of air change rates and statistical summary for each studied bedroom.

				Air Change Rates, h^{-1}			
Bedroom	Nr Nights	Nr CO_2 events	Sleeping period (minutes)	Mean ± SD	Median	Min	Max
1	3	8	374	1.94 ± 1.01	1.64	0.96	3.77
2	3	15	568	2.60 ± 1.27	1.91	1.08	4.38
3	3	4	187	3.56 ± 1.25	3.71	2.04	4.80
4	2	5	209	3.53 ± 1.64	2.68	2.30	6.10
5	2	7	341	0.72 ± 0.19	0.65	0.46	0.96
6	2	8	277	3.75 ± 1.06	3.72	2.29	5.38
7	1	5	167	2.69 ± 0.38	2.59	2.34	3.28
8	3	12	618	0.99 ± 0.55	1.02	0.15	2.35
9	1	5	300	0.96 ± 0.60	1.11	0.32	1.62
10	2	11	433	0.75 ± 0.40	0.80	0.29	1.52

Table S 5. Spearman correlations between indoor air parameters monitored during the sleeping period. Values in bold refer to significant correlations ($p\text{-value} < 0.050$).

	T	**RH**	**ACHs**	**CO$_2$**	**CO**	**CH$_2$O**	**VOCs**	**PM$_{2.5}$**	**PM$_{10}$**	**Fungi - N**	**Fungi - M**	**Bacteria - N**	**Bacteria - M**
T	1	-0.39	-0.47	-0.05	-0.32	0.04	-0.62	0.19	0.27	0.04	-0.20	-0.05	0.32
RH		1	-0.25	**0.71**	0.26	0.56	0.56	0.20	0.01	0.15	0.22	**0.70**	0.39
ACHs			1	**-0.78**	-0.01	-0.55	0.47	-0.25	-0.22	0.02	0.14	-0.13	-0.08
CO$_2$				1	0.26	**0.66**	0.05	0.22	0.15	0.22	0.13	0.45	0.03
CO					1	-0.18	**0.67**	0.16	0.28	-0.19	-0.32	0.03	-0.27
CH$_2$O						1	-0.08	0.09	-0.07	0.22	0.27	0.44	0.09
VOCs							1	0.09	0.05	0.04	0.08	0.33	0.07
PM$_{2.5}$								1	**0.95**	0.28	0.49	0.55	0.05
PM$_{10}$									1	0.30	0.39	0.42	-0.12
Fungi - N										1	**0.83**	0.58	-0.03
Fungi - M											1	0.60	-0.09
Bacteria - N												1	0.42
Bacteria - M													1

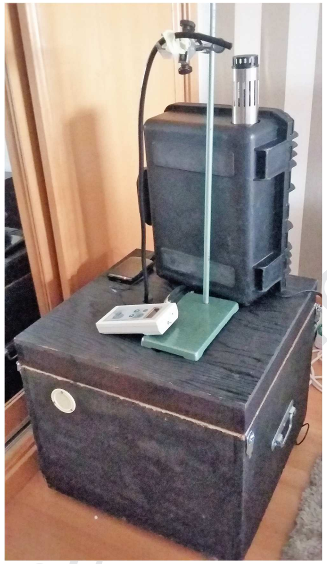

Figure S 1. Apparatus of IAQ monitoring during sleep with detail of the soundproofed wooden box and the real-time monitors.

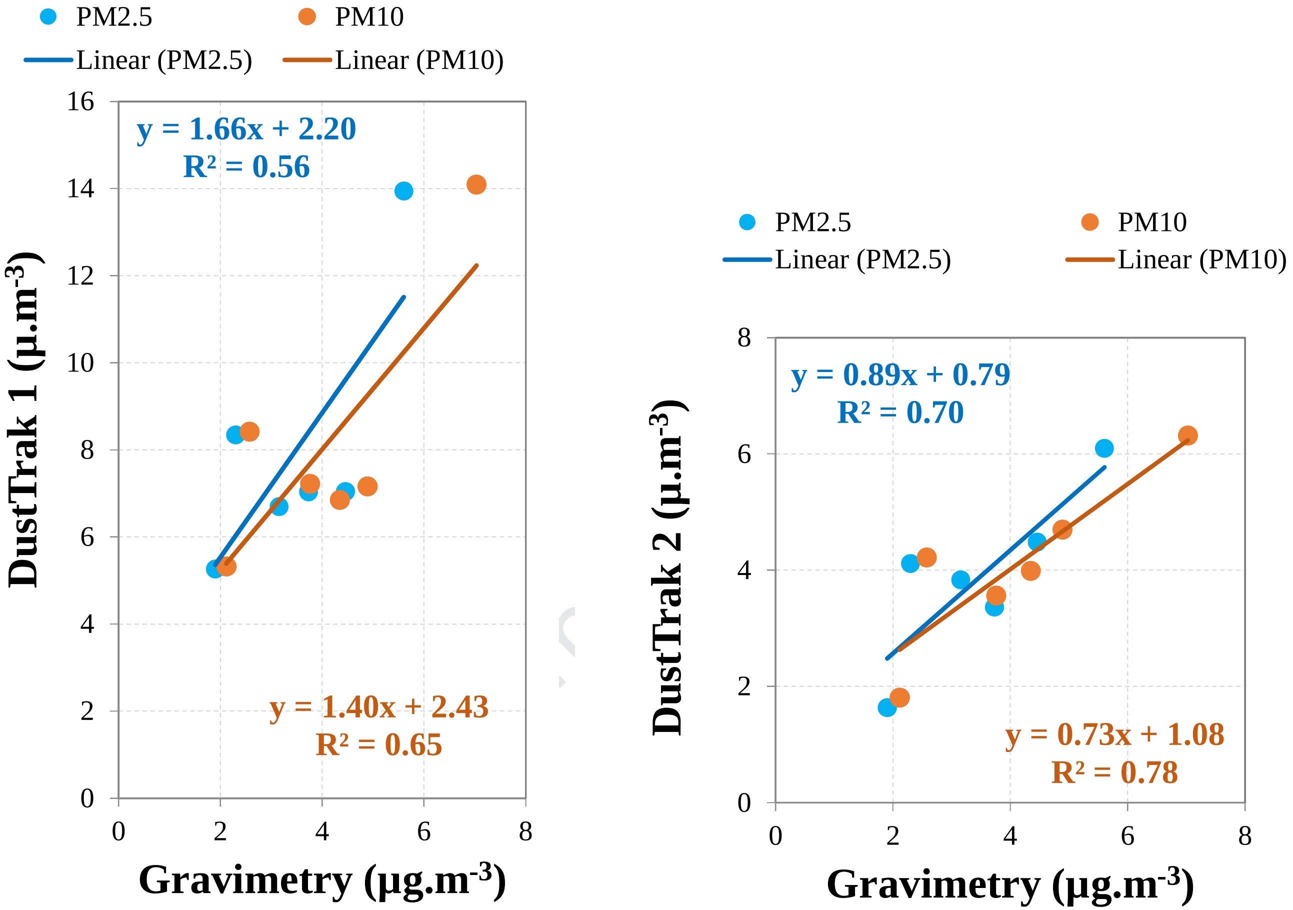

Figure S 2. Inter-comparison exercise of measuring PM concentrations (µg.m^{-3}) with the two DustTrak devices used in this study and the gravimetric method in an indoor environment.

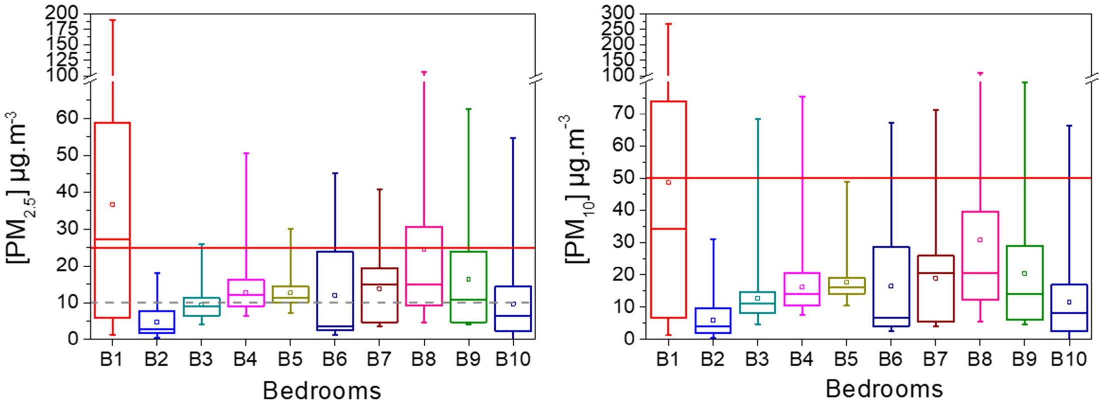

Figure 1. PM levels during the sleeping period in the 10 studied bedrooms: (left) PM$_{2.5}$ and (right) PM$_{10}$. Red lines represent the limit values established by the Portuguese Ordinance no. 353-A/2013, whilst the dash grey line is the guideline value recommended by the World Health Organisation. Box plots present the 25, 50 and 75 percentiles, with minimum, average (square) and maximum values.

Compliance of indoor air quality during sleep with legislation and guidelines – a case study of Lisbon dwellings

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HIGHLIGHTS

- $PM_{2.5}$ always exceeded the WHO guideline of 10 µg.m^{-3} during the sleeping period
- Temperature, CO_2, VOCs and bacteria were above thresholds in 70% of bedrooms
- Ventilation guidelines are not enough to promote compliance with IAQ legislation