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# Indoor environmental quality in offices and risk of health and productivity complaints at work: A literature review

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## ABSTRACT

Many service jobs are carried out in modern offices, with individual offices being increasingly replaced by open-plan settings. The high number of adult people working in office buildings, in most situations sharing the workplace with many others during a considerable part of their daily time, highlights the importance of providing adequate guidance to ensure the quality of office environments. This paper aims to summarize existing data on modern offices' indoor environmental quality (IEQ) conditions in terms of air pollution (volatile organic compounds (VOC), particulate matter and inorganic pollutants), thermal comfort, lighting and acoustics and the respective associations with health and productivity-related outcomes in workers. Evidence shows that although many offices present acceptable IEQ, some office settings can have levels of air pollutants, hygrothermal conditions/thermal comfort and illuminance that do not comply with the existing international standards and recommendations. In addition, findings suggest the existence of significant associations between the assessed IEQ indicators and the risk of detrimental effects on health and productivity of office workers. In particular, airborne particles, $CO_2$, $O_3$ and thermal comfort were linked with the prevalence of sick building syndrome symptoms. Poor lighting and acoustical quality have also been associated with malaise and physiological stress among office workers. Similarly, better productivity levels have been registered for good indoor air quality conditions, in terms of VOC, airborne particles and $CO_2$. Overall, the evidence revised in this work suggests that for promoting health and productivity recommendations for office building managers include actions to ensure that: i) all relevant IEQ indicators are periodically controlled to ensure that levels comply with recommended limit values; ii) declared indoor pollution sources are avoided; iii) adequate ventilation and acclimatization strategies are implemented; and iv) there is the possibility of conduct personalized adjustments to environmental conditions (following workers' preferences).

## 1. Introduction

Services are the sector that employs more people, followed by industry, manufacturing, construction, and agriculture (OECD, 2021). Currently, many service jobs are carried out in modern office buildings, which are often characterized by sealed facades, increased use of air conditioning and mechanical ventilation systems and equipped with several sorts of electronic devices, such as computers, monitors, printers, and audiovisua conference equipment (Sakellaris et al., 2016). For instance, office design has been changing throughout the last decades, with individual offices being increasingly replaced by open-plan settings. The fact that workers share the workplace with many others during an important percentage of their daily time highlights the importance of providing good indoor conditions for everyone in office environments.

The importance of indoor environmental quality (IEQ) on occupants' conditions is well recognized, representing an essential factor that can affect health and well-being (Bluyssen et al., 2011). Occupational health complaints have been reported among office workers, frequently related to sick building syndrome (SBS) symptoms, which prevalence might be dependent on building-related factors, as high indoor temperature and light intensity, low fresh air ventilation, higher than desirable air pollutants levels and poor cleaning (Burge, 2004). Additionally, IEQ

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represents a critical aspect of promoting office workers' productivity and decision-making capacity (Bartzis et al., 2013; Kang et al., 2017; Satish et al., 2013; Wargocki et al., 2000; Wyon, 2004).

Multiple factors characterize IEQ, including indoor air quality (IAQ, i.e., indoor air pollution levels), ventilation, thermal comfort, lighting, and acoustic conditions (Olesen, 2012; Sarbu and Sebarchievici, 2013). In particular, IAQ is considered acceptable when no chemical and biological pollutants are present at harmful levels in the indoor air, and the majority of occupants do not express dissatisfaction (ASHRAE, 2019). Nevertheless, several air pollutants can occur at exceptionally high concentrations in indoor settings, originating from distinct sources that can be located inside the building and in the surrounding outdoor environment. Focusing on indoor contributions in offices, electronic equipment, building materials and furnishings, occupants' activity and cleaning products can constitute sources of hazardous air pollutants, such as ozone ($O_3$), volatile organic compounds (VOC), aldehydes, particles ($PM_{2.5}$ and $PM_{10}$) and ultrafine particles (UFP) (Kagi et al., 2007; Lee et al., 2001; Spinazzè et al., 2020).

Although poor IAQ can result in exposures that may significantly impact workers' health, thermal comfort is identified as the most critical factor influencing overall satisfaction with IEQ (Frontczak and Wargocki, 2011), representing the "condition of mind which expresses satisfaction with the thermal environment" (ISO 7730, 2005). Air temperature, mean radiant temperature, air velocity, turbulence intensity, and relative humidity are the meters typically used to determine indoor thermal conditions (Bluyssen, 2009). Two indices have been developed to characterize thermal comfort conditions in spaces served by heating, ventilation and air conditioning (HVAC) systems: predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) (ISO 7730, 2005). Predicted mean vote is calculated considering both environmental and personal parameters, including workers' clothing and activity level, and indicates the mean value of the votes of a group of people on the thermal sensation scale. In comparison, PPD is a function of PMV and shows the number of dissatisfied people for a given criterion.

Lighting conditions are also essential in occupational health (Boyce, 2010; van Duijnhoven et al., 2019). Good lighting quality of a room entails the creation of "a visual environment that enables people to see, to move about safely and to perform visual tasks efficiently, accurately and safely without causing undue visual fatigue and discomfort" (ISO 8995-1, 2002). For indoor workplaces are established lighting requirements for people to conduct visual tasks efficiently, which can be achieved with practical energy-efficient solutions. The assessment of lighting conditions has been mainly based on the measurement of illuminance, defined as luminous flux striking a given surface and its distribution on task area and surroundings are important parameters due to the influence on safety and comfort of workers performing a visual task. Another related parameter commonly studied is color temperature.

Acoustics represents a vital building characteristic, particularly in offices, where noise has been identified as a source of annoyance among workers (Evans and Johnson, 2000). The acoustical quality of a given indoor space is characterized by sound properties and physical parameters of the room, including sound level, frequency, duration, absorption, insulation and reverberation time (Bluyssen, 2009).

Considering all the above, this paper aims to revisit the existing literature to answer the following questions: "Are the current IEQ conditions in modern offices acceptable, based on the existing standards?", "What are the well-established associations between IEQ in offices and health effects among workers?" and "What are the associations between IEQ conditions and productivity at office work?". Thus, the ultimate goal of this work is to summarize the primary evidence on IAQ, thermal comfort, lighting and acoustic conditions found in modern offices worldwide to derive evidence-based recommendation for further research and policies targeting health, comfort, and productivity in office workplaces.

## 2. Method

A literature search was carried out in order to select studies assessing IEQ conditions in office settings, in particular physical and chemical factors: air pollutant levels (VOC, semi-VOC (SVOC), $PM_{2.5}$, $PM_{10}$, UFP, carbon dioxide and monoxide ($CO_2$, CO), $O_3$, and nitrogen dioxide ($NO_2$)), thermal comfort, lighting and acoustics conditions. Therefore, parameters such as asbestos, mold, and bacteria were excluded from this review. Additionally, studies establishing associations between IEQ in offices with workers' health and productivity were also searched. For that purpose, studies published in the last 2 decades (from 2003 to the time of writing (April 2023)) were searched in the Scopus database using the following search strings: offices AND (VOC or "volatile organic compounds"), offices AND (SVOC or "semi volatile organic compounds"), offices AND (PM2.5 or PM10 or UFP or "ultrafine particles" or particles or "particle matter"), offices AND (CO2 or "carbon dioxide"), offices AND (CO or "carbon monoxide"), offices AND (O3 or ozone), offices AND (NO2 or "nitrogen dioxide"), offices AND "thermal comfort", offices AND illuminance, offices AND noise, offices AND (IAQ or IEQ) AND (health or productivity). Only studies assessing IEQ conditions in real office buildings were considered for the discussion of IEQ levels. Other typology of works, such as experimental and intervention studies, were only included for discussion of the effects on health and productivity. For $CO_2$ and PM parameters, only studies included in the review of Felgueiras et al. (2022) and publications published after this review were considered. In order to prioritize outcomes from assessments conducted in the occupants of the surveyed offices, studies conducting risk assessment based on the measured pollutant levels were excluded from the discussion of health effects. Overall, it was found 22 studies reporting data on IAQ parameters, 9 for thermal comfort and hygrothermal conditions, 3 studies for lighting, and 4 for noise. In terms of health and productivity associations, 31 studies were included for review. Information on the selected studies is summarized in the Supplementary Material, namely regarding the IEQ parameters that were assessed in offices (Table S1) and associated effects on health and productivity among workers (Table S2). The main findings of the reviewed studies are described and discussed in detail below.

## 3. Indoor air quality: air pollutant levels

### 3.1. Volatile organic compounds

VOC are characterized by having high vapor pressure and low water solubility, with many VOC species' anthropogenic origin (US EPA, 2022). Outdoor air can constitute an important contributor of VOC to indoor concentrations, particularly for BTEX compounds (benzene, toluene, ethylbenzene, and xylenes) (Spinazzè et al., 2020). Nevertheless, VOC are typically found in greater levels in indoor environments than outdoors, due to the presence of ubiquitous indoor sources, such as computers, laser printers, photocopiers, desks and walls materials, furniture age, carpets, flooring, paints, air fresheners and cleaning products (Kagi et al., 2007; Lee et al., 2001; Spinazzè et al., 2020; US EPA, 2022).

### 3.1.1. Levels of VOC in offices and compliance with guidelines

The total VOC (TVOC) concentrations in offices has been assessed worldwide. Interestingly, some evidence shows that office rooms can present high airborne VOC levels compared to open-plan offices (Salonen et al., 2009). In addition, sealed offices recently decorated and offering poor ventilation conditions can also be particularly prone to present increased indoor VOC concentrations (Liu et al., 2022). Additionally, some authors have compared VOC concentrations in offices over the years and found a decreasing trend (Liu et al., 2022; Wallenius et al., 2022). Although TVOC has been widely assessed to characterize chemical pollution, no global limit value is currently established. However, some countries have defined limits for indoor

TVOC, ranging from 200 (e.g. Belgium) to 1000 $\mu$g/m$^3$ (e.g. South Korea) (ISIAQ, n.d.). In that regard, considering a limit of 200 $\mu$g/m$^3$, some studies found levels within that value (Salonen et al., 2009; Wallenius et al., 2022), and others detected greater concentrations (Faria et al., 2016; Hui et al., 2006; Rios et al., 2009). Additionally, to properly assess chemical exposure, it is essential to identify and quantify individual VOC substances (Fromme et al., 2019). WHO established exposure limits for some VOC species in indoor air, namely for formaldehyde (0.1 mg/m$^3$, 30 min mean), naphthalene (0.01 mg/m$^3$ annual mean) and tetrachloroethylene (0.25 mg/m$^3$, annual mean) (WHO, 2010). For species such as benzene, polycyclic aromatic hydrocarbons, and trichloroethylene, no safe levels of exposure can be recommended. In offices, a wide range of VOC species has been identified, including aromatic hydrocarbons (benzene, ethylbenzene, xylenes, toluene), alcohols (1-butanol, 2-ethyl-1-hexanol, 2-(2-ethoxyethoxy)ethanol, styrene, 1,2-propanediol), terpenes ($\alpha$-pinene, limonene), carboxylic acids (acetic acid), organosiloxanes (decamethylcyclopentasiloxane), glycol ethers (2-butoxyethanol), aliphatic hydrocarbons (hexane) and aldehydes (formaldehyde, acetaldehyde, benzaldehyde, acrolein, propanal, glutaraldehyde, nonanal and hexanal) (Ongwandee et al., 2011; Salonen et al., 2009; Spinazzè et al., 2020; Wallenius et al., 2022). Overall, levels of the critical VOC reported for offices did not exceed the respective WHO, and the higher levels of benzene, toluene, limonene, and formaldehyde have been detected in tight offices with inadequate ventilation (Liu et al., 2022; Ongwandee et al., 2011). In particular, formaldehyde is a very common airborne chemical found indoors, which sources in offices comprise indoor building materials (wooden furniture, adhesives, coatings, carpets, textiles, floors) and the number of laser printers (Liu et al., 2013; Spinazzè et al., 2020). Some works (Glas et al., 2015; Hui et al., 2006; Salonen et al., 2009; Wallenius et al., 2022) reported levels of formaldehyde within the current WHO guideline for indoor air, while other investigations (Fang et al., 2022; Faria et al., 2016), especially those conducted in recently renovated offices, detected concentrations exceeding the referred limit value in up to 91% of the assessed buildings.

#### 3.1.2. *Effects of occupational exposure to VOC*

Some studies identified that VOC and formaldehyde concentrations typically found in offices are too low to cause symptoms such as sensory irritation in the eyes and airways among office workers (Rios et al., 2009; Wolkoff, 2013). Nevertheless, particular attention should be dedicated to some compounds that are documented as causing acute non-carcinogenic effects due to high concentrations exposure and the carcinogenic effects of long-term exposure to lower concentrations, such as benzene (WHO, 2010). Furthermore, other VOC species assessed in office settings have been linked to health symptoms. In that regard, Sakellaris et al. (2021) investigated VOC levels in 148 offices rooms (37 office buildings among 8 EU countries) and, regarding information from 1299 participants, the authors reported statistically significant associations between i) xylenes and headache, tiredness and skin symptoms; ii) ethylbenzene with eye irritation and respiratory symptoms; iii) a-pinene and respiratory and heart symptoms; iv) D-limonene and general symptoms (such as headache and tiredness); v) styrene and skin symptoms; vi) formaldehyde and respiratory and general symptoms; vii) acrolein and respiratory symptoms; viii) propionaldehyde and respiratory, heart, and general symptoms; ix) hexanal and general SBS. In addition, Zamani et al. (2013) also found a significant association between high levels of TVOC and the prevalence of SBS symptoms among office workers.

In terms of productivity, in the work of Allen et al. (2016), 24 participants spent 6 full work days in environmentally controlled office settings, with the main goal of studying the effect of "green" (low indoor levels of TVOC, around 45 $\mu$g/m$^3$) and conventional (high indoor levels of TVOC, 500 $\mu$g/m$^3$ or above) environments on human performance, by assessing cognitive function with a software tool. Briefly, the authors obtained the highest cognition scores in workers occupying the "green" offices, suggesting that exposure to low concentrations of VOC may be associated with high levels of cognitive function, which can significantly promote productivity.

Based on the evidence collected, strategies focused on source control, namely consisting of avoiding the introduction of indoor VOC sources and preferring low-emitting materials, and ensuring proper ventilation, especially during and after emitting events (e.g., renovations), can promote low VOC levels in office settings while minimizing the risk of health detriments and productivity loss.

### 3.2. *Semi-volatile organic compounds*

Semi-volatile organic compounds (SVOC), partitioned among gas, particles, and dust fractions, are a subgroup of VOC with low volatility that comprise brominated flame-retardants, polychlorinated biphenyls, perfluorinated substances, polycyclic aromatic hydrocarbons, pesticides and phthalates, etc., constituting a group of toxic contaminants that can impair IAQ (Sonne et al., 2022). The main sources of SVOC for office environments are electronics, building materials, flooring, carpets, textiles, furniture, and cleaning products. Exposure to SVOC has been linked to the development of various health risks, and thus it of utmost importance to control the levels of SVOC in indoor environments (Ataei et al., 2022).

#### 3.2.1. *Levels of SVOC in offices*

Compared with VOC, SVOC are described to appear in typically lower concentrations indoors. According to existing evidence, phthalates are the most abundant class of SVOC to which office workers are exposed at the workplace (Young et al., 2021). A limited number of studies included the assessment of exposure to these substances, with the most of the existing evidence coming primarily from Asian countries. As example, Song et al. (2015) found phthalate esters mean levels of 4748 ng/m$^3$ in Chinese offices, with diethyl phthalate, dibutyl phthalate, and di(2-ethylhexyl) phthalate being the most abundant species assessed. Those species were also detected in the work of Wang et al. (2014), added to dimethyl phthalate and di-n-butyl phthalate, a work also carried out in China, but finding lower phthalate esters concentrations. For Japanese offices, Toda et al. (2004) identified dibutyl phthalate and diethylhexyl phthalate, being dibutyl phthalate present at great concentrations (350 o 780 ng/m$^3$). For offices located in Poland, Szewczyńska et al. (2021) assessed phthalate esters concentrations in gas phase and particulate fraction in newly renovated rooms and after 7 months after renovation. The mean levels were greater than those reported in previous works, ranging from 4.4 to 39.8 $\mu$g/m$^3$ in air and deposited on particles, and di(2-ethylhexyl) phthalate, dibutyl phthalate and diethyl phthalate were the species detected. Additionally, the authors reported total phthalate concentrations after 7 months of renovation decreasing in mean by 76% compared with levels obtained in newly renovated office rooms. In terms of organophosphate flame retardants, Saito et al. (2007) reported concentrations of up to 260 ng/m$^3$ in Japanese offices. In fact, exposure to SVOC in offices can vary among countries. In that regard, Young et al. (2021) assessed the exposure to SVOC using silicone wristbands among occupants in office buildings in the USA, UK, China, and India. The authors found higher exposure levels to phthalates, pesticides and polycyclic aromatic hydrocarbons among office workers in China and India than in the other countries studied, possibly due to the fewer chemical restrictions and greater outdoor contributions that were found to exist in India and China. Nevertheless, exposure to phthalates was also influenced by individuals-related factors (namely related to use of personal care products, such as perfume, makeup, and deodorant) and building materials. Exposure to some brominated flame retardants and organophosphate ester species was higher in the USA and UK, because of the more intensive use of flame retardants. Similarly to some VOC species, guidelines are missing for SVOC that are of particular importance to control emerging species (Sonne et al., 2022).

#### 3.2.2. Effects of occupational exposure to SVOC

The health effects of SVOC are well documented, with some groups such as phthalates and polycyclic aromatic hydrocarbons being described as endocrine-disrupting chemicals (Ataei et al., 2022). Furthermore, SVOC can cause acute health effects, including eye, nose, and throat irritation, and headaches, while long-term exposure to great levels may lead to reproductive, respiratory and cardiovascular problems, immune suppression, allergic conditions, and cancers (Sonne et al., 2022). Particularly for office environments, and according to the search conducted for this review, there are no published research works linking indoor SVOC levels with health and productivity among office workers.

### 3.3. Airborne particulate matter ($PM_{2.5}$, $PM_{10}$, UFP)

Indoor airborne particulate matter can originate from combustion (including candles and incense), photocopiers, printers, computers, carpeting, tobacco smoke, air intakes, HVAC filters, cleaning, biological contaminants and outdoor air (Leung, 2015; US EPA, 2022).

#### 3.3.1. Levels of airborne particulate matter in offices and compliance with guidelines

Due to the potential for those pollutants to cause detriments to human health, WHO defined guidelines for exposure to size fractions $PM_{2.5}$ and $PM_{10}$: 15 and 45 μg/$m^3$ (24 h mean), respectively (WHO, 2021). In terms of smaller size particles such as UFP, levels below 1000 particles/$cm^3$ are considered as low levels and above 10,000 particles/$cm^3$ (24 h mean) or 20,000 particles/$cm^3$ (1 h mean) are considered to be high and then of concern (WHO, 2021). A recent study has revisited the air particles levels in offices (Felgueiras et al., 2022). Briefly, existing evidence shows that office workers may be exposed to higher than desirable concentrations of airborne particles in the workplace. The mean level of $PM_{2.5}$ calculated for offices was 36 $\mu g/m^3$, with 61% of the studies reporting levels above the WHO guideline. For $PM_{10}$, mean concentration was 63 $\mu g/m^3$ and 33% of the works reported concentrations exceeding the guideline. Overall, the highest airborne concentrations were measured in naturally ventilated offices, with an important impact of the high levels in the surrounding environment. In additional studies, mean $PM_{2.5}$ concentrations up to 6 $\mu g/m^3$ were obtained during working hours in office buildings worldwide (Laurent et al., 2021; Othman et al., 2020). Although a substantially lower number of studies included the assessment of UFP levels in office settings, the findings consistently showed that the assessed UFP levels exceeded 1000 particles/$cm^3$ at least in one building studied (Nur Fadilah and Juliana, 2012; Sultan et al., 2022; Zamani et al., 2013). High levels of UFP were detected even in studies that investigated the impact of air cleaners with high efficiency particulate air (HEPA) filters (Sultan et al., 2022). Air cleaners reduced UFP concentrations in offices, however, the reduction was not significant (from 24 to 43% in terms of indoor-to-outdoor ratio) with indoor levels registered near 3000 particles/$cm^3$. Generally, the great UFP levels were found in older buildings (Nur Fadilah and Juliana, 2012; Zamani et al., 2013), explained by the existence of carpet and air fresheners in open areas with photocopiers (Nur Fadilah and Juliana, 2012).

#### 3.3.2. Effects of occupational exposure to airborne particulate matter

According to WHO, exposure to particulate matter, even at low concentrations, can be linked to the risk of the development of adverse effects on health (WHO, 2018). Particularly for susceptible people, exposure to particles is likely to cause cardio-pulmonary effects (Wolkoff, 2013). For office environments, Zamani et al. (2013) investigated IAQ conditions in one recent (occupied less than 4 years) and one old building (occupied more than 15 years) and observed strong associations between the exposure to $PM_{2.5}$ and $PM_{10}$ levels and the prevalence of SBS among office workers of the old building. The same association was found for exposure to UFP but for workers of the recent office building. In fact, the authors reported an increased risk of developing SBS 13.8 times in office workers working in offices with UFP concentrations above 1642.5 particles/$cm^3$. Those associations were found for buildings presenting the highest concentrations of $PM_{2.5}$ and $PM_{10}$ (old building) and UFP (recent building). Regarding productivity, Zhou et al. (2023) conducted an intervention study in an office building to evaluate the effect of portable air purifiers on $PM_{2.5}$ levels removal, IAQ perception and productivity. The results showed that self-reported productivity was significantly higher in the intervention (3.7 μg/$m^3$ $PM_{2.5}$) than in the control group (18.0 μg/$m^3$ $PM_{2.5}$). In addition, Laurent et al. (2021) found a significant association between $PM_{2.5}$ and cognitive test performance metrics for levels above 12 μg/$m^3$. Nevertheless, it is important to consider the possible synergetic effect that can exist with other air parameters, such as $CO_2$ (Wu et al., 2021).

Having the above in mind, promoting natural ventilation when acceptable ambient air quality exists, removing indoor sources of particles such as air fresheners, photocopiers, and printers (e.g., reallocating in a specific space for that purpose), and ensuring proper cleaning of carpets are recommendations that can promote better IAQ conditions in offices and prevent SBS symptoms. Although source control should be prioritized, the use of air purifiers, particularly in spaces where safe levels of airborne particulate matter cannot be achieved, should be considered a complementary strategy to promote health and productivity.

### 3.4. Inorganic air chemicals ($CO_2$, CO, $O_3$, $NO_2$)

#### 3.4.1. Levels of inorganic air chemicals in offices and compliance with guidelines

Carbon dioxide ($CO_2$) concentrations can be used as an indicator of ventilation conditions, particularly in spaces with a high occupancy density. Similarly to TVOC, each country stated a limit for indoor levels. In particular, Denmark and The Netherlands established specific $CO_2$ limits for office settings ranging from 750 to 1200 ppm (Binnenklimaattechniek, 2021; Lahrz et al., 2008). Nevertheless, indoor environments presenting levels equal to or below 1000 ppm are commonly considered as having good or excellent IAQ conditions (Lowther et al., 2021). Based on the existing reports, office environments present, in general, acceptable ventilation conditions (665 ppm mean) (Felgueiras et al., 2022). Still, in terms of maximum $CO_2$ values, concentrations up to 1700 ppm have been documented. Cases of worst ventilation conditions, based on $CO_2$ levels, have been identified for offices with recognized high occupancy density and inadequate operation of HVAC systems, namely low percentage of fresh air introduced indoors. A similar $CO_2$ mean (723 ppm) was obtained in a more recent study (Laurent et al., 2021), however levels above 1000 ppm can also be found in office settings (Woo et al., 2021).

Carbon monoxide (CO) can be found indoors due to the presence of combustion sources and infiltration from outdoor air (WHO, 2010). WHO defined a limit of 4 mg/$m^3$ (24 h mean) (WHO, 2021). Studies assessing CO concentrations in offices are scarce. From the available information, CO is not a critical parameter in these indoor environments, since all studies reported levels far below the WHO guideline (Nur Fadilah and Juliana, 2012; Faria et al., 2016; Zamani et al., 2013).

$O_3$ is formed in the atmosphere by reactions involving $NO_2$ and VOC, with absorption of light from solar radiation and oxygen (WHO, 2021). And it is considered an important pollutant in outdoor and indoor environments, particularly in office settings, which present typical emission sources of this chemical as photocopiers, printers, and high-voltage air cleaning devices (Leung, 2015; US EPA, 2022). In terms of existing guidelines, WHO established a limit of 100 μg/$m^3$ (8 h mean) (WHO, 2021). Exploring the data in the literature, mean $O_3$ levels in office environments are typically within WHO guideline (Glas et al., 2015; Hui et al., 2006; Othman et al., 2020; Salonen et al., 2018; Spinazzè et al., 2020). The worst case was reported for 1 out of the 7 evaluated office buildings located in urban areas in which mean $O_3$ concentration was 170 μg/$m^3$ characterized by the presence of a high amount of electronic equipment (Faria et al., 2016). In fact, increased $O_3$ levels typically occur during working hours due to emissions from printers and photocopiers (Othman et al., 2020). Although the possibility of the existence of indoor sources, higher concentrations were often found in the outdoor environment than in offices (Othman et al., 2020; Salonen et al., 2018). As expected, because in summer a higher amount of ultraviolet radiation exists, levels of $O_3$ measured in offices during summer are higher than the concentrations obtained for the winter period due to the greater contributions from the outdoors (Spinazzè et al., 2020). Moreover, $O_3$ may react with other pollutants due to its oxidant properties, generating secondary toxic products, such as formaldehyde. Indeed, Spinazzè et al. (2020) observed those reactions in offices during summer.

Nitrogen dioxide ($NO_2$) is a common pollutant detected in indoor environments due to emissions resulting from combustion appliances and infiltration from outdoor air (mainly resulting from traffic-related sources) (WHO, 2010). The most recent WHO guideline defines a value of 25 $\mu g/m^3$ (24 h mean) (WHO, 2021). Among the existing studies that included the assessment of $NO_2$ concentrations in offices, it can be found works that report levels that are below (Hui et al., 2006; Spinazzè et al., 2020), and above guideline value (Glas et al., 2015; Salonen et al., 2019; Szigeti et al., 2017). Some factors such as the height of the floor in which the office room is located and outdoor traffic seem to be important contributors to indoor levels (Salonen et al., 2019). In particular, an inverse relation between $NO_2$ concentrations and floor height has been reported, i.e. offices on lower floors presented greater levels due to the proximity to emissions sources in surrounding areas.

### 3.4.2. Effects of occupational exposure to inorganic air pollutants

Evidence is still conflicting regarding the impact of exposure to high $CO_2$ concentrations on health and productivity (Lowther et al., 2021). Regarding health, some works linked $CO_2$ to the prevalence of SBS symptoms (Tsai et al., 2012; Zamani et al., 2013). Some works found evidence suggesting that office workers exposed to $CO_2$ concentrations higher than 800 ppm are more likely to suffer from eye irritation and upper respiratory symptoms (Tsai et al., 2012). In contrast, experimental studies in which ventilation rates were adjusted (Maula et al., 2017) and $CO_2$ artificially raised to 5000 ppm (Zhang et al., 2016) reported no significant results. Nevertheless, the same experimental studies found that although no changes were detected in task performance when $CO_2$ was raised to 5000 ppm in the experiment of Zhang et al. (2016), the decrease in ventilation rate showed a weak but notorious, adverse effect on workers' performance (Maula et al., 2017). Also related to productivity, Tsai et al. (2012) found great levels of difficulty in remembering things or concentrating when workers were in conditions of $CO_2$ exceeding 800 ppm. Furthermore, in the work of Allen et al. (2016), best cognition scores were also obtained in controlled offices with lower $CO_2$ levels (500 ppm) compared to offices with moderate or high $CO_2$ concentrations (around 900 or 1400 ppm, respectively). A similar relation was also reported in the work of Laurent et al. (2021), in which lower ventilation rates (assessed by $CO_2$ levels) were associated with a decrease in response times and work accuracy.

Regarding health, Zamani et al. (2013) found that CO influenced the prevalence of SBS symptoms in an old office building in Malaysia where levels ranged from 1.4 to 2.1 ppm. Further works would be needed to properly confirm the identified associations.

Noteworthy, concerning the effect of $O_3$ on the health of office workers, Sakellaris et al. (2021) found associations with those levels (median: 3.0 $\mu g/m^3$, maximum: 42 $\mu g/m^3$) and all symptom groups in study namely SBS, eye irritation, respiratory, heart and skin.

The influence of $NO_2$ on health conditions was investigated by Glas et al. (2015), who obtained some significant associations with perceived symptoms obtained by questionnaires administrated to office workers. Although the authors did not specify with which symptoms the associations were detected, the symptoms assessed were: general symptoms (fatigue, heavy-headedness, headache, nausea/dizziness, and difficulties concentrating), mucosal symptoms (dry eyes, itching or irritation of the eyes, dry nose, irritated/stuffy or runny nose, hoarse or dry throat, and coughing), and skin symptoms (dry facial skin, flushed facial skin, itching/stinging/tight or burning sensations on facial skin, and itching skin on the body).

According to search conducted for this review study, there are no published research works linking indoor CO, $O_3$ and $NO_2$ levels with productivity among office workers.

Overall, based on information on inorganic air pollutants load found in office environments, ensuring that the occupancy of spaces is adjusted to the office dimensions and existing ventilation conditions while guarantying the correct operation and maintenance of mechanical ventilation systems (including the amount of fresh air), always having in mind ambient conditions. Identically to recommendations for airborne particle levels, the office environment and its workers would beneficiate from a reallocation of printers and photocopiers due to the contribution of these equipment for indoor $O_3$ concentrations.

## 4. Thermal comfort

### 4.1. Hygrothermal conditions in offices and compliance with guidelines

In office environments, the presence of some equipment that may work as heat sources can promote an undesired increment in indoor temperature and consequently compromise individuals' comfort. Electronic equipment, occupancy density, and lighting represent putative heat sources, with electronic equipment being recognized as one of the main thermal sources with large heat dissipation in office buildings (Li and Zhang, 2022). In particular, for offices, the Occupational Safety and Health Administration (OSHA) provide guidance for employers concerning air temperature and relative humidity ranges (20 – 24.4 ˚C and 20 – 60%, respectively) (OSHA, n.d.). Research works have been carried out to characterize office indoor environments conditions during working hours, including measurements of air temperature and relative humidity levels, and the reported mean values have generally been in compliance with OSHA recommendations. In the scope of the European Commission founded OFFICAIR project, the overall air temperature was 24.7 ˚C for summer and 23.7 ˚C for the winter period, while average relative humidity levels were 46.4% and 32.3% during summer and winter, respectively (Mandin et al., 2017). For works conducted in other continents, between April 2012 and January 2013, in multi-story office buildings located in Ghana, the mean indoor temperature ranged from 24.3 to 28.4 ˚C and mean relative humidity was between 51.2 and 71.6% (Simons et al., 2014). In the USA, in an insurance company located in Orlando, Hedge et al. (2005) found average temperature values of 22.8 ˚C and relative humidity of 40.8% during the winter period. In addition, mean temperature and relative humidity ranging from 18.8 ˚C to 23.1 ˚C and 45.4% to 65.3%, respectively, were obtained for 8 natural ventilated offices situated in Bogotá (Colombia) between February and May 2018 (García et al., 2019). Between the same months of 2008, Hwang and Kim (2013) found that air temperature values ranged between 21.4 ˚C and 25.9 ˚C and relative humidity 21.7% to 73.0% in 5 floors of a Korean office building. Similar air temperatures and relative humidity levels were reported in additional works (Laurent et al., 2021; Hui et al., 2006; Rios et al., 2009; Woo et al., 2021), except for relative humidity levels measured during winter in non-sealed office buildings located in Brazil, where values ranging from 72.5 to 85.2% were obtained due to the contribution of high outdoor levels (85%) (Rios et al., 2009). Overall, some studies have detected air temperatures and relative humidity levels in offices out of OSHA recommendations, particularly exceeding the maximum values established.

### 4.2. Thermal comfort indexes in offices

Air temperature and relative humidity parameters are used in the determination of PMV and PPD indexes, which allow predicting the average thermal comfort in indoor environments where a group of people shares an indoor space. In the case of PMV, the thermal sensation scale is divided into 7-point scale: hot (+3), warm (+2), slightly warm (+1), neutral (0), slightly cool (–1), cool (–2), and cold (–3) (ISO 7730, 2005). Those indexes have been calculated for offices workplaces. Hwang and Kim (2013) obtained PMV values ranging from –0.58 to 0.34. The PPD was 10%, which was also in line with the results of a questionnaire applied, in which workers showed general satisfaction with thermal conditions. The authors recognized that the low relative humidity levels registered in offices (see subchapter 4.1.) were likely to be the reason for the cases of thermal annoyance. Woo et al. (2021) also found PMV from slightly cool to neutral and PPD levels up to 16% in Australian offices. In a work conducted in offices located in Ghana, PMV ranged from 0.2 to 1.5, while PPD varied between 6.3% and 51.4% (Simons et al., 2014). The warm thermal sensation (PMV of 1.5), corresponding to the highest PPD, was obtained for the naturally ventilated office building where the average temperature and relative humidity were 28.4 °C and 71.6%, respectively. The authors also compared the calculated PMV index with the actual mean votes (AMV) obtained through a questionnaire application, and it was found that workers of the assessed offices had an AMV of 0.5. These results contrast with the findings of Beizaee and Firth (2011), who reported that PMV underpredicts the thermal sensation compared with AMV in naturally ventilated houses and offices in the UK. It is important to have in mind that PMV may only partially predict thermal sensation in naturally ventilated spaces, as occupants could be using adaptative measures such as personal fans, and the proximity to open windows can influence it as well.

In terms of subjective assessments, some experimental tests have been carried out to evaluate comfort in relation to different indoor temperatures. In the work of Geng et al. (2017), participants were exposed in a controlled office environment to air temperatures around 16, 18, 20, 22, 24, 26, and 28 °C and filled out a survey regarding their perception of IEQ factors and underwent a test of productivity. The highest thermal satisfaction was observed at 24 °C, with most subjects reporting feeling "neutral". Deviations from air temperature of 24 °C (less or more) seemed to increase reported thermal dissatisfaction. Moreover, the authors concluded that comfort levels were associated with an increase in comfort expectation with other IEQ factors, including IAQ and lighting. Furthermore, Lipczynska et al. (2018) investigated the effect of high temperatures and air movement on thermal comfort and productivity in Singapore. For that purpose, experimental conditions were: 23 °C (temperature set-point recommended in the country) without fan and 26 and 27 °C with fan. The best thermal comfort condition (almost "neutral") was obtained when the indoor temperature was set at 26 °C with ceiling fans working. The change from 23 to 26 °C allowed to achieve energy savings (since cooling was implemented due to elevated outdoor temperatures during the study days: 25.5 – 30.7 °C) and a pronounced increment in thermal satisfaction from 59% to 91%. In terms of relative humidity, the levels were reduced (61.5 to 53.4%) but remained within the recommended range.

It is important to note that beyond environmental and personal parameters, other factors could influence thermal comfort, including the characteristics of the building, ventilation and air renovation conditions, outdoor climate, and season (Frontczak and Wargocki, 2011). The most common control strategies consist of improvements in the HVAC system and operation, as well as adjustments in the building design and use (Bluyssen, 2009). Additionally, individual aspects could also affect thermal comfort perception, as Maykot et al. (2018) proved. Although no significant differences were detected, the authors found that general thermal comfort temperature for women was higher (24.0 °C) than the temperature reported by men (23.2 °C). Likewise, in the work of Maula et al. (2016), women perceived 23 °C colder than men participants.

### *4.3. Effects of thermal comfort on workers*

Thermal comfort can influence health. For instance, during the heating season, indoor temperatures below 18 °C have been linked with an increase in the risk of cardiovascular and respiratory morbidity and mortality for regions with temperate or cold climates (Wolkoff et al., 2021). In turn, temperatures above 26 °C can aggravate acute symptoms such as fatigue, depression and low concentration capacity. Respiratory health may also be particularly affected when values are above 30 °C. Additionally, health complaints, such as dry eye symptoms, can be reduced, and work performed be improved with high humidity levels in contrast with conditions reported in offices with very dry air (Wolkoff et al., 2021). Regarding relative humidity levels, an association between the risk of development of adverse health effects (in eye tear film stability, physiology and osmolarity of the upper airways) and exposure to relative humidity levels lower than 30% has also been reported (Wolkoff, 2018). Particularly for office environments, recent findings show that workers who spend the majority of time in relative humidity conditions between 30 and 60% were 25% less stressed than workers exposed to drier conditions (Razjouyan et al., 2020). Considering this, some offices presented relative humidity values in percentage that can compromise occupants' health and aggravate SBS symptoms (<30%), as well as can promote microbial growth in poorly ventilated spaces (>65%).

Along with IAQ, the study of the effect that thermal comfort has on the performance of office work is well documented (Wargocki and Wyon, 2017). Significant associations between thermal comfort in office-like environments and workers' productivity and cognition have been explored in epidemiological and experimental studies (Wolkoff et al., 2021). A field study in an insurance company allowed data collection from thermal conditions and productivity during 16 consecutive workdays (Hedge et al., 2005). The authors found that computer work performance (based on the keystroke indicator) was highest for the thermal comfort zone and decreased in other thermal conditions. This effect was observed for quality and quantity of work performed and was linked to air temperature (19.8 to 25.6 °C) and not to relative humidity levels, possibly due to the restricted range of relative humidity levels observed (30.9 to 58.2%). Tsutsumi et al. (2007) tested the effect of different humidity levels (30, 40, 50, and 70%) on subjective performance using climate chambers. The experiments had a duration of 15 and 180 min and subjects' performance remained the same under all tested conditions. In this case, the fact of experiments being conducted during a short period, can justify the lack of associations. As the authors stated, changes in productivity would be expected in more extended periods of exposure to humidity conditions. Additionally, the use of objective measurements would be interesting to observe the effect on performance.

In the work of Geng et al. (2017), the authors obtained the best productivity levels for thermal sensations "neutral" and "slightly cool". Indeed, the increase in thermal satisfaction was associated with an improvement in office productivity. Similarly, Lan et al. (2010) studied the effect of different air temperatures (17, 21, and 28 °C) in controlled office experiments during the same period of 2 h, finding that thermal discomfort related to low or high temperatures influenced negatively workers' productivity (measured through subjective and objective measures). Vimalanathan and Babu (2014) also tested the same range of air temperatures and conducted a neurobehavioral test to assess office work performance in a laboratory setting. The authors found that work performance improved at 21 °C, with air temperature contributing to performance in about 39%. In addition, moderately uncomfortable environment promotes a decrease in motivation to work and an increase in the effort to maintain work performance. In fact, work performance, based on the ability to concentrate, alertness, and work productivity, is more remarkable as greater is thermal satisfaction among office workers, which may not be necessarily linked to indoor temperature (Lipczynska et al., 2018). The implications of deviations from thermal comfort range on productivity were explored by Maula et al. (2016), who compared the exposure to a slightly warm temperature of 29 °C to a neutral temperature of 23 °C in a laboratory study for 3.5 h. The slightly warm temperature negatively affected only one memory task, increasing the reaction time and reducing the accuracy, with other tasks related to attention and memory not changing significantly.

Nevertheless, the deterioration of subjective performance was obtained for conditions of 29 °C, which can impact task execution in the long-term. Moreover, Kosonen and Tan (2004) estimated significant productivity loss in PMV values of +0.5, corresponding to a slightly warm thermal sensation. Interestingly, some authors found improvements in performance when office workers were exposed to moderately cold temperatures in their workplaces. Tham and Willem (2010) described a better mental state and performance in tasks demanding attention among volunteer subjects expressing low thermal sensation and reduced thermal comfort at 20 °C in a simulated office environment.

Based on the existing evidence, it is clear that thermal comfort in offices is an essential factor that may affect workers' performance. For regions with temperate or cold climates, indoor temperatures ranging from 22 to 24 °C have been reported as ideal for promoting good indexes of productivity (Wolkoff et al., 2021).

Therefore, it is of major importance to guarantee proper hygrothermal conditions, avoiding extreme air temperature and relative humidity levels. "Neutral" sensation of thermal comfort or near would improve office workers' satisfaction with the indoor environment and promote health and productivity.

## 5. Lighting

### 5.1. Lighting conditions in offices and compliance with guidelines

The requirements for lighting conditions are established for several types of activities in offices buildings (ISO 8995–1, 2002). In terms of maintained illuminance, minimum limit values are defined for the following tasks/spaces: filing, copying, circulation (300 lx); writing, typing, reading, data processing (500 lx); technical drawing (750 lx); CAD (computer aided design) workstation (500 lx); conference and meeting rooms (500 lx); reception desk (300 lx) and archives (200 lx). Additionally, based on the principle that illuminance should change gradually, the uniformity parameter was created. Following ISO 8995–1 (2002), the uniformity of illuminance is defined as the ratio between the minimum value and the average value of illuminance, and it should not be less than 0.7 on the work surface. Regarding the immediate surrounding areas, the criterion is that the uniformity level should be not less than 0.5.

Illuminance has been studied in office settings due to its significant impact on comfort and safety for workers performing visual tasks. Hwang and Kim (2013) measured the physical conditions of the lighting environment in an office building with all-glass walls located in Seoul (Korea), including illuminance on the work plane and uniformity factor. The authors obtained an average value of around 800 lx (620 – 1019 lx) of illuminance and uniformity of 0.7 (0.5 – 0.9). Nicol et al. (2006) investigated desktop illuminance in 26 European office buildings, reporting average illuminance levels of 410 lx in Greece, 469 lx in France, 527 lx in Sweden, 530 lx in Portugal, and 648 lx in the UK. Overall, illuminance levels in offices appear to be within the requirements of ISO 8995–1 (2002) for office settings, however, some spaces presented values slightly below 500 lx (the most common value used for current office work). In that regard, a link was established with outdoor climatic conditions, i.e., lower indoor illuminance levels were in overcast skies, while high indoor illuminance levels were registered on days with clear skies. A wider range of illuminance levels have been measured by Woo et al. (2021), with values from 102 to 1526 lx. The impact of color temperatures on lighting comfort has been investigated as well. Color temperature in terms of appearance, values ⟨3300 K result in warm light, color temperature ranging from 3300 to 5300 K is categorized as intermediate, and values ⟩ 5300 K result in cool light. And, according to the findings, a consensus exists for the preference for intermediate color temperatures (Manav, 2007; Wang and Luo, 2016). In this respect, Wang and Luo (2016) observed that 4000 K condition (with 750 lx of illuminance) was linked to better scores of comfort than 6500 and 8000 K conditions, and, Manav (2007) also concluded that a color temperature approximate to 4000 K was preferred to 2700 K. Though, cooler light colors could be preferential in warm climates, while in cold climate zones, warmer light colors appearance is preferred (ISO 8995-1, 2002).

Based on recent research data, a combined effect with thermal comfort can also exist and influence satisfaction with lighting. The findings of Bellia et al. (2021) obtained in a mechanically ventilated test room were that cooler light conditions (6000 K) change thermal sensation to cold, also suggesting that warm light can be linked to warm thermal sensation. Besides, Chinazzo et al. (2020) investigated the effect of indoor temperature on visual perception and concluded that temperature affected participants' perception of daylight warmth. Briefly, participants reported more frequent warm light sensations in higher temperatures than when they were exposed to colder temperatures, suggesting an association between temperature and the apparent warmth of daylight in office-like environments.

### 5.2. Effects of lighting conditions on workers

Lighting conditions have been associated with impacts to health. According to Boyce (2010), light may affect health in three ways: 1) damages on eye and skin through both thermal and photochemical mechanisms; 2) impact on the visual system, including eyestrain; and 3) interferences with the circadian system, including sleep patterns. In particular for offices, focusing on eye symptoms, color temperature was associated with blurred vision, difficulty focusing, eye discomfort, eye fatigue, eyestrain and irritability and illuminance with eye pain (van Duijnhoven et al., 2019). In terms of physical and physiological health, color temperature was linked to fatigue, light headedness and vitality, while illuminance seems to influence the prevalence of headache, malaise, physical well-being and skin dryness. The impact on sleep patterns was also studied among office workers, with color temperature affecting factors such as alertness, daily sleep timing, energy, evening fatigue, lethargy, sleep duration, sleep quality, sleepiness during the day and tiredness, and illuminance causing insomnia. Overall, higher color temperatures (17,000 K vs. 4000 K) improved workers' conditions referred above (van Duijnhoven et al., 2019). In addition, light intensity was correlated with office workers' well-being and health (skin conditions and eye pain), with poor lighting being associated with a higher prevalence of those symptoms and malaise.

To evaluate the impact of lighting conditions on office workers' productivity, studies have been investigating daylight, illuminance and color temperature, mostly resorting to experimental investigations. Considering studies assessing real lighting office conditions, and in terms of the source of the lighting, De Carli et al. (2008) reviewed some evidence and concluded that when proper daylight is the main lighting resource, a significant improvement of productivity and performance can be observed. Likewise, Nicol et al. (2006) found the use of artificial lights in offices linked to a small but significant reduction in self-reported productivity levels. Additionally, the authors also showed that productivity improved when blinds were open, supporting the theory that the view (or high levels of daylight) might enhance productivity in these indoor environments. Regarding experimental works, for illuminance, in the work of Smolders et al. (2012), two levels were tested at the work surface (200 and 1000 lx, keeping the color temperature at 4000 K) during 60 min in both morning and afternoon periods. Objective performance along with alertness and vitality factors, improved in more intense light conditions of 1000 lx. Additionally, Vimalanathan and Babu (2014) estimated improvements in reaction time and error response (around 20% and 5%, respectively) for higher illuminance levels of 1000 lx than with 500 and 750 lx. About color temperature, Ishii et al. (2018) carried out an experimental work to investigate intellectual productivity, through objective concentration ratio measures, in different lighting conditions: conventional ceiling light ambient (color temperature of 5000 K), task ambient lighting with intermediate color temperature (color temperature of 5000 K in both ceiling and task lights) and task ambient lighting with high color temperature (color temperature of 5000 K in the ceiling and 6200 K in task lights). In all experiments, illuminance levels were 750 lx on the desk surface. This study observed an increase of 5% in concentration capacity levels in task ambient lighting with greater color temperature than in conventional ambient lighting. Bao et al. (2021) combined the study of both illuminance and color temperature. Subjects (student participants) were exposed in a laboratory setting to distinct illuminance levels (300, 750, and 1000 lx) and color light temperatures (3000, 4000, and 6500 K). Overall, the best results (lowest mental workload) were obtained for the combination of 750 lx of illuminance and 3000 K of color temperature, but no association was detected between illuminance and color temperature for mental workload in office settings. Whereas, in the work of Wang and Luo (2016), 750 lx (vs. 350 and 550 lx) and 6500 K (vs. 4000 and 8000 K) were the combinations for the best task performance. Nicol et al. (2006) stressed the importance of considering the degree of adaption to different intensities of light that were noteworthily manifested among office workers and that can compromise the evidence of improvements in productivity due to exposure to distinct lighting conditions. In other words, the change of lighting conditions may promote a change in productivity; however, with time, workers can become accustomed to new lighting, and the performance return to baseline conditions. In that context, variable lighting conditions could overcome this factor of adaption. Improvements in productivity have been identified by either decreasing or increasing lighting levels in accordance with the tasks' needs. The results of this type of study may be skewed due to the possibility of the phenomenon "Hawthorne effect" which consists of the change in participants' behavior just because they are part of an experimental study. This represents an important limitation particularly for lighting investigations, as the subjects are not blinded and clearly notice changes in the lighting environment (Hoonhout and Vanpol, 2009).

## 6. Acoustics

### 6.1. Acoustical conditions in offices and compliance with guidelines

In offices, noise is commonly generated mostly from conversations, office equipment (such as telephones, printers), air conditioning and ventilation systems and outdoors (Leather et al., 2003). For workplaces, OSHA defined a permissible exposure limit of 90 dBA for all workers (8 h mean), also referring that employers should implement a hearing conservation program when exposure is equal or above 85 dBA (OSHA, n.d.). In particular for offices, no global limit is currently established; however, some countries defined specific levels for these work environments (e.g., China: 55 dBA) (Huang et al., 2012). Measurements of noise in offices have demonstrated the existence of acceptable levels. Overall, mean sound levels ranging from 30 to 65.4 dBA have been reported for offices worldwide (Huang et al., 2012; Hwang and Kim, 2013; Leather et al., 2003; Woo et al., 2021). Although levels were within OSHA recommendation, occupants disclosed acceptable noise below 49.6 dB (Huang et al., 2012). The comfort related to acoustics has been investigated in offices with distinct designs. Jensen et al. (2005) assessed occupants satisfaction levels through surveys in 142 office buildings and concluded that workers in open plan offices were more satisfied with noise and speech privacy than occupants of closed offices. The authors gave two possible reasons to explain it: i) private conversations are possible in open offices when nobody is within earshot after a visual check, and ii) privacy expectations are lower in open offices, and occupants adapt their listening and speaking accordingly. Nevertheless, further studies would be needed to confirm that result. Office design is a critical aspect in sound propagation. For instance, inadequate partition design and unadjusted sound absorption can cause high reverberation together with insufficient noise isolation, making a generated sound in workplace being heard (Hodgson, 2008). Jensen et al. (2005) also found that the overall lack of speech privacy was more impacting than the noise level in terms of dissatisfaction with IEQ. Concerning noise level, conversations among co-workers seemed to have the greatest negative effect on satisfaction with the acoustic environment (Kang et al., 2017), even when compared with footsteps, ventilation, or office equipment noises (Artan et al., 2019).

### 6.2. Effects of acoustical conditions on workers

The impact of noise on office workers' health have been studied. Lee et al. (2016) stated that noise disturbance in offices have affected self-rated health. In addition, although Evans and Johnson (2000) did not find differences in stress perception between workers in noisier and quieter offices, Leather et al. (2003) found that lower noise levels can buffer the negative impact of psychosocial job stress. In terms of productivity, in the survey study conducted by Jensen et al. (2005), 50% of the 23,450 office workers respondents reported that acoustics affects their job performance. In fact, acoustical quality can also refer to a noise-free environment where occupants can perform their tasks without disturbance (Artan et al., 2019). For instance, for research work carried out in open offices, the quality of the acoustic environment was determined as the most impacting factor on the productivity of young academics (Kang et al., 2017). In addition, a comfortable acoustical environment allows occupants to maintain work performance and concentration without disturbances while enabling verbal communication at the voice level (Hodgson, 2008).

## 7. Conclusions and future trends

This literature review emphasizes the importance that IEQ in offices have in workers' health and productivity. Although most offices presented proper IEQ conditions, some studies have demonstrated that office settings can have IAQ, hygrothermal conditions/thermal comfort, and illuminance levels out of the existing international standards and recommendations. Although a decreasing trend in the prevalence of health detriments has been noticed over the years in office environments (Bluyssen et al., 2016), the impact of workplace IEQ on office workers' health has been investigated and, associations were found with IEQ factors, even when these were in agreement with the guidelines. For instance, occupational exposure to air pollutants contributes to human health risk. In particular, airborne particles, $CO_2$, $O_3$ and thermal comfort were linked with the prevalence of SBS symptoms. Poor lighting and acoustical quality were also linked to malaise and physiological stress occurrence among office workers. Moreover, office workers seemed to report better productivity when workplaces presented good IAQ conditions and when they were more satisfied with thermal comfort, lighting and acoustic environment. Indeed, actions for ensuring adequate office environment conditions may be responsible for improving workers' productivity up to 20%, which can represent significant annual economic gains for companies (Al Horr et al., 2016; Fisk, 2000). Therefore, for health promotion and productivity enhancement it is crucial that office building managers take actions to ensure that workplaces: i) are IEQ periodically controlled to ensure that levels are in compliance with recommended limit values; ii) are free of avoidable indoor pollution sources; iii) have adequate ventilation and acclimatization strategies; and iv) can be properly adjusted in accordance with standards and workers' preferences.

According to the search work conducted in this study, consensual guidelines worldwide may still be missing for some parameters. In addition, a research gap related to the lack of studies covering a comprehensive and multidisciplinary panel of IEQ indicators (air quality, ventilation, thermal, lighting, and acoustic comfort) and workers' outcomes (satisfaction, health, and productivity/performance) was also identified. Furthermore, there is a need for further studies aiming to assess the real office environmental conditions and their associations with health and productivity among workers using objective measurements. Indeed, future studies would benefit from considering a holistic characterization of office environments that considers the investigation of the interactive effects between IEQ factors (e.g., multi-pollutant approaches). This would allow to enhance the understanding of the real patterns of exposures to environmental aggressors and of the etiology of the observed adverse effects and to use this understanding to promote healthy office environments.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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## Supplementary materials

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