The impact of microclimate strategies for the improvement of indoor air quality on well-being and productivity of industrial workers

Caporale A.*, Botti L., Galizia F.*, Mora C.*, Bortolini M.*, Ferrari E.***

** Department of Industrial Engineering, University of Bologna, Viale del Risorgimento, 2 40135 – Bologna – Italy (alice.caporale2@unibo.it, francesco.galizia3@unibo.it, cristina.mora@unibo.it, marco.bortolini3@unibo.it, emilio.ferrari@unibo.it)*
*** Interdepartment Research Center on Security and Safety, University of Modena e Reggio Emilia, via Pietro Vivarelli, 10 41125 – Modena – Italy (lucia.botti@unimore.it)*

Abstract: In the last years, in industry, the adoption of effective microclimate strategies for the improvement of the indoor air quality (IAQ) has been considered an important topic for its effects on the workers' health and safety, but it is recently more relevant than ever in the light of the current coronavirus pandemic. The ongoing coronavirus pandemic is moving the scientific community's attention to the study of new microclimate strategies to reduce the transmission of respiratory viruses within industrial settings. Experimental studies showed that increased ventilation and controlled relative humidity levels influence the buoyancy of the expiratory clouds ejected during human respiratory. The result is a reduced contamination range of the suspended droplets containing the respiratory viruses. The existing literature outlines eight Indoor Environmental Quality (IEQ) factors impacting occupants' health and well-being. Among these, IAQ and thermal comfort rise as the most influential ones. The Italian National Institute of Health recently defined a set of strategic implementation measures to improve the IAQ in industrial environments and, ultimately, contain the transmission of the SARS-CoV-2. Moreover, the World Health Organization recommends an increase in the ventilation rate of industrial environments through natural aeration or artificial ventilation. However, these microclimatic variations may cause thermal stress, discomfort and other adverse effects on workers' health and safety. As the literature lacks studies reviewing the effects of these microclimatic strategies, this paper aims to investigate their impact on the well-being and productivity of industrial workers. At the same time, this work is also of interest to industries as it analyses the technologies adopted in the industry to improve IEQ. The findings of this paper describe the critical contents of mid-long term strategies for reducing the transmission of respiratory infections, as the common seasonal flu and the recent coronavirus disease 2019 (COVID-19).

Keywords: Indoor Air Quality, Health and safety, Sars-CoV-2, Occupant comfort and productivity; Microclimate technologies

1.Introduction

As people spend a third of their life at work and, in most cases, indoors, it becomes essential to examine the factors that affect the internal work environment. Stefanović et al. (2019) argue that the work environment affects the well-being, ability, working performance and health of workers at a workplace. The concept of Indoor environmental quality (IEQ) is defined when considering the quality of an environment in relation to the health and well-being of its occupants. Although numerous factors are influencing the IEQ, this review focuses more on microclimate factors. Indoor air quality (IAQ), which refers to the air quality within buildings in relation to the health and comfort of occupants, and thermal comfort represent the main factors that determine the conditions of the environment itself. A good indoor environmental quality (IEQ) is usually associated with high indoor air quality (IAQ) and thermal comfort. On the other hand, uncomfortable thermal sensation leads to significant declines in physical and mental performances (Sugg et al., 2019), while a poor IAQ is responsible for indoor pollution, causing several respiratory diseases and symptoms (Mentese et al., 2020). Al Horr et al. (2016) pointed out that a high concentration of pollutants due to poor ventilation of industrial environments causes sick building syndrome (SBS). Among the most common SBS symptoms, mental fatigue leads to a reduction in productivity. At the same time, dryness, itching, burning eyes and nose and respiratory irritation affect people more sensitive to viral diseases (Lan et al., 2011). Consequently, IAQ is a crucial factor for the safety of workers made even more essential today by the rapid spread of the coronavirus pandemic. In this context, the World Health Organization (WHO), the continental institutions such as the European Agency for Safety and Health at Work (EU-OSHA) and the individual national bodies, e.g. the Italian National Institute of Health (Istituto Superiore di Sanità, ISS) in Italy, drew up guidelines for SARS-Cov-2 containment at the workplace. Based on experimental studies, these recommendations pay particular attention to improving IAQ through increased ventilation rates and control of relative humidity and temperature levels, with positive effects on the reduction of contamination. Indeed, Abuhegazy et al. (2020) prove that environmental conditions influence the buoyancy of the cloud and consequently the range of contamination of droplets in suspension. However, these microclimatic variations can cause thermal stress, discomfort and other adverse effects on the health and safety of workers (Kershaw and Lash, 2013; Gasparrini et al., 2015; Nico et al., 2015; Castaldo et al., 2018; Li et al., 2018; Salata et al., 2018; Wolkoff, 2018). This paper aims to analyse the impact of these strategies on the well-being and productivity of industrial workers. To this aim, the following research questions (RQs) are defined: (1) Which are the main factors that determine indoor environmental quality? (2) What are the effects of these factors on the health and productivity of industrial workers?

To answer the RQs, the remainder of this paper is organized as follows: Section 2 presents the research method, Section 3 analyses the relevant literature about the factors determining a good IEQ and the analysis of the most adopted industrial technologies to improving IEQ. Section 4 presents the key outcomes and discussion, while Section 5 introduces a reference case study about the impact of microclimate strategies for improving IAQ in the context of the containment of the SARS-Cov-2 virus. Finally, Section 6 concludes the paper with final remarks and future opportunities for research.

2.Research method

This paper aims to perform a systematic literature review about the influence of microclimate strategies on the productivity and well-being of industrial workers. The presented analysis concerns microclimatic factors that determine IEQ and their interdependencies, focusing on IAQ and thermal comfort. In addition, this paper presents the related technologies adopted by the industry. The literature analysis consists of three consecutive phases: (1) definition of relevant keywords, (2) search and (3) selection of articles. About the first phase, the keywords *microclimate/Indoor Air Quality* combined with *comfort/productivity/health* are considered, including their combinations. The search phase was performed in Scopus database and returned 1066 papers. Afterward, the initial search was refined according to three different criteria, i.e. considering only journal articles, the subject area "engineering" and the publishing date between 2009 and 2020 to evaluate only the most recent contributions. The final number of papers obtained implementing such criteria is 185. Discarding duplicates allowed us to select 42 articles. In addition, we considered the reports and guidance papers drawn up in 2020 by the World Health Organization (WHO), Italian National Institute of Health (ISS), United States Centers for Disease Control and Prevention (CDC), International Labour Organization (ILO) and Italian Association of Air Conditioning, Heating and Refrigeration (AiCARR) about the analysis of microclimate strategies in the context of COVID-19 pandemic and technologies adopted by industries.

3.Literature Review

Several studies (Akimoto et al., 2010; Lan et al., 2011; Kershaw and Lash, 2013) stress the close correlation between the indoor environment and work performances. In particular, a good IEQ can effectively reduce occupant complaints and improve work productivity. On the other hand, the decline in work performance caused by poor IEQ could lead to substantial economic loss (Wu et al., 2021). The following sub-sections present an analysis of the main influencing factors.

3.1 IAQ and Ventilation

IAQ is a complex entity to measure because it depends on interdependent physical factors such as relative humidity, temperature and atmospheric contaminants. Such parameters are influenced by external conditions (climate), building conditions (material, structure and construction), heating, ventilation and air-conditioning systems (HVAC) and interior space arrangement (furniture, furniture, equipment) (Zhu et al., 2020). IAQ can be managed by increasing the ventilation rate through ambient air dilution to reduce the concentration of atmospheric pollutants emitted by indoor sources. As a result, the ventilation rate is an efficient IAQ monitor in a building. In fact, a good IAQ corresponds to high ventilation rates (about 25 l/s per person) (Al Horr et al., 2016). On the other hand, reduced ventilation rates lead to lower IAQ and symptoms attributable to SBS. In addition, there is a reduction in cognitive performance and an increase in short-term sick leave with a consequent decrease in productivity. The introduction of "clean" external air can occur naturally, through the opening of the windows, or mechanically, with the aid of ventilation systems. The main advantage of natural ventilation concerns the ability to improve IAQ and thermal comfort in hot climates without consuming a significant amount of energy (Salcido et al., 2016). Furthermore, opening the windows allows to increase the particle output fraction by about 38% and helps to reduce aerosol deposition on individuals in the environment by about 80% (Abuhegazy et al., 2020). However, window opening time should be optimised according to the number of people and activities carried out to avoid overcooling, especially in cold industrial environments, or loss of cooling/heating energy (Salcido et al., 2016; Morawska et al., 2020).

Natural ventilation is an effective and sustainable method to improve IAQ. However, in particular conditions, it is not recommended to rely on the direct introduction of outside air. For example, during the winter period, it is crucial to control the indoor temperature. In fact, temperature below 18 °C increases the risk of cardiovascular and respiratory morbidity and mortality during cold seasons for regions characterized by temperate or cold climates (Wolkoff et al., 2021). A further risk factor concerns the dryness of the cold air introduced, which can cause local irritation of mucous membranes, eyes and skin, making sensitive subjects more affected by internal pollutants (Salata et al., 2018). In addition, the outside air itself can contain contaminants that can affect health if inhaled outdoors or indoors. Ventilation can carry these contaminants into interior spaces. However, it is essential to maintain high ventilation rates to limit internal pollutant levels within industrial environments. Where natural ventilation involves risks for the occupants, air exchange must be guaranteed through mechanical ventilation systems. HVAC systems play an important role in improving air quality and thermal comfort of building environment.

Those systems can extract moisture from the exhaust air and return it to the supply air. Consequently, during the winter season, HVAC systems make the dry air more humid. During the summer, they produce a cooling effect by evaporating the humidity in the supply airflow. However, humidity has a significant impact on the energy consumption of the HVAC system. Shehadi (2018) showed that, in an effective ventilation system, reducing the indoor relative humidity (RH) setting from 60% to 50%, the total energy consumption increases up to a maximum of 22.4%. In general, HVAC systems are the most expensive building tools for improving IEQ, accounting for near 40% of the building's total energy consumption (Zhu et al., 2020; Yuan et al., 2021). Despite the significant energy footprint, industrial occupants are often dissatisfied with their thermal comfort. The causes are manifold: first of all, workers cannot self-regulate the temperature; secondly, they cannot change the settings in real-time and, finally, these systems do not respond to the uneven distribution of the internal environment (Frontczak et al., 2012). Mixed-mode ventilation (MMV) systems solve the problems associated with predominantly natural ventilation and the use of HVAC systems. MMV employs the combination of natural ventilation from manually or automatically controlled windows and mechanical air conditioning to provide air distribution and a form of cooling only when necessary. Their primary goal is to maximize the building's internal thermal comfort, avoiding unnecessary energy use (Salcido et al., 2016). In HVAC systems, the control of the IAH significantly increases, as does the energy expenditure of the building. On the other hand, in MMV systems, the energy expenditure is lower thanks to the introduction of air through the opening of the windows; however, this makes it difficult to adjust the IAH. While representing the leading technologies for improving IAQ, the ventilation, conditioning and humidification systems can be a source of microbial spread, e.g. viruses, bacteria, fungi, molds and volatile compounds, with consequent health problems for workers, e.g. infections, allergic reactions, SBS symptoms.
High-Efficiency Particulate Air filters (HEPA) are added to the heating and ventilation systems to limit the spread of pathogens in different environments. To maintain filters' efficiency, they require proper cleaning, maintenance and replacement operations. Inside the humidification systems, the addition of bioacids to the nebulized water prevents the growth of pathogens. However, these substances can cause irritation or allergic reactions in exposed subjects. The relationship among IAQ, ventilation and thermal comfort depend on physical factors related to the environment and individual characteristics. The use of mechanical ventilation systems, controlled by users and equipped with HEPA filters in the correct state of maintenance, can significantly benefit the health and comfort of operators. However, the investment in these systems is justified by a significant increase in the operators' health, safety, and productivity.

3.2 Indoor air humidity (IAH)

Indoor air humidity (IAH), in terms of perceived dry air (dryness) and potentially associated health effects, is an essential parameter in the industrial environment, where the recommended minimum IAH level is 30%-40 (Wolkoff, 2018). However, in particular conditions due to temperature and pollutants (for example dust), the perception of dry air can also occur with relative humidity levels of 50% (Byber et al., 2016). Prolonged exposure to low humidity levels within industrial environments causes the so-called perception of "dry air", a sensation of sensory irritation similar to cold (Zhao et al., 2011; Dalton et al., 2018). This sensation, caused by less mucociliary activity, increases the susceptibility of the mucous membranes to sensory irritants, e.g. oxidants, particles, bioaerosols, and infections (Wolkoff, 2018). In contrast, an increase in IAH relieves both the perception of "dry air" and the symptoms of dry eyes and upper airways. Byber et al. (2016) consider an IAH of 45% as optimal for the self-cleaning function of the airways. However, even high IAH levels can negatively affect workers' health. As stated by WHO (2009), an IAH between 60% and 90% favors mold growth. Furthermore, microbial growth due to high IAH appears to have correlations with SBS. Finally, IAH affects the emission rate of pollutants from building materials, increasing or decreasing their presence in the environment (Byber et al., 2016). There are different ways to control IAH. Central interventions, often coupled to the ventilation system, regulate the IAH of the entire building through air conditioning split or humidifiers. Otherwise, it is possible to use separate air humidifiers, intervening locally at the ambient level. These humidifiers can be of different types: those producing steam by thermal evaporation, cold atomizers that nebulize water thanks to a high-frequency fan and ultrasonic atomizers that create steam by ultrasonic waves (Byber et al., 2016). Central interventions, coupled with the ventilation system, ensure a correct level of IAH within industrial environments. In addition, those interventions permit a higher control of the relationships among the various factors that determine both the IAQ and IEQ.

3.3 Thermal comfort

Thermal comfort is a psychological and physiological condition that expresses the thermal perception of the human being towards the environment (Salata et al., 2018). Due to both the psychological and physiological nature, the thermal conditions of the environment play a leading role in influencing the health and productivity of workers. Al Horr et al. (2016) defined 21-25°C as a stable temperature range for office productivity, while workers' performance decreases by 2% with each 1°C increase in the 25-30°C temperature range. In this field, the study proposed by Ormandy and Ezratty (2012) shows that keeping the temperature of the environment within the range of thermal comfort implies the protection of workers' health. Nico et al. (2015) highlight that employees working in suitable hygrothermal conditions are more productive and attentive and less prone to absenteeism and complaints, with a significant reduction in the risk of accidents during working hours. On the other hand, thermal stress from both cold and heat negatively affects workers' performance in industrial environments (Cai et al, 2018). In particular, high temperatures cause an increase in body 'core' temperature, leading to fatigue and decreased muscle endurance; cold temperatures cause vasoconstriction and lowering of tissue temperatures, which result in numbness, decreased manual dexterity and reduced strength. Even if the overall effect size for heat is comparable to that for cold, the physiological responses caused by cold can persist for longer than those attributed to heat (Gasparrini et al., 2015). Achieving thermal comfort is a complex issue (Li et al., 2018). In fact, thermal comfort depends on different physical parameters, which create a thermal state, and on subjective human responses to that thermal state. The American Society of Heating, Refrigerating and Air-Conditioning Engineering (ASHRAE) with *Standard 55* defined thermal comfort as *"a state of mind that expresses satisfaction with the thermal environment"*. Due to its subjective nature, a state of thermal neutrality often does not correspond to a pleasant thermal sensation (Salata et al., 2018). For this reason, in the workplace, thermal comfort is measured by analyzing the number of complaints. In addition, occupants' thermal sensation and comfort level can change over time, so they should be monitored in real-time. Thermal comfort and ventilation are closely linked. As a subjective state, the possibility of individual adjustment of the temperature by the opening of windows improves the comfort and satisfaction of workers (Akimoto et al., 2010). The analysis of the literature shows that thermal satisfaction leads to fewer complaints, limited absenteeism and improved productivity. However, in industrial environments, the traditional operation of HVAC systems cannot be self-regulated in real time, causing comfort instability and energy waste (Li et al., 2018; Zhu et al., 2020).

3.4 Lighting and daylighting

Daylight is considered a fundamental component of the sustainability of industrial buildings, both for the benefits in terms of workers' health and productivity and the potential energy savings (Turan et al., 2020). People naturally prefer sunlight over artificial light due to physiological and psychological reasons. Above all, daylight is considered the best light source because it offers the optimal visual condition (Yang and Nam, 2010). Secondly, natural light strongly influences melatonin production, keeping the circadian rhythm of the human organism regular. The benefits of this mechanism concern the regulation of hormonal levels, sleep-wake rhythm and metabolism. In addition, daylight directly affects workplace thermal state. Windows absorb and transfer a significant amount of solar radiation into the indoor environment. However, natural light should be balanced with artificial light sources within industrial settings to reduce worker dissatisfaction (Al Horr et al., 2016). If from one side a low level of lighting can lead to eye discomfort, on the other side, excessive direct sunlight can cause glare resulting in visual pain, fatigue and headache (Hamedani et al., 2020). The solution to operators' visual problems is related to connectivity and big data. Modern lighting systems help protect operators' visual performance while maintaining their productivity level, varying the intensity and color of LED lights based on changes in natural light.

3.5 Biophilia

The presence of plants or elements that recall nature positively affects the occupants' satisfaction within industrial spaces. Elzeyadi (2011) reports a 10% reduction in worker absenteeism due to the introduction of biophilia in offices. Besides, the vegetation outside the building, visible through the windows, helps to reduce the stress and anxiety of workers (Ko et al., 2020). Nature within working environments positively influences productivity and negatively the occupants' stress and represents a sustainable but untapped solution to improve IAQ. Plants, through the process of photosynthesis, are able to absorb CO2 and volatile compounds produced by indoor furniture and synthetic materials. In addition, plants increase indoor air humidity levels by generating water vapor (Smith and Pitt, 2011). The introduction of plants and natural elements is not sufficient to improve IAQ in the industry. However, it certainly has a positive impact on the operators' comfort.

3.6 Noise and acoustic

Noise and acoustics have a strong impact on workers' well-being and productivity. Legislative Decree 81/08 establishes the limit levels for noise exposure. In particular, the allowed daily noise exposure level is in the range of 80-85dB (A), while the value of 87dB (A) represents the limit level. Standard UNI EN ISO 1999: 1990 allows the forecast calculation of the damage corresponding to a given long-term exposure to noise, marking that continuous and prolonged exposure to noise generates stress and anxiety in industrial workers. In addition, this kind of exposure is responsible for increasing blood pressure levels and stress hormones, creating long-term health problems (Salata et al., 2018). Both noises from outside the building (transport/traffic) and internal noise caused by operating machinery are responsible for the decline in performance. Building elements like sound-absorbing materials and interior layout design are sufficient to protect workers' health and productivity from outside noises. However, internal noises and, in particular, the gas flows inside the ducts represent the primary source of risk in the industrial environment. To counteract this noise, there are two types of industrial silencers: cylindrical and parallelepiped. Both devices consist of a metal casing containing sequences of sound-absorbing materials. The differences concern the presence of perforated metal partitions in the cylindrical silencers and perforated protective plates in parallelepiped type silencers. These devices are positioned inside ducts, turbines and ventilation systems (cylindrical or with square/rectangular section). Their operation involves the absorption of energy through the fluid with the sound-absorbing materials, causing a drastic reduction in the residual sound pressure levels downstream of the silencer (Evdokimova and Rumyantseva, 2020).

4.Key outcomes and discussion

The literature analysis allowed us to outline an overall picture of the positive and negative influence of each factor on IEQ. However, such research also revealed the complex existing relationships between the various factors that define the IEQ. The relationship between ambient temperature and health effects can be represented as a concave curve. The analyzed studies show that the range between 21 ° C and 25 ° C corresponds to optimal cognitive and working performance. On the other hand, higher or lower temperatures are associated with health problems and decreased work performance. In fact, at low temperatures, the risk of cardiovascular and respiratory diseases increases. Cold suppresses mucociliary defenses and other immunological reactions, resulting in local inflammation and increased risk of respiratory infections. Furthermore, exposure to cold provides alternative stimuli that distract attention from the task (focusing on feeling cold rather than completing the given cognitive task). On the other hand, high temperatures cause dry eyes and worsen respiratory symptoms. They also cause an increased body temperature, leading to fatigue and decreased muscle endurance. The consequences foresee bad decision-making, errors and in an increased risk of accidents. As for IAH, values between 40% and 60% are optimal for health, work performance and the lowest risk of infection. A lower IAH decreases the self-cleaning function of the eyes and respiratory tract, causing dryness and irritation of the mucous membranes. In particular, dry eye-like symptoms represent one of the main factors causing deterioration of cognitive performance during visual visualization work. Inadequate lighting conditions amplify this adverse effect. Raising the IAH level relieves dry eye and airway symptoms, improving the occupant's mucociliary activity. In addition, it reduces fatigue, increasing worker productivity. On the other hand, the elevation of the IAH above 60% increases the risk of mold growth and SBS symptoms in cold and poorly ventilated spaces. To date, the value of IAH is significant for the containment of viruses in industrial environments. Both dry air (IAH <40%) and highly humid air (IAH> 90%) favor transmission and infectivity. However, optimal levels (40% <IAH <60%) lead to the deposition of the particles, reducing their resuspension. This principle is valid not only to viruses but also to particles charged with internal pollutants. Ventilation can have the same effect on reducing the concentration of indoor air pollutants, improving the well-being of the occupants and increasing their productivity. The analyzed studies highlight the importance of personal ventilation control concerning the satisfaction of thermal well-being due to both the physical and psychological impact of this factor. Although an increase in natural or mechanical ventilation corresponds to good IAQ, attention must be paid to introducing external pollutants and the temperature of the outdoor air. In particular, during the winter period, the introduction of cold air can generate thermal stress in workers, e.g. muscle spasms, excessive physical effort, anxiety, fatigue and confusion. Furthermore, the dryness of the introduced air can increase the pollutant load of the indoor air, favoring airway symptoms related to SBS. Finally, we can conclude that ventilation is a modifying factor that should be integrated with both the IAH and the ambient temperature in a joint strategic control to satisfy the perceived IAQ, health, working performance and minimize the risk of infection.

5.Microclimate strategies in the context of COVID-19 Pandemic

COVID-19 is caused by the new SARS-Cov-2 coronavirus, with over 110 million known infections by February 2021 worldwide. Transmission occurs mainly through inhalation of SARS-CoV2-laden droplets and aerosol particles through direct contact with an infected person or a contaminated surface (Jayaweera et al., 2020). Effective mitigation measures require a clear understanding of droplets and aerosols transport, surface retention and evaporation kinetics in different environments and conditions (Mittal et al., 2020). In indoor environments, some of the generated particles come out of the system through ventilation. Some particles are deposited on the room's surfaces and can return in suspension and others can be inhaled directly. The aim of the mitigation measures to reduce virus transmission is to maximise the fraction of particles leaving the system and minimise the deposition of aerosols to humans. Abuhegazy et al. (2020) show that the total fraction of particles depositing on the source individual, on the ground and the surfaces close to him increases significantly with increasing particle size. The COVID-19 pandemic represents a global health crisis and an international economic threat due to the vast closures needed to contain the spread of the virus (Kabadayi et al., 2020). In such a scenario, it is clear that work represents a decisive dimension in the context of the Sars-Cov-2 pandemic. New findings on the spread of infections allowed a constant update of the guidelines the industrial field must adopt. ILO entrusted employers with the obligation to carry out risk assessments to ensure that industries meet strict safety and health criteria for employees. On 27 February 2020, The WHO published a guidance paper entitled *"Preparing the workplace for COVID-19"* to resume the various productive activities (World Health Organization, 2020). In November 2020, a study published by the CDC showed that asymptomatic is the most extensive transmission channel. As a result, the containment actions focused on controlling the transmission by bio-aerosol through adequate ventilation of industrial spaces. Moreover, the European Agency for Safety and Health at Work (EU-OSHA) expressed the need to ensure good ventilation, open windows and doors, encourage air exchange, and improve IAQ. The researchers of the ISS published reports and updates to provide essential and urgent guidance in emergency management. In particular, the report Covid-19 n5/2020 Rev stressed the importance of IAQ as a virus mitigation strategy. Scientific studies and guidelines highlight the importance of ventilation and internal humidity levels in the fight against the spread of the virus in industrial spaces. Ventilation encourages the escape of infected particles, while the elevation of the IAH increases particles' size and weight, speeding up their deposition and limiting their resuspension. In addition, a higher IAH increases the occupant's mucociliary clearance, decreasing the infectivity of viruses and pollutants. In this context, the outbreak of the SARS-Cov-2 epidemic led the industrial sector to turn attention to HVAC systems. AiCARR, in his *"protocol for the reduction of the risk from the spread of Sars-CoV-2 in the management and maintenance operations of existing air conditioning and ventilation systems"*, argues that, in the presence of mechanical ventilation systems, actions aimed at maximizing the quantity of external air introduced are therefore generally recommended. The use of local or centralized recirculation air, combined with the introduction of external air, allows energy savings; however, it requires HEPA filters or treatment and/or abatement technologies (e.g. ultraviolet lamps) to reduce contamination (AiCARR, 2020).

6.Conclusions and future research

In recent years, industrial companies adopted effective microclimate strategies to improve Indoor Environmental Quality (IEQ) and Indoor Air Quality (IAQ). However, these strategies are often responsible for heat stress, discomfort and other adverse effects on the health and safety of workers. This paper aimed to perform a literature review about the impacts of ventilation, temperature, IAH, lighting and biophilia in improving IEQ, considering the effect of each factor on the well-being and productivity of industrial workers. Three of the five elements have proved to be of particular interest as, to date, they represent effective microclimatic strategies in containing the transmission of the Sars-Cov-2 virus within industrial spaces. The increase in natural or mechanical ventilation and the control of temperature and IAH demonstrated a substantial impact on employees' well-being, health and productivity, and as a contagion-reducing effect, acting on the dispersion deposition and limitation of resuspension of the pathogenic cloud. Since high comfort values favor productivity, this review highlights for each factor the range of optimal values and the consequences of the deviation from these values. In addition, it presents the positive and negative relationships that exist among the key factors and the supporting technologies for the improvement of IEQ. Analyzing the interactions among the different factors that define the IEQ is a complex task that needs further investigation. In particular, this review did not consider the subjective variables (e.g. sex, age, and environment) that can modify workers' comfort perception and performance. Among these, age represents an interesting factor to be explored in the near future. Indeed, understanding the relationships between progressive physical and cognitive decline and the critical aspects of IEQ will lead to new strategies to support the aging workforce.

References

Abuhegazy, M., Talaat, K., Anderoglu, O. and Poroseva, S. V. (2020). Numerical investigation of aerosol transport in a classroom with relevance to COVID-19. *Physics of Fluids*, 32(10).

Akimoto, T., Tanabe, S., Yanai, T. and Sasaki, M. (2010). Thermal comfort and productivity - Evaluation of workplace environment in a task conditioned office. *Building and Environment*, 45(1), pp. 45–50.

Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M. and Elsarrag, E.(2016). Occupant productivity and office indoor environment quality: A review of the literature. *Building and Environment*, 105, pp. 369–389.

Byber, K., Flatz, A., Norbäck, D., Hitzke, C., Imo, D., Schwenkglenks, M., Puhan, M. A., Dressel, H. and Mutsch, M. (2016). Humidification of indoor air for preventing or reducing dryness symptoms or upper respiratory infections in educational settings and at the workplace. *Cochrane Database of Systematic Reviews*, 2016(6).

Cai, X., Lu, Y. and Wang, J. (2018). The impact of temperature on manufacturing worker productivity: Evidence from personnel data. *Journal of Comparative Economics*, 46(4), pp. 889–905.

Castaldo, V. L., Pigliautile, I., Rosso, F., Cotana, F., De Giorgio, F. and Pisello, A. L. (2018). How subjective and non-physical parameters affect occupants' environmental comfort perception. *Energy and Buildings*, 178, pp. 107–129.

Dalton, P., Soreth, B., Maute, C., Novaleski, C. and Banton, M. (2018). Lack of respiratory and ocular effects following acute propylene glycol exposure in healthy humans. *Inhalation Toxicology*, 30(3), pp. 124–132.

Elzeyadi, I. (2011). Daylighting-bias and biophilia: quantifying the impact of daylighting on occupants health. *School of Architecture & Allied Arts*, pp. 1–9.

Evdokimova, A. and Rumyantseva, N. (2020). Complex of measures to reduce noise on the environment and power plant personnel. *E3S Web of Conferences*, 221, pp. 1–5.

Frontczak, M., Schiavon, S., Goins, J., Arens, E., Zhang, H. and Wargocki, P. (2012). Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. *Indoor Air*, 22(2), pp. 119–131.

Gasparrini, A., Guo, Y. and Hashizume, M. (2015). Mortalité attribuable au froid et à la chaleur: Analyse multi-pays. *Environnement, Risques et Sante*, 14(6), pp. 464–465.

Hamedani, Z., Solgi, E., Hine, T. and Skates, H. (2020). Revealing the relationships between luminous environment characteristics and physiological, ocular and performance measures: An experimental study. *Building and Environment*, 172(January), p. 106702.

Jayaweera, M., Perera, H., Gunawardana, B. and Manatunge, J. (2020). Transmission of COVID-19 virus by droplets and aerosols: A critical review on the unresolved dichotomy. *Environmental Research*, 188(May).

Kabadayi, S., O'Connor, G. E. and Tuzovic, S. (2020). Viewpoint: The impact of coronavirus on service ecosystems as service mega-disruptions. *Journal of Services Marketing*, 34(6), pp. 809–817.

Kershaw, T. and Lash, D. (2013). Investigating the productivity of office workers to quantify the effectiveness of climate change adaptation measures. *Building and Environment*, 69, pp. 35–43.

Ko, W. H., Schiavon, S., Zhang, H., Graham, L. T., Brager, G., Mauss, I. and Lin, Y. W. (2020). The impact of a view from a window on thermal comfort, emotion, and cognitive performance. *Building and Environment*, 175(March), p. 106779.

Lan, L., Wargocki, P. and Lian, Z. (2011). Quantitative measurement of productivity loss due to thermal discomfort. *Energy and Buildings*, 43(5), pp. 1057–1062.

Li, D., Menassa, C. C. and Kamat, V. R. (2018). Non-intrusive interpretation of human thermal comfort through analysis of facial infrared thermography. *Energy and Buildings*, 176, pp. 246–261.

Mentese, S., Mirici, N. A., Elbir, T., Palaz, E., Mumcuoğlu, D. T., Cotuker, O., Bakar, C., Oymak, S. and Otkun, M. T. (2020). A long-term multi-parametric monitoring study: Indoor air quality (IAQ) and the sources of the pollutants, prevalence of sick building syndrome (SBS) symptoms, and respiratory health indicators. *Atmospheric Pollution Research*, 11(12), pp. 2270–2281.

Mittal, R., Ni, R. and Seo, J. H. (2020). The flow physics of COVID-19. *Journal of Fluid Mechanics*, 894, pp. 1–14.

Nico, M. A., Liuzzi, S. and Stefanizzi, P. (2015). Evaluation of thermal comfort in university classrooms through objective approach and subjective preference analysis. *Applied Ergonomics*, 48, pp. 111–120.

Ormandy, D. and Ezratty, V. (2012). Health and thermal comfort: From WHO guidance to housing strategies. *Energy Policy*, 49, pp. 116–121.

Salata, F., Golasi, I., Verrusio, W., de Lieto Vollaro, E., Cacciafesta, M. and de Lieto Vollaro, A. (2018). On the necessities to analyse the thermohygrometric perception in aged people. A review about indoor thermal comfort, health and energetic aspects and a perspective for future studies. *Sustainable Cities and Society*, 41(June), pp. 469–480.

Salcido, J. C., Raheem, A. A. and Issa, R. R. A. (2016). From simulation to monitoring: Evaluating the potential of mixed-mode ventilation (MMV) systems for integrating natural ventilation in office buildings through a comprehensive literature review. *Energy and Buildings*, 127, pp. 1008–1018.

Shehadi, M. (2018). Review of humidity control technologies in buildings. *Journal of Building Engineering*, 19(April), pp. 539–551.

Smith, A. and Pitt, M. (2011). Healthy workplaces: Plantscaping for indoor environmental quality. *Facilities*, 29(3), pp. 169–187.

Stefanović, V., Urošević, S., Mladenović-Ranisavljević, I. and Stojilković, (2019). Multi-criteria ranking of workplaces from the aspect of risk assessment in the production processes in which women are employed. *Safety Science*, 116(March), pp. 116–126.

Sugg, M. M., Stevens, S. and Runkle, J. D. (2019). Estimating personal ambient temperature in moderately cold environments for occupationally exposed populations. *Environmental Research*, 173(January), pp. 497–507.

Turan, I., Chegut, A., Fink, D. and Reinhart, C. (2020). The value of daylight in office spaces. *Building and Environment*, 168(August 2019), p. 106503.

Wolkoff, P. (2018). Indoor air humidity, air quality, and health – An overview. *International Journal of Hygiene and Environmental Health*, 221(3), pp. 376–390.

Wolkoff, P. (2018). The mystery of dry indoor air – An overview. *Environment International*, 121(October), pp. 1058–1065.

Wolkoff, P., Azuma, K. and Carrer, P. (2021). Health, work performance, and risk of infection in office-like environments: The role of indoor temperature, air humidity, and ventilation. *International Journal of Hygiene and Environmental Health*, 233 (September 2020), p. 113709.

Wu, J., Hou, Z., Shen, J. and Lian, Z. (2021). A method for the determination of optimal indoor environmental parameters range considering work performance. *Journal of Building Engineering*, 35(October 2020), p. 101976.

Yang, I. H. and Nam, E. J. (2010). Economic analysis of the daylight-linked lighting control system in office buildings. *Solar Energy*, 84(8), pp. 1513–1525.

Yuan, X., Pan, Y., Yang, J., Wang, W. and Huang, Z. (2021). Study on the application of reinforcement learning in the operation optimization of HVAC system. *Building Simulation*, 14(1), pp. 75–87.

Zhao, K., Blacker, K., Luo, Y., Bryant, B. and Jiang, J. (2011). Perceiving nasal patency through mucosal cooling rather than air temperature or nasal resistance. *PLoS ONE*, 6(10).

Zhu, H. C., Ren, C. and Cao, S. J. (2020). Fast prediction for multi-parameters (concentration, temperature and humidity) of indoor environment towards the online control of HVAC system. *Building Simulation*, pp. 649–665.