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Towards the new generation of courtyard buildings as a healthy living concept for post-pandemic era

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ABSTRACT

COVID-19 has laid a context for holistic research and practical approaches towards health issues in buildings. This study focuses on one particular residential building type, which is a combination of a modern apartment building with private double-oriented terraces, and a traditional courtyard building. This principle improves several aspects of healthy buildings and contributes to address indoor-outdoor interactions, daylighting, and the use of natural ventilation. The purpose of this study is to determine the factors underlying a particular type of semi-outdoor space within building forms and to explain their microclimatic behavior in buildings. One solid model and twelve porous apartment buildings with different numbers of porous sides, and terrace widths are evaluated using computational fluid dynamics. The k–ε turbulence model is adapted to simulate airflow in and around a four-story building. CFD simulations were validated against the wind-tunnel measurements. Investigations indicated that increasing the number of porous sides reduces the internal mean and maximum ages of air by -15.75 and -36.84%, which means improved ventilation performance. However, it leaves a negative trace on ventilation of the semi-outdoor spaces. Meanwhile, increasing the width of the terraces enhances the ventilation performance by reducing the mean age of air in units, courtyards, and terraces by -20%, -20%, and -9%, respectively.

1. Introduction

In early 2020, the world witnessed the outbreak of the COVID-19 pandemic that claimed millions of lives (Morawska et al., 2020). The lockdown during the pandemic proved the importance of the home as a fundamental context for pursuing all aspects of life, and controlling infectious diseases (Elrayies, 2022). Moreover, numerous mental and physical problems became more evident due to inadequate passive ventilation, natural daylight, and lack of green space in and around traditional high-rise residential buildings (Isaac and Hemeida, 2022). After the pandemic, house is not just a place to live, but also a comprehensive infrastructure for numerous activities, including working, studying, exercising, shopping, and even telehealth (Meagher & Cheadle, 2020; Brooks et al., 2020). During the quarantines, despite people's attempts to adapt their living spaces to the new conditions (Liston, n.d.), it was proved that current housing designs (apartment buildings) are unable to support several aspects of healthy buildings, provide adequate daylighting and natural ventilation, and address social and psychological challenges (Elrayies, 2022). Although most of these goals could be achieved in courtyard buildings, constraints in large cities have severely limited the ability to build courtyard buildings. Following the history demonstrates the significant trace of epidemics on architecture development and housing reforms for healthier environments (Tokazhanov, Tleuken, Guney, Turkyilmaz, & Karaca, 2020; Allam & Jones, 2020; Hamouche, 2020). Therefore, it is crucial to introduce a new generation of housing that utilizes the potential of apartments and courtyard buildings to adequately meet the needs of people in the post-pandemic period. This research is significant for two reasons: first, it introduces a new type of building that utilizes the potential of apartment and courtyard buildings, meets most of the goals of healthy architecture, and serves as an appropriate pattern for post-pandemic architecture. Second, considering the fundamental role of natural ventilation and IAQ on reducing the risk of COVID -19 and other types of infectious respiratory diseases (Shen et al., 2021), a design framework for post-pandemic resilient homes is developed that reduces the risks of the pandemic by improving natural ventilation.

The primary objective of this study is to introduce a new type of courtyard building that meets the post-COVID requirements by

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combining modern multi-family apartment buildings, with semi-outdoor spaces in the form of terraces and courtyards. It also aims to improve natural ventilation in the proposed models by evaluating the relationship between the physical configurations of the semi-outdoor spaces and natural ventilation performance.

A semi-outdoor space is an area exposed to the outdoor environment, including man-made structures (such as roofs or walls) that mitigate the effects of outdoor conditions (Spagnolo & de Dear, 2003). These spaces that are connected to the building are partially open to the outdoors (Hwang & Lin, 2007). Balconies are considered shaded, semi-outdoor spaces that provide much-needed thermal relief to flat dwellers during hot seasons. Courtyards, on the other hand, as open spaces surrounded by walls or buildings, are classified as semi-outdoor spaces because they are bounded laterally (Chen & Clarke, 2020). A semi-outdoor space in the form of a terrace, courtyard, balcony, or deck is an important architectural feature in tropical climate (Gamero-Salinas et al., 2022).

The introduction of semi-outdoor spaces into a multi-family apartment building with a central courtyard is the point that distinguishes this model from its counterparts. This concept accumulates advantageous of two different building typologies; apartment buildings and courtyard buildings. Traditional courtyard buildings, despite their sundry virtues, offer accommodations for single families with a limited number of floors. Modern apartment buildings, on the other hand, meet several demands of modern life, and offer accommodation for ever-growing urban population owing to their vertical spread and multiple floors. However, they lack most of the positive aspects of courtyard buildings. It is hypothesized that the concept of combining these patterns paves the way for utilizing the positive aspects of both patterns, combining them in a common context, meeting the requirements of healthy buildings in post-pandemic era, and improving double-sided natural ventilation in buildings.

2. Literature review

In this section, a comprehensive review of various characteristics of healthy buildings and their influence on mental and physical health under normal and COVID conditions are presented. Then, architectural measures to meet these requirements are discussed. Considering the importance of natural ventilation in the COVID and post-COVID era, this research provides a thorough review of studies on the impact of semi-outdoor spaces (terraces, balconies, and courtyards) on natural ventilation.

Numerous investigations have evaluated the attributes of healthy buildings. **Indoor air quality** (IAQ) is one of the effective factors that is influenced by outdoor contaminants and indoor sources (Awada et al., 2022; Heinsohn & Cimbala, 2003). Poor IAQ can cause shortness of breath, cancer, lung disease, and bronchitis (Loomis et al., 2013). This parameter became more acute during the pandemic, since improved IAQ is a solution against COVID-19, and controls the infection risk of COVID-19 via airborne transmission (Zhang, 2020; Morawska et al., 2020a; Afshari, 2020). Airborne pollutants also have severe neuro-cognitive effects, from behavioral changes to aggressive behavior and mental fatigue (Szyszkowicz et al., 2009; S. Chen et al., 2019; Evans, 2003). During the crisis COVID-19, air quality was introduced as a priority among environmental factors affecting residents' mental health (Akbari et al., 2021). **Ventilation** is the second factor that improves IAQ and decreases reported health symptoms by eliminating and diluting pollutants as well as controlling indoor humidity, and airborne contaminants (Bornehag et al., 2005; Group et al., 2009; Awada et al., 2021). A higher value of air change rate supplies fresh air, decreases the concentration of indoor pollutants, and extracts the contaminated air (Meiss et al., 2013). The longer the air remains indoors, the more it can become contaminated with pollutants such as dust, virus, and mold spores. Covid-19 transmission can occur through "long-distance airborne transmission" in poorly ventilated indoor environment. This fact proves that ventilation plays an important role in preventing airborne transmission of the virus and creating a healthy environment (Lewis, 2022). Hence, to attain well-being targets, providing natural ventilation by decreasing the age of air (droplet residence time) and increasing the air change rate is essential. The improper ventilation and concentration of environmental pollution lead to a change in mood, increase stress level, and decrease overall indoor well-being (Schwartz, 2019). **Daylight** is another key factor in healthy buildings protects the individuals from osteoporosis (Holick, 2004), reduces the risk of type-2 diabetes, lowers blood pressure, and improves eye health (Healthonics, 2019). Daylight is associated with enhanced alertness levels, better mood, and suppressed depression (Burns et al., 2021; Akbari et al., 2021; Plano et al., 2017). Sunlight as a rich source of vitamin D improves the immune system against COVID-19, increases recovery speed, and lowers the death rate due to COVID-19 (Meo et al., 2020; Ali, 2020; Asyary & Veruswati, 2020; Muhammad et al., 2022). Exposure to sunlight is also an underlying factor in mental health during COVID-19 (Korman et al., 2022). **Acoustics** is an important issue in healthy buildings (Mahdavi & Najaf Khosravi, 2020). Exposure to loud noise can cause numerous problems, including Noise Induced Hearing Loss (NIHL), heart disease, and hypertension (Stanley, 2022). Noise pollution can impair the quality of life and lead to negative mental effects (Basner et al., 2014) such as sleep disturbances (Pirrera et al., 2010; Basner et al., 2014; Basner et al., 2011), and psychosomatic disorders (Watkins et al., 1981). Noise pollution is a crucial environmental factor relevant to the occurrence and severity of COVID -19 (Díaz et al., 2021). A good acoustic environment can mitigate the negative emotional effects during the lockdown period (Wu et al., 2022). Interaction with **nature** is a key factor in healthy buildings that can be incorporated through biophilic design, fresh air, natural sounds, or views of nature (Pellow et al., 2011). Plants help improve IAQ by filtering air, balancing energy, improving human health and controlling temperature (Wei et al., 2021; Kim et al., 2018; Lee et al., 2020). Human-nature contact leads to stress reduction, healing, and the growth of perceptual and expressive skills (Berman, M et al. 2008). Plants reduce the transmission of COVID by regulating indoor humidity, as virus transmission decreases considerably at humidity levels of 40-60% (Bhattacharyya et al., 2015). Research has shown that indoor plants alleviate the psychological stress of occupants by exuding positive energy during the pandemic period (Liu et al., 2022).

In post-pandemic architecture, **spatial organizations** should focus on **physical and psychological health** while improving **social interactions** among residents. To promote physical and mental health in buildings, physical activity, indoor air quality, natural ventilation, daylighting, planting, and acoustics must be considered in the design process (Fig. 1).

During the COVID-19 crisis, buildings should provide residents with opportunities for **physical activity** by creating appropriate spaces in the form of open and semi-outdoor areas (roof garden, courtyard), as well as dedicated rooms for each housing unit in the form of a balcony or terrace. Research has shown that access to an open spaces is positively associated with an increase in physical activity and maintenance of physical health during the COVID-19 crisis (Morawska et al., 2020; Liu et al., 2022). **Indoor Air Quality** (IAQ) is the second factor that can be improved by non-pharmaceutical measures and engineering controls. Improving natural ventilation and diluting air contaminants (Morawska et al., 2020), removing pollutants and capturing airborne particles by air purifiers, implementing carbon-based filters (which absorbs NO_2 and VOCs)(Molina-Sabio & Rodríguez-Reinoso, 2004), ionization air purifiers, and indoor plantating are some of the measures to improve IAQ (Agarwal et al., 2021; El-Tanbouly et al., 2021). **Natural ventilation** as one of the fundamental factors in the spatial organization of post-pandemic buildings is under the influence of numerous parameters such as typology (Hariri et al., 2016), building allocation, general form, envelope (Najaf Khosravi & Mahdavi, 2021), internal planning, and external supplements (Najaf Khosravi et al., 2016). The introduction of atriums, courtyards, and terraces in solid buildings is usually considered an effective strategy to enhance wind-driven and stack ventilation in

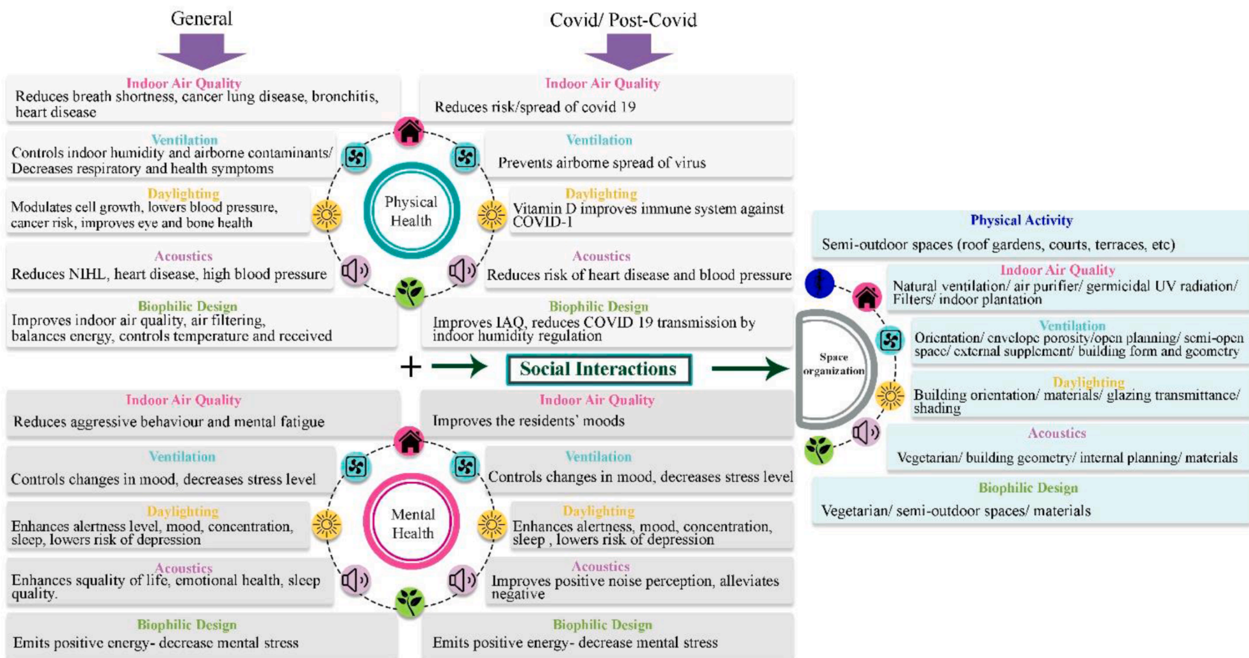


Fig. 1. Effective factors on physical and mental health in general, COVID and post-COVID conditions. Architectural measures to address mental, physical health, and social interaction in buildings.

buildings (Tablada de la Torre et al., 2005; Mohammed et al., 2020; Saadatjoo et al., 2018; Saadatjoo et al., 2019). The aspect ratio of courtyards (Saligheh & Saadatjoo, 2020), morphological configurations as well as their connectivity to the surrounding environment significantly affect their performance (Rose et al., 2011; Ok et al., 2008). Aligning shorter building axes with the prevailing wind direction (Felkner & Chatzi, 2014a), enlarging exposed surface and pressure difference (Allard & Santamouris, 1998), and using relatively wide and low buildings with narrow footprint and high aspect ratios (long and shallow plan) are drastic parameters which influence the wind behavior greatly (Heiselberg, 2004). The effectiveness of ventilation can be further improved by upgrading some advances in the design of openings on the building façade (Shetabivash, 2015). **Daylighting** as a critical factor for healthy buildings, is influenced by surrounding obstructions, building orientation (Rao, 2015), building geometry (Ghasemi et al., 2015), material properties (Majeed et al., 2019), glazing light transmittance, shading and position (Bokel, 2007). **Planting** in apartment buildings (the predominant typology) in the form of green roofs, terraces, and vertical forests proposes a high-quality environment with natural components in the post-pandemic era (Wang et al., 2020). It increases livability and sustainability by shading and protecting the building from direct solar radiation (Dunnett & Kingsbury, 2008), increasing the energy saving by evapotranspiration (Coma et al., 2017), thermal insulation, enhancing building **acoustic** performance (Wong et al., 2010), improving air quality through continuous airflow and absorption of fine particles and pollutants (Perini et al., 2013). At the same time, it provides a suitable context for urban agriculture.

Restrictions during COVID-19 dispersal and distancing measures changed the nature of **social interactions** and reduced face-to-face interactions significantly (Cheung & Leung, 2011). To establish and improve social interaction among residents within apartment buildings, the introduction of appropriate spaces such as common rooms, shared courtyard, and terraces is essential (Stoiljkovic, 2022).

Among the numerous attributes of a healthy building, this research concentrates on natural ventilation, as the emergence of COVID-19 has proven the significance of natural ventilation and IAQ in buildings (Tanabe & Takewaki, 2020). Indoor air quality (IAQ), including strategies to control natural ventilation, dilutes polluted indoor air more quickly and reduces the risk of airborne transmission of COVID-19 and other infectious respiratory diseases (Zhang, 2020; Morawska et al., 2020; Van Dijken & Roerstra, 2021). Studies have shown that the residence time of an aerosol in a poorly ventilated space increases tenfold (Park et al., 2021; Bazant & Bush, 2021). Even in countries with adequate vaccination coverage, epidemics can reoccur if indoor ventilation is not adequately addressed (Chen et al., 2021). During this period, experimental tests and CFD simulations were used to study indoor dispersion of infectious particles and assess infection risk as a function of exposure dose (Li et al., 2020). In 2022, Kuwahara and Kim demonstrated that frequent natural ventilation with short intervals effectively reduced indoor transmission of COVID-19 in a university setting (Kuwahara and Kim, 2022). Che and colleagues proved the effects of airflow deflectors and pollutant source locations on infection probabilities in classrooms (Che et al., 2022). Ren and colleagues proved the effectiveness of physical barriers in mitigating the risk of infectious disease transmission while providing sufficient ventilation (Ren et al., 2021). In 2021, Shen et al. demonstrated the effectiveness of multiscale IAQ control strategies such as elevated outdoor airflow rates, high-efficiency filters, advanced air distribution strategies, and stand-dalone air purification technologies to reduce the risk of infection in different scenarios (Shen et al., 2021).

A semi-outdoor space affects the indoor and outdoor thermal environment by influencing wind performance and natural ventilation (Gamero-Salinas et al., 2022; Rajapaksha et al., 2003). The natural ventilation performance of a semi-outdoor space (courtyard, terrace, balcony, etc.) is linked to a wide range of physical configurations such as openness, aspect ratio, orientation, shape, environment, opening positions, etc. (Yang et al., 2020). Balconies as semi-outdoor spaces have significant impacts on wind flow patterns and pressure distribution on buildings (Ai et al., 2011; Montazeri & Blocken, 2013; Kahsay et al., 2019) and indoor comfort (Prianto & Depecker, 2002). Mozaffari Ghadikolaei, Ossen, and Mohamed (2020) studied single-sided ventilation of balconies with wing walls and demonstrated the effectiveness of wing walls on NVP (Mozaffari Ghadikolaei et al., 2020). Izadyar and colleagues (2020) studied nine buildings with different balcony depths and introduced this variable as an effective factor for indoor air distribution, mean air velocity, and air temperature (Izadyar et al., 2020). Montazeri and Blocken evaluated wind-induced pressure on building facades with and without balconies and demonstrated that the pressure coefficient behaves differently for high-rise buildings than for low-rise buildings (Montazeri & Blocken, 2013). Mohammadi and colleagues compared the performance of natural ventilation in two double-story houses in Kuala Lumpur with and without balconies. Despite previous studies, they indicated that the introduction of balconies did not improve natural ventilation performance and indoor air quality (Mohammadi et al., 2010). In contrast, Bhikoo et al. indicated that the presence of balconies reduced the number of overheating days in low-income houses in Bankok due to natural ventilation improvement (Bhikhoo et al., 2017). Omrani et al. evaluated the effect of balconies on natural ventilation and thermal comfort in high-rise buildings, indicating that the adding a balcony to a building with single-sided ventilation can improve ventilation performance, while worsening it in cross-ventilated models (Omrani et al., 2017). Some studies concluded that the presence of balconies leads to a reduction in indoor pollutant concentrations and an improvement in air quality (Cui et al., 2013). Hirano and colleagues demonstrated the effects of permeable office buildings on NVP by comparing a 50% permeable model to a solid case (Hirano et al., 2006). According to Muhsin and colleagues, increasing the permeability level to 50% improves the natural ventilation potential of residential units by 50.88% (Muhsin et al., 2017). Konidari et al. (2014) presented porosity as an efficient solution to improve natural ventilation potential and reduce cooling energy demand for new buildings in dense cities (Konidari & Fedeski, 2014). Saadatjoo and colleagues studied terraced buildings with different porosity ratios (20% to 50%) and demonstrated that increasing the number of terraces and porosity ratio has an impact on NVP (Saadatjoo et al., 2021). In another study, the cases with terrace depth of 1.2 m showed better natural ventilation performance compared to terraces with depth of 1.5 and 1.8 meters (Saadatjoo et al., 2018).

The courtyard is another semi-outdoor space in a building that influences the ventilation performance through different physical configurations. According to investigations, **transparency and connection to surroundings** increase the velocity of airflows in the semi-outdoor spaces in relation to their dimensions and positions (Ok et al., 2008). Meanwhile, the presence of lower openings, designed according to the prevailing wind direction yields more comfortable conditions in the courtyards (Berkovic & Yezioro, 2017). An investigation of the void connections of a light well on upflow with different wind directions (0°-45°-90°) illustrated the significant role of the vertical and horizontal position of the voids on ventilation. Cross-flow and double-level voids indicated better performance by increasing the upward flow as well as decreasing the air temperature (Farea et al., 2015). Hao and colleagues compared airflow patterns in an open courtyard to a closed structure with a similar building configuration. According to their results, the natural ventilation behavior of the courtyard benefited from the proper first floor openings (Hao et al., 2019).

The composition between the openings in the building envelope and the courtyard affects the internal ventilation, airflow pattern, and indoor thermal conditions. The ventilation and thermal performance in the courtyards that act as air funnels are better than in the cases that act as suction zones (Rajapaksha et al., 2003).

Aspect ratio and dimensions are critical factors affecting airflow patterns in semi-outdoor spaces (Rodríguez-Algeciras et al., 2018). A good combination of courtyard layout and aspect ratio can improve the use of natural ventilation by increasing free cooling during hot summer and reducing cold wind in winter (Xu et al., 2018). Moonen and his colleagues proved that exchange flux improves with increasing the courtyard length, and is optimal for a length-to-width ratio of 10 or more (Moonen et al., 2011). In the research conducted by Tablada and his colleagues, five different courtyard ratios (width/height) were simulated. According to their results, courtyards with ratios of 1.0 and 0.7 had the best potential for natural ventilation, as they developed a strong vortex and high flow velocities (Tablada de la Torre et al., 2005). In 2014, Abdulbasit Almhafdy and his colleagues demonstrated that aspect ratio and cantilevered roof have a significant effect on wind speed and consequently on thermal comfort. Aspect ratio (1:2) performs better than aspect ratio (1:1) (Almhafdy et al., 2015). Higher solar heat gains and ventilation rates were observed in the courtyards with greater width and length (Toris-Guitron et al., 2022). Using computer simulations, Saligheh and Saadatjoo demonstrated that for courtyards with identical volume-to-surface area ratios, changing the width of the central courtyard affects internal ventilation, cooling load, and the amount of shaded area (Saligheh & Saadatjoo, 2020; Saadatjoo et al., 2016).

The surrounding geometry of a courtyard, in addition to its physical structure, plays an essential role in determining the velocity quantities (V/Uref). The study of air velocity in cases with different obstacles showed that courtyards without obstacles have the highest velocities. In contrast, courtyards with obstacles on the downstream side have the lowest velocities (Tablada de la Torre et al., 2005).

The effect of **courtyard position** on natural ventilation was evaluated by simulating 21 different cases, and the courtyard in the center of the building was presented as the most efficient case with maximum internal ventilation ratio (Abdelhady, 2021). Lopez-Cabeza et al. studied a real-scale prototype in Hungary to analyze the thermal and ventilation performance of courtyards. They used monitoring data to calibrate a simulation model that predicts thermal performance for different wall configurations and ventilation situations. The results showed that the thermal inertia and ventilation inside the courtyard reduced tempering potential during the day, but also reduced overheating at night and can increase the thermal comfort depending on wind speed (López-Cabeza et al., 2023).

In spite of numerous studies in the field of COVID and post-COVID architecture, no research has yet presented comprehensive solutions for creating healthy residential houses that simultaneously satisfy various aspects of healthy buildings, while promoting natural ventilation and improving indoor air quality. As shown in the review of previous research, extensive studies have focused on the effects of courtyard and terrace (or balcony) as two semi-outdoor spaces on natural ventilation. Combining these two elements and evaluating their simultaneous effects on building natural ventilation is a topic that has not yet been studied.

Experimental and on-site investigations could provide deep insight into the relationship between physical features and natural ventilation performance. However, as proved by many studies, computational fluid dynamics can be a reliable and fast tool to understand the complex flow patterns and natural ventilation performance in different buildings (Motamedi et al., 2022). Table 1 presents the evaluation methods, objectives, performance indicators, turbulence model, simulation conditions, and results of a literature review in the field of courtyard configurations and ventilation performance.

3. Methodology

3.1. The city of Bandar Abbas

Bandar Abbas, the capital of Hormozgan province, is located at latitude 27°18′ N and longitude 56°26′ E with an average elevation of 9 m above sea level (Fig. 2) . The average annual temperature in Bandar Abbas is 27.1 degrees Celsius, and the average annual relative humidity is 65.5% (Roshan et al., 2019). With an average annual rainfall of 18.2 millimeters, it is known as an arid climate according to the Beller climate classification (Zabolbbasi et al., 2007).

The city has experienced considerable growth in built-up areas in recent decades. New construction during 2000-2012 resulted in an increase in population density to 77.27 persons per hectare, as well as a decrease in spatial harmony (Sarai & Moayedfar, 2008). With an area of approximately 100 km^2, Bandar Abbas consists of 4 central regions, and each region consists of several districts (Dadras et al., 2014). Residential buildings are distributed almost across all regions, but each region seems to have a specific type of density. High-density buildings are found

Table 1
Literature review on semi-outdoor spaces' ventilation performance.

Authors	Methods	Objectives	Performance Indicators	Dimension/ Semi-outdoor space type	Turbulence Modeling	Inlet Profile	Validation
(Sharples & Bensalem, 2001)	Wind tunnel	Typology (courtyard and atrium), openings of the atrium	Pressure regimes, non-dimensional flow coefficient	3D/ courtyard, atrium	Wind tunnel tests	ABL	Y
(Rajapaksha et al., 2003)	CFD	Potential of the inner courtyard for passive cooling	Several airflow patterns	3D/ Internal courtyard	RANS (standard k- ε)	ABL	N
(Tablada et al., 2005)	CFD	Ratio of courtyard, presence of obstructions	Relative velocity magnitude, Pressure coefficient	2D/ Courtyard	RANS (standard k- ε)	ABL	Y
(Ok et al., 2008)	Wind tunnel	Position and proportions of openings	Mean wind speed	3D/ Courtyard	Wind tunnel tests	-	Y
(Mohammadi et al., 2010)	CFD	Presence of balconies	Volume flow, Temperature, Humidity	3D/ Balcony	RANS (standard k- ε)	ABL	N
Moomen et al. (2011)	CFD	Ratio of courtyard (L/H)+ wind direction	Normalized exchange flux	3D/ Courtyard	RANS (realizable k– ε)/LES	Uniform	N
(Montazeri & Blocken, 2013)	CFD	Geometry of building facade	Surface pressure coefficients	3D/ Balcony	RANS (Standard k-ε, RNG k-ε, RSM, Standard k-ω)	ABL	Y
(Almhafdy et al., 2015)	CFD	Ratio of courtyard, cantilevered roof	Ai velocity, air temperature	3D/ Courtyard	RANS (standard k- ε)	-	N
(Farea et al., 2015)	CFD	Vertical and horizontal opening of the light well, wind direction	Upward flow velocity, temperature, airflow pattern	3D/ Light well (courtyard)	RANS (RNG k– ε)	ABL	Y
(Saadatjoo et al., 2016)	CFD	Proportions of courtyard	Air velocity	3D/ Courtyard	RANS (standard k- ε)	ABL	N
(Omrani et al., 2017)	CFD	Balcony type, balcony depth, ventilation type, and wind angle	Air velocity, Standard effective temperature	3D/ Balcony	RANS (standard k- ε)	ABL	Y
(Rodríguez-Algeciras et al., 2018)	RayMan model	Geometry of large courtyards, height to width ratio and orientation	Outdoor thermal conditions	3D/ Courtyard	-	-	N
(Saadatjoo et al., 2018)	CFD	Depth of terraces (TD)	Mean air velocity, mean age of air are	3D/ Terrace	RANS (standard k- ε)	ABL	Y
(Xu et al., 2018)	CFD	Performance of traditional courtyard, spatial layout of courtyard, aspect ratio	Wind speed, temperature	3D/ Courtyard	RANS (standard k- ε)	-	N
(Hao et al., 2019)	CFD	effects of courtyards on the thermal performance	Indoor and outdoor air temperature, airflow patterns	3D/ Courtyard, verandas and overhangs	RANS (standard k- ε)	ABL	Y
(Tuck et al., 2019)	Field measurements (experimental)	high-density polyethylene (HDPE) nets as roof covers for shading over the roof	Thermal comfort, surface temperature	3D/ Corner of terrace	-	-	N
(Saligheh & Saadatjoo, 2020)	CFD- Thermal simulations	Courtyard aspect ratio	Air velocity/ cooling load/ amount of shaded area	3D/ Courtyard	RANS (standard k- ε)	ABL	Y
(Mozaffari Ghadikolaei et al., 2020)	CFD	Balconies with wing walls	Air velocity/ indoor air distribution	3D/ Balcony	RANS (standard k- ε)	ABL	Y
(Abdelhady, 2021)	CFD	Placement of yards and building rotation	Average air velocity	3D/ Courtyard	–	-	N
(Gamero-Salinas et al., 2021a)	Experimental	Height to depth ratio and open space ratio, void to solid ratio, height to depth ratio, height from ground level, green plot ratio and open space ratio	Air temperature, mean radiant temperature, air velocity, relative humidity	3D/ Voids, terraces	-	-	N
(Gamero-Salinas et al., 2021b)	Experimental	height-to-depth ratio, open space ratio, and green plot ratio	Air temperature, mean radiant temperature, relative humidity, and air velocity	3D/ Voids, terraces	-	-	N
(Saadatjoo et al., 2021)	CFD	Permeability ratio (number of terrace)	Air velocity/ age of air/ cooling load	3D/ Terrace	RANS (standard k- ε)	ABL	Y
(López-Cabeza et al., 2023)	CFD - BES	Three wall configurations with different inertia and two situations: the closed courtyard and the ventilated courtyard	Air temperature , air velocity, relative humidity	3D/ Courtyard	RANS (RNG k-ε)	-	Y

3D = 3dimensional, ABL = atmospheric boundary layer, RANS = Reynolds-averaged Navier-Stokes, RSM = Reynolds Stress Model, k= Turbulent Kinetic Energy [m^2/s^2], ε= Turbulent Dissipation rate [m^2/s^3], ω= Specific Dissipation rate [$1/s$].

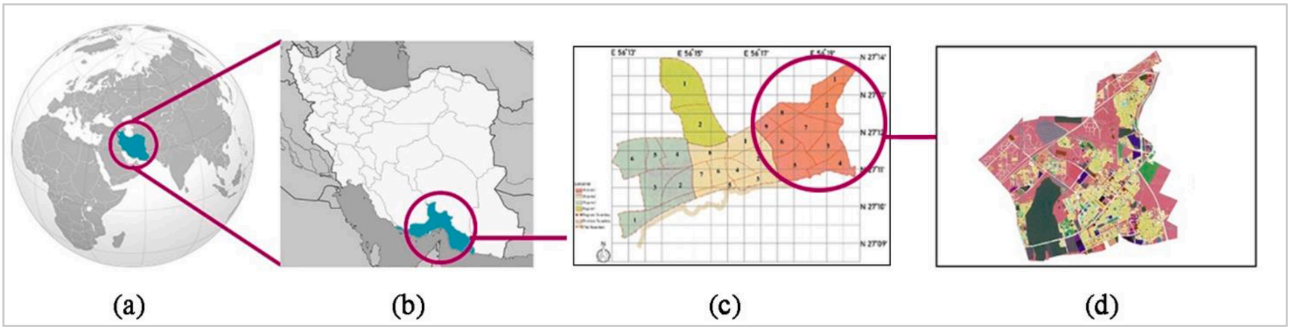


Fig. 2. a) Location of Iran on the world map, b) Location of Bandar Abbas in Iran, c) Urban regions and districts of Bandar Abbas (Sharmand, 2008), d) Land-use map of region 1(study site) (Sharmand, 2008).

primarily in Region 4, while medium-density buildings are found in Region 1. Regions 2 and 3 consist of both low and medium density buildings (Fig. 2).

This study focuses mainly on Region 1, which is generally occupied by medium-density residential buildings (Fig. 2). The study of several city plans and related documents led to the recognition of the neighborhood pattern prevalent in this region. As a result, a typical neighborhood pattern was extracted and used as the basis for our simulations.

3.2. Models morphology

Over the centuries, climatic considerations have been fundamental principles in the design of vernacular architecture in Iran. The investigation of vernacular houses in Bushehr indicated that the predominant building typology in these regions is semi-introverted buildings with free bilateral openings, large and deep terraces, and free floor plans (Fig. 3). The distribution pattern of living spaces around the central courtyard on 3 or 4 levels with several semi-outdoor spaces among them promotes the privacy, increases the shadow-casting capability, and natural ventilation performance inside the courtyard and living spaces by providing double-sided ventilation (Nikghadam, 2015).

The use of terraces (semi-outdoor spaces), a central courtyard, and bilateral windows to the courtyard and outdoor spaces are some of the measures that promote natural ventilation in the buildings (Fig. 3). These critical interstitial spaces provide a connection between indoor and outdoor spaces (Shojaei & Salari, 2021), and increase occupants' satisfaction to enjoy the fresh air, engage in physical activities, and grow plants (Akbari et al., 2021). The central courtyard provides the possibility of double-sided natural ventilation and lighting for surrounding residential units, while introducing a context for physical activity. On the other hand, the presence of trees and vegetation in this space reduces the annoying sounds and purifies the air before entering the residential units. Shading by trees moderates the received radiant energy by the façade, hence moderating the temperature in housing units. Finally, the central courtyard provides a suitable context for communication and expansion of social interactions among residents during the COVID and post-COVID eras. Private terraces offer a suitable space for physical activities, work (when working remotely), and recreation. Terraces are intermediate spaces between indoor and outdoor areas that direct wind flows into the courtyard. Vegetation on terraces absorbs disturbing noise, purifies the air that enters the building, and shades the building facade. They improve social interactions among neighbors while maintaining social distance. The introduction of porosity in courtyard buildings is a solution to promote natural ventilation performance that has been applied by MVRDV and other well-known architects (Fig. 3).

In this study, the target model is a combination of a modern apartment building with private double-oriented terraces, and a traditional courtyard building. These porous buildings are open and accessible to their surroundings, allowing for a seamless transition between indoor and outdoor spaces, more natural ventilation and access to daylight (Saadatjoo et al., 2019) (Fig. 4b).

The models in this study are courtyard buildings surrounded by four-

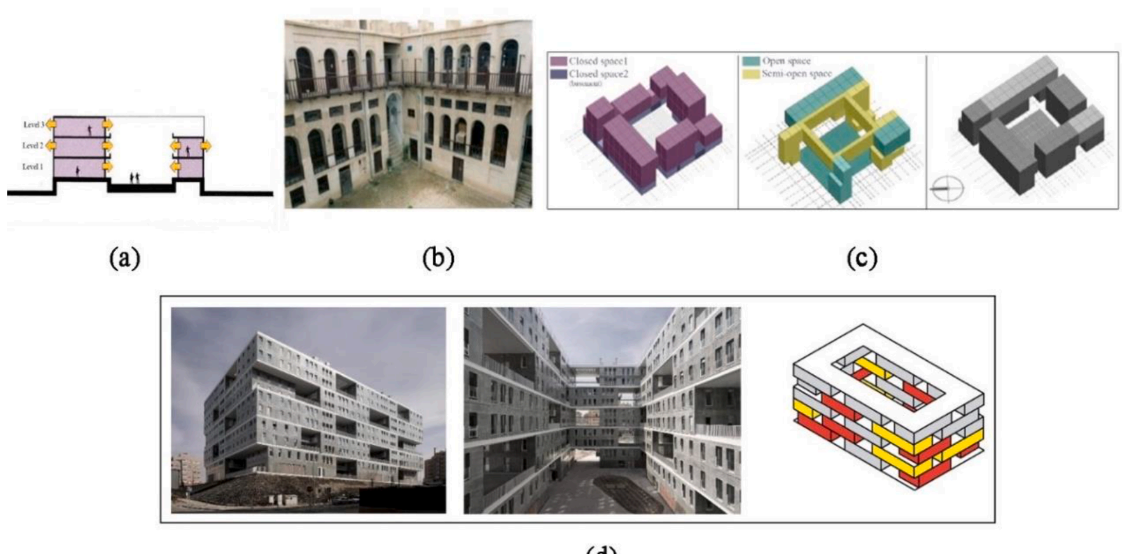


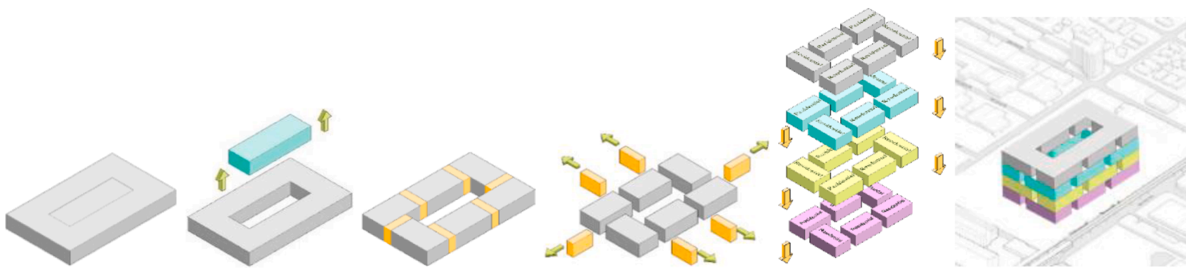
Fig. 3. a: Schematic patterns of Busher houses, b: Golshan house in Bushehr, c: Open coding of semi-outdoor, open, and closed residential spaces in Golshan House (Bushehr) (Nikghadam, 2015), d: CELOSIA project in Sanchinarro, Madrid, designed by MVRDV (MVRDV, 2009).

story blocks. Each level consists of numerous residential units with private terraces in between. These models encompass two types of semi-outdoor spaces: double-oriented terraces with bilateral walls and a ceiling, and a central courtyard with four peripheral walls. However, considering the research objective, the term "semi-outdoor space" in this study refers to double-oriented terraces. Each housing unit has a private terrace, which influences the physical and psychological aspects of healthy buildings in the COVID and post-COVID era.

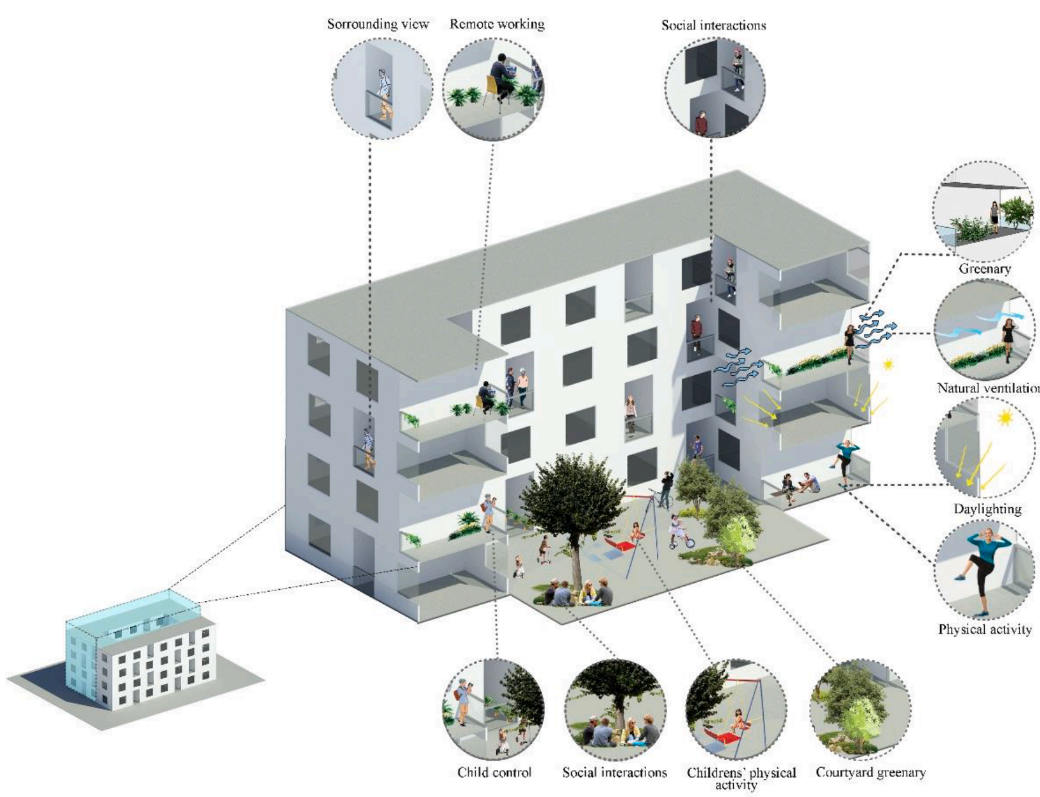
Thirteen different models were simulated to investigate the effects of size and location of lateral semi-outdoor spaces on natural ventilation. These building models can be divided into three groups, depending on the zone of porosity distribution. The models including terraces in four, two and one sides are called LT, DO and SI respectively. It is worth mentioning that all terraces in all models are open on two sides and covered with a ceiling. The reference building is a solid case without porosity. The dimensions of the building and the courtyard, the number of residential units, as well as openings are identical in all cases. The overall dimensions of the models are 30, 18 and 14 meters in X, Y and Z directions, respectively, and include a central courtyard of 6×18 meters and 24 residential units. In other words, 20% of the total area of the plot is allocated to the inner courtyard. The above models consist of 4 floors, and each floor includes 6 housing units with the same width and height (6×3 m) and variable length (Fig. 4a). The length of the housing units varies from 12 to 10.4 m, depending on the width and number of semi-outdoor spaces (Table 2). All models have 32 openings facing inward and 64 openings facing outward. The length of the openings was adjusted to keep the ratio between open and closed spaces constant (0.27). The detailed characteristics of the simulated models are shown in Table 2.

3.3. Governing equations

The success of a CFD simulation depends on the proper selection of the flow model. Most indoor and outdoor flow models are turbulent, and



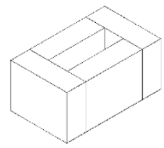
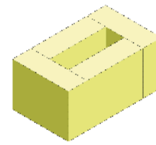
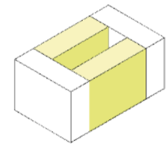
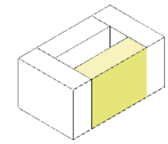
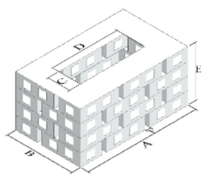
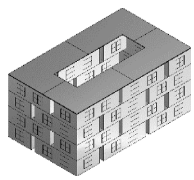
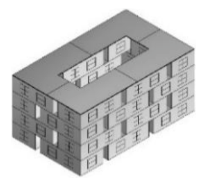
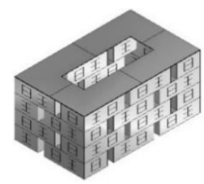
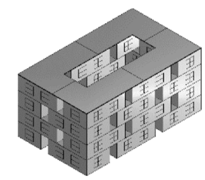
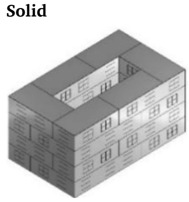
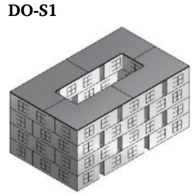
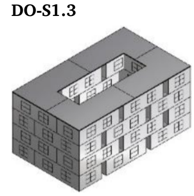
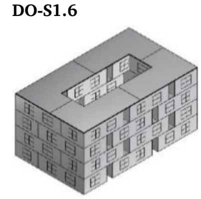
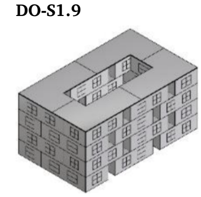
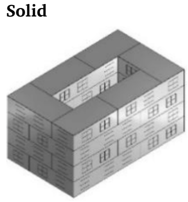
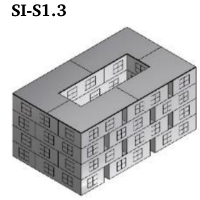
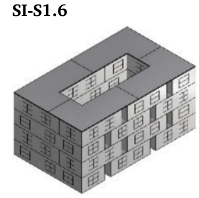
(a)



(b)

Fig. 4. a: Generation process of the models, b: physical and mental aspects of semi introverted buildings with bilateral openings.

Table 2
Configurations of research models.

	Porosity Distribution Zones				
	Porosity Width (m)				
	0	Solid	-	-	-
	1	-	LT1	DO-S1	SI-S1
	1.3	-	LT2	DO-S2	SI-S2
	1.6	-	LT3	DO-S3	SI-S3
	1.9	-	LT4	DO-S4	SI-S4
	Models				
	Solid	**LT1**	**LT1.3**	**LT1.6**	**LT1.9**
					
Number of semi-outdoor spaces	0	24	24	24	24
Enclosed space volume (m^3)	6048	5544	5392.8	5241.6	5090.4
Semi-outdoor space volume (m^3)	0	504	655.2	806.4	957.6
Opening area (m^2)	480	441.6	422.4	414.72	403.2
Width of semi-outdoor space- F (m)	0	1	1.3	1.6	1.9
	Solid	**DO-S1**	**DO-S1.3**	**DO-S1.6**	**DO-S1.9**
					
Number of semi-outdoor spaces	16	16	16	16	16
Enclosed space volume (m^3)	6048	5611.2	5510.4	5409.6	6048
Semi-outdoor space volume (m^3)	0	436.8	537.6	638.4	0
Opening area (m^2)	480	441.6	436.48	428.8	480
Width of semi-outdoor space- F (m)	0	1	1.3	1.6	1.9
	Solid	**SI-S1**	**SI-S1.3**	**SI-S1.6**	**SI-S1.9**
					
Number of semi-outdoor spaces	16	8	8	8	8
Enclosed space volume (m^3)	6048	5880	5829.6	5779.2	5728.8
Semi-outdoor space volume (m^3)	0	168	218.4	268.8	319.2
Opening area (m^2)	480	467.2	460.8	458.24	454.4
Width of semi-outdoor space- F (m)	0	1	1.3	1.6	1.9

among turbulent models, the Reynolds-averaged Navier-Stokes equations (RANS) and large-eddy simulation (LES) are commonly used. These models are widely used by researchers to solve various building ventilation problems (Bangalee et al., 2012; Allocca et al., 2003). LES is a promising approach. However, it is very time-consuming and, therefore, can only be used when extreme precision is required. There are several turbulence models that can be used with RANS, although studies have found the RNG k-ε model to be the most suitable option for indoor airflow simulations (Bangalee et al., 2012). In this study, the RANS model is used with the RNG k-ε turbulence model to evaluate wind performance with lower computational costs by introducing the following equations:

$$I = 0.16(\mathrm{Re})^{\frac{-1}{8}} Re = 0.5 \times L \times V \times 10^4 \quad (1)$$

$$k(y) = 3/2\left(u_{avg}(y)I(y)\right)^2 \quad (2)$$

$$\varepsilon(y) = Cu^{\frac{3}{4}\times\frac{k^{\frac{3}{2}}}{l}} \quad (3)$$

Where I is Turbulence Intensity, Re is Reynolds number, V is velocity of flow (ms^{-1}), k is turbulent kinetic energy (m^2s^{-2}), u_{avg} is mean velocity (ms^{-1}), I is turbulent intensity at distance y from the wall, ε is the turbulence dissipation rate (m^2s^{-3}), C_u is an empirical constant equal to 0.09, l is Turbulent length scale. l= 0.07 L, where L is the length of the windward face (m).

In this research, the flow is steady, turbulent, and incompressible. The RANS equations for a Newtonian fluid are written in the following form:

$$Continuity = \frac{\partial}{\partial x_j}\left(U_j\right) = 0, \qquad j = 1, 2, 3 \quad (4)$$

$$Momentum = \rho U_j \frac{\partial}{\partial x_j}(U_j) = -\frac{\partial_p}{\partial x_j} + \frac{\partial}{\partial x_j}\left[(\mu + \mu_r)\frac{\partial U_i}{\partial x_j}\right], \quad i = 1,2,3 \ and \ j = 1,2,3 \quad (5)$$

Where U is the x component of velocity (m s^{-1}), x, y, and z are the corresponding directions to the velocity components, μ is the fluid viscosity (Kg $m^{-1}s^{-1}$), μ_r is molecular viscosity of the fluid (Kg $m^{-1}s^{-1}$), ρ is the density of the fluid (kg m^{-3}), and p is the pressure (kg $m^{-1}s^{-2}$).

4. CFD validation study

4.1. Description of the wind-tunnel measurements

Jiang et al. conducted a wind tunnel experiment (WTE) with a small cube in a highly turbulent airflow at Cardiff University (Jiang et al., 2003). The working section of the wind tunnel was 2.0 m long, and had a cross-section of 2.0 m× 1.0 m, which was covered with a combination of blocking and surface roughness to simulate urban atmospheric boundary conditions. The maximum airspeed in the tunnel is approximately 12 m/s.

The experimental model is a simple, small-scaled, transparent Perspex cube with dimensions of 250mm×250mm×250mm. The model consists of two rectangular openings (84mm×125mm- length- height) on the windward and leeward walls that provide cross ventilation for the building (Fig. 5a).

The instrument used to measure velocity around and within the model was a one-dimensional LDA with a resolution of ±0.5 m/s, which provided the possibility of velocity measurements in highly turbulent and recirculating flows. The fog mist was injected into the inlet as seeding of the LDA system. A computer-controlled traversing arm with a vertical and horizontal resolution of ±0.5 mm and ±1.0 mm adjusts the position of the measurement probe. All experimental tests were conducted at a wind direction of θ=180°.

Velocity measurements were conducted through a central section of the model along 10 vertical lines, each line consisting of 18 points (Fig. 5b).

3.2. Computational domain and boundary conditions

The computational model consists of a simple double-ventilated cube with similar dimensions as the experimental model. The computational domain was set according to best practice guidelines (Franke & Baklanov, 2007; Tominaga et al., 2008). The downstream, lateral, and top boundaries were set 5H, and the outflow boundary was set 10H away from the target model, while H is the height of the building. The resulting computational domain size is 2.75 m in the Y-direction, 4 m in the X-direction and 1.5 m in Z-direction (Fig. 5c). The blockage ratio was about 1.5% that is smaller than the maximum recommended value of 3% suggested by Baetke et al. (Baetke et al., 1990).

In the computational domain and numerical studies, a wind profile was generated that corresponds to the profile in the WTE. The maximum air speed in the wind tunnel was 12 m/s (U_∞=20m/s).

The boundary conditions are given in Table 1. Based on the profile of turbulence intensity (Iu) generated in the WTE, k and ε profiles were generated vertically in the inlet of the computational domain using Eqs. (1-3). The walls and roof of the computational domain are symmetric, while the standard wall function is used for the floor, and zero static overpressure is used for the outlet of the domain.

The convergence down to 10^{-5} is acceptable for the scaled residuals (Asfour, 2010), but this value must be considered much lower to reach the converged solution in validation studies. In this research, the results with different convergence criteria were monitored, starting with larger residuals convergence criteria 10^{-5} up to 10^{-7}. There was no significant difference in results in the case of using 10^{-6} and 10^{-7} convergence critertion compared to 10^{-5}, indicating that the solution converged. So, the residual of convergence criteria 10^{-5} was used to save the simulation time.

3.3. CFD validation: Grid discretization

To reduce the discretization error, it is essential to perform a grid sensitivity analysis and compare the results with experimental tests. The simulation domain was divided into structured hexahedra elements. A growth rate of 1.3% in all directions was used according to the standard COST. According to Franke et al. (Franke & Baklanov, 2007) , the expansion ratio between two consecutive cells should be less than 1.3 in regions with high gradients. However, some other sources recommend a maximum ratio of 1.2 for the expansion ratio (Bartzis et al., 2004). A growth rate of 1.3% in all directions was applied. The maximum grid sizes vary from 0.025 to 0.04, while the minimum size of cells is defined as10^{-3}. Tests on the sensitivity of the grid were performed for 3 different mesh sizes. In this study, three cases with fine, medium, and coarse mesh size were generated, and the obtained results were compared with those of the experimental tests. The fine, medium and coarse mesh size cases consist of 1352400 meshes (case A), 853200 (case B) and 582120 (case C), respectively. The first evaluation points are located above the third

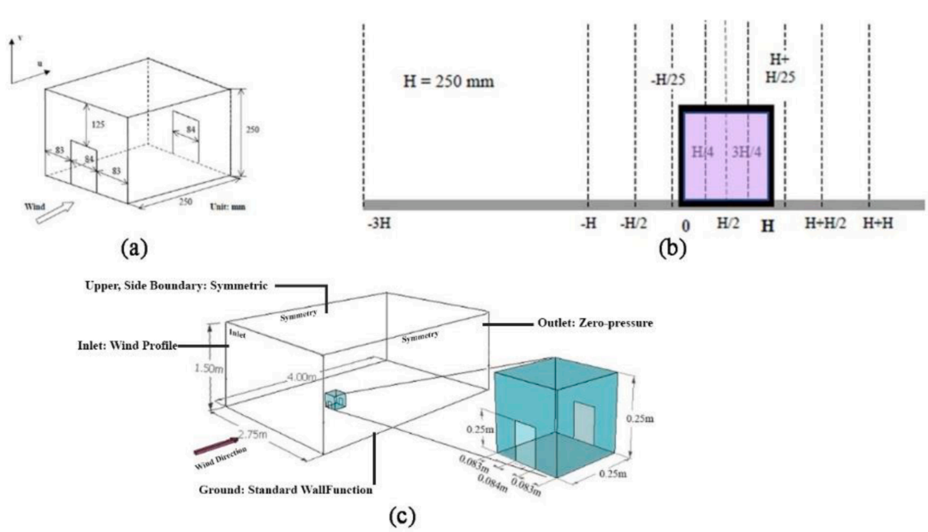


Fig. 5. a: Perspective of the experimental model, b: Position of vertical lines where air velocities were recorded (Jiang et al., 2003). c: Perspective view of computational domain in the numerical study, building model location, and dimension

grid from the ground surface.

The measured fluctuating velocities through 10 vertical lines in the mid-plane in experimental and CFD models determined the best grid size. The tests showed that case A with fine mesh size and average velocity variation of 10.29% with WTE had the best agreement with experimental results. While the medium and coarse mesh size cases are the next priorities with 10.94% and 11.46% velocity deviation, respectively. Considering the negligible discrepancy between the results of case A and case B and the considerable reduction in simulation time in the second case, the medium mesh model would be the best option (Fig. 6).

The grid resolution is defined based on the AIJ standard, which suggests a minimum grid resolution of 1/10 of the building scale (Franke et al., 2007; Tominaga et al., 2008). However, COST standard recommends that at least 10 cells should be generated per building side as well as per cube root (Franke & Baklanov, 2007).

To evaluate the accuracy of measured values in CFD simulations and compare them to experimental results, RMSE (Root Mean Square Error) was calculated by the following equation (Chai & Draxler, 2014):

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\widehat{y}_i - y_i)^2}{n}} \tag{6}$$

Where n is the number of data points being analyzed, $\widehat{y}_i$ is the measured value from the simulation, and y_i is the actual value from the experimental test. Wind velocity was measured at 25 points along 6 vertical lines (125 points in total) in each model with different mesh sizes. The RMSE values for models A, B, and C (fine, medium, and coarse) were calculated to be 0.14, 0.154, and 0.148, respectively. Based on these values of RMSE (all smaller than 0.75), it can be concluded that the accuracy of the measured values in the CFD simulations is very good.

4. CFD simulations

4.1. Computational geometry and boundary conditions

In this study, the dimensions of the computational domain were defined on the basis of AIJ guidelines (Tominaga et al., 2008). The height of the target building is 14 meters. The upstream and downstream lengths were defined 5H=70m and 15H=210m, respectively. The distance between the lateral, upper boundary, and the target buildings were considered 5H, equal to 70 meters. The resulting dimensions of the calculation area are W × L × H= 170 × 298 × 84 m^3.

At the inlet of calculation domain, atmospheric boundary layer inflow profile was defined. The mean wind speed during the 6 warm months of the year was calculated using weather data from meteorological sites. Mean air velocity and prevailing wind direction were calculated using weather data for the last 20 years, from 1995 to 2015. The inflow velocity was assumed to be 3.38 m/s at a height of 10 meters and a prevailing wind direction of 180°. At the Bandarabbas station, the prevailing wind was found to be mainly from southerly directions, which occurred 29% to 41% of the time. Due to the high frequency and strength of the south wind, it was selected as the basis for the simulations.

The retrofitted values for the height of the domain were calculated and defined by the following equations:

$$\frac{\overline{V}_z}{\overline{V}_{z10}} = \left(\frac{Z}{Z_{10}}\right)^{\alpha} \tag{7}$$

Where $\overline{V}_z$ is air speed at the height of Z, $\overline{V}_{z10}$ is the mean air speed at the height of 10 meters. The coefficient α, which is based on surface smoothness, is considered to be 0.36. The simulations are conducted using Airpak 3. The RNG k-ε turbulence model is used for the

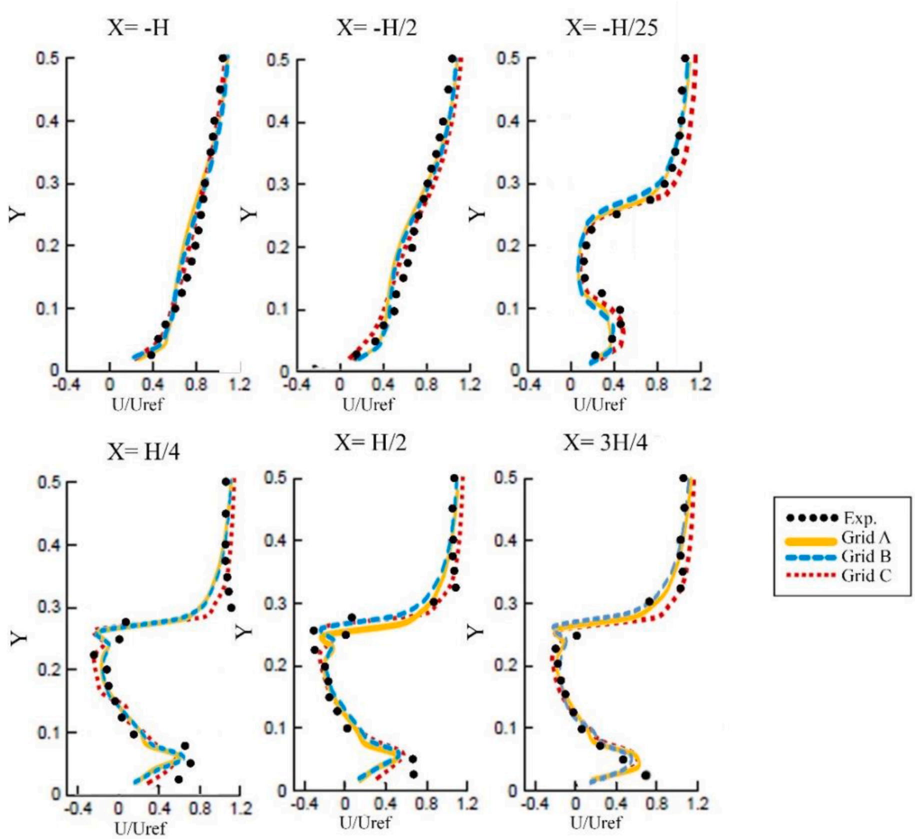


Fig. 6. Mean velocity distribution for cross ventilation through 10 vertical lines on a central plane in the models in Experimental, model with fine mesh (A), medium mesh (B), and coarse mesh (C).

simulations, and the k and ε profiles were generated vertically in the inlet of the computational domain using Eqs. (1-3).

The outlet was defined as zero-pressure, while the upper and side boundaries were defined as symmetric. The ground surface was modeled using the standard wall function.

4.2. Grid sensitivity analysis

In this research, to reduce the grid discretization errors and minimize the computational analysis time, a grid sensitivity analysis was conducted. This analysis was performed for the reference solid courtyard building with three different mesh sizes. The total number of cells for the fine, reference, and coarse grid sizes were 3,026,948, 1,785,530, and 997,364, respectively (Fig. 7).

Air velocity along a horizontal line through the middle unit of the fourth floor was measured and compared in cases with three different grid sizes. An average deviation of 9.11% was found between the results of models with coarse and fine meshes, while the average deviation between the basic and fine grids was 4.06% (Fig. 8). Based on these results, the simple grid was selected for further simulations.

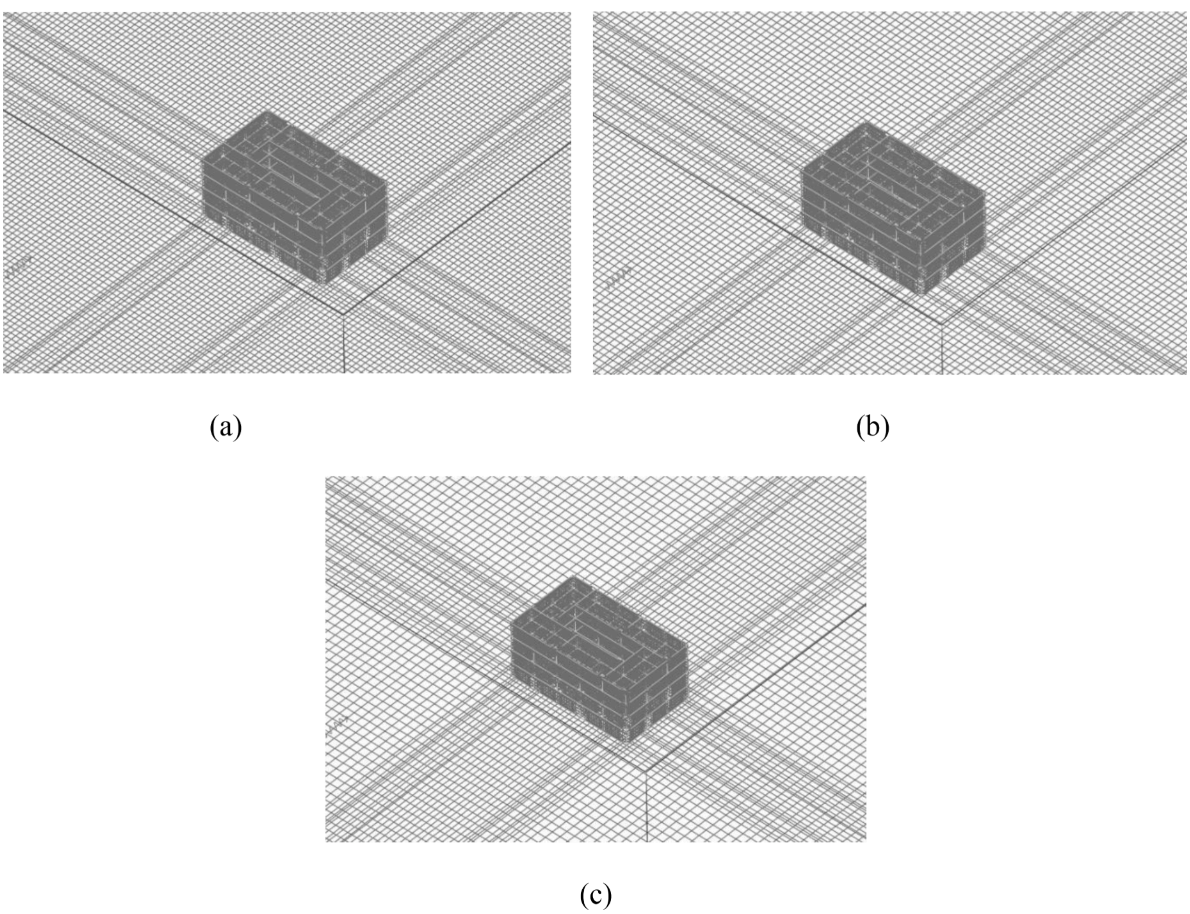
The analysis domain consists of hexahedra 2,542,866 cells with a growth ratio of 1.2. The grid resolution was defined based on grid sensitivity analysis explained in Section 3.3. The minimum and maximum cell size in the analysis domain were defined 0.012 m^3 and 3.37 m^3 respectively.

5. Results

This research aims to investigate the effect of the number and width of semi-outdoor spaces on the natural ventilation efficiency of buildings. The performance of the models is evaluated based on several measured numerical indicators, including mean/maximum velocity and age of air in units, terraces, and courtyards, as well as graphical contours at three levels for all housing units, terraces, and central courtyards. The age of air is the average time that a particle takes to travel from an inlet point to measurement point. Mean age of air is widely used in ventilation and indoor air quality (IAQ) assessment (Buratti & Palladino, 2020). It is used to evaluate air-change effectiveness and air distribution in buildings (Van Buggenhout et al., 2006). COVID-19 transmission occurs through droplets spread by coughing or sneezing from an infected individual (Rothan & Byrareddy, 2020). The age of air in a room affects the concentration of these droplets, and their ability to remain suspended in the air. Higher values for age of air lead to lower IAQ and higher concentration of respiratory droplets and potentially increase the risk of COVID-19 transmission (Health Ontario, 2022). At each step, comparative and correlation analyses were conducted to determine the relationship between the numerical indicators of natural ventilation and the spatial characteristics of the building.

5.1. Data analysis

To evaluate the normality distribution of the data, the Kolmogorov-Smirnov statistical test was applied. This test is based on the maximum difference between the empirical and hypothetical cumulative distribution functions (Massey, 1951). The p-value provided by SPSS 26 is evidence to reject the null hypothesis ($p>0.05$) that the variables follow a normal distribution. Additionally, the difference in whisker length and the mismatch between the median and box center confirm the nonparametric distribution of the data. However, for two groups of mean and maximum velocity, the achieved p-values (0.77 and 0.2)



(a) (b) (c)

Fig. 7. Different grid sizes for grid-sensitivity analysis. (a) Fine grid with 3,026,948 cells, (b) basic grid with 1,785,530 cells, and (c) coarse grid with 997,364 cells.

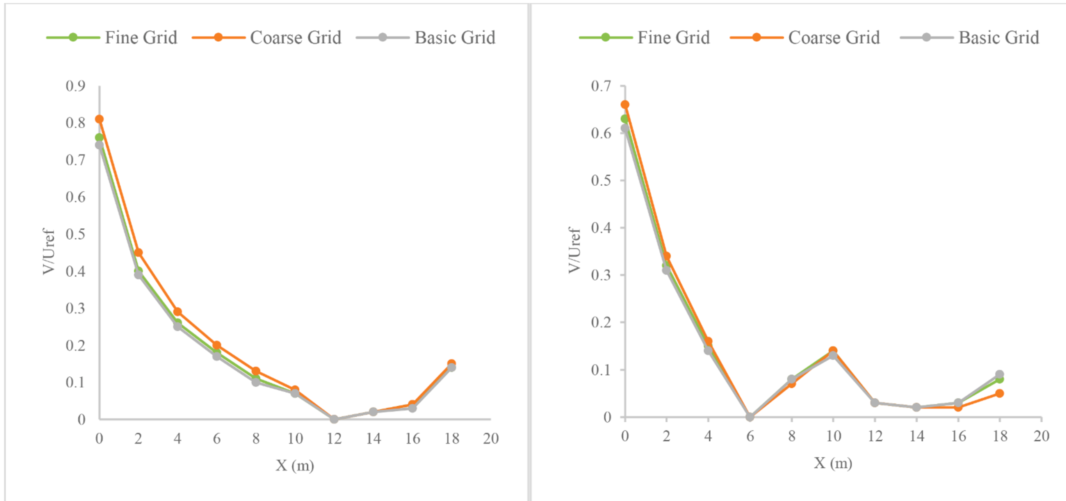


Fig. 8. Results of grid sensitivity analysis. Recorded air velocity through: (a) vertical line A, and (b) vertical line B.

confirm the null hypothesis that the variables follow a normal distribution. In the boxplots for these groups, the whiskers are approximately equal in length, and the median is almost in the middle of the boxes (Fig. 9).

Spearman correlation analysis was performed in R 4.2.1, a language and environment for statistical computing and graphics, to determine the strength of the relationship between indicators of natural ventilation and spatial building characteristics. It is a nonparametric statistical measure for determining the strength of a monotonic relationship between paired data. This method is most appropriate for the nonparametric data sets in this study, based on the results of the Kolmogorov-Smirnov statistical test (Ali Abd Al-Hameed, 2022).

The correlation matrix visualizes Spearman's coefficients (r_s), and illustrates the monotonic relationship between paired data (Fig. 10). The closer r_s values to ± 1 indicate a stronger monotonic relationship between paired data. In these analyses, the main data groups are ventilation indicators and special attributes. Although the intragroup correlation coefficients between variables in each category are calculated and presented in the matrix, the focus of this study is on the intergroup correlation coefficients. Achieved coefficients are interpreted as measures of the relationship strength between variables. Table 3 represents the results of the statistical significance test (P-Value) defined as the probability of obtaining results, given that the null hypothesis is true. If it is less than 0.05, it indicates the significance of the relationship between the two variables.

5.2. Number of semi-outdoor spaces

In this phase of the research, the effect of the number of porous sides on natural ventilation indicators, such as the average and maximum air velocity and the age of air inside the units and semi-outdoor spaces was evaluated. To better assess the relationship between the variables, the

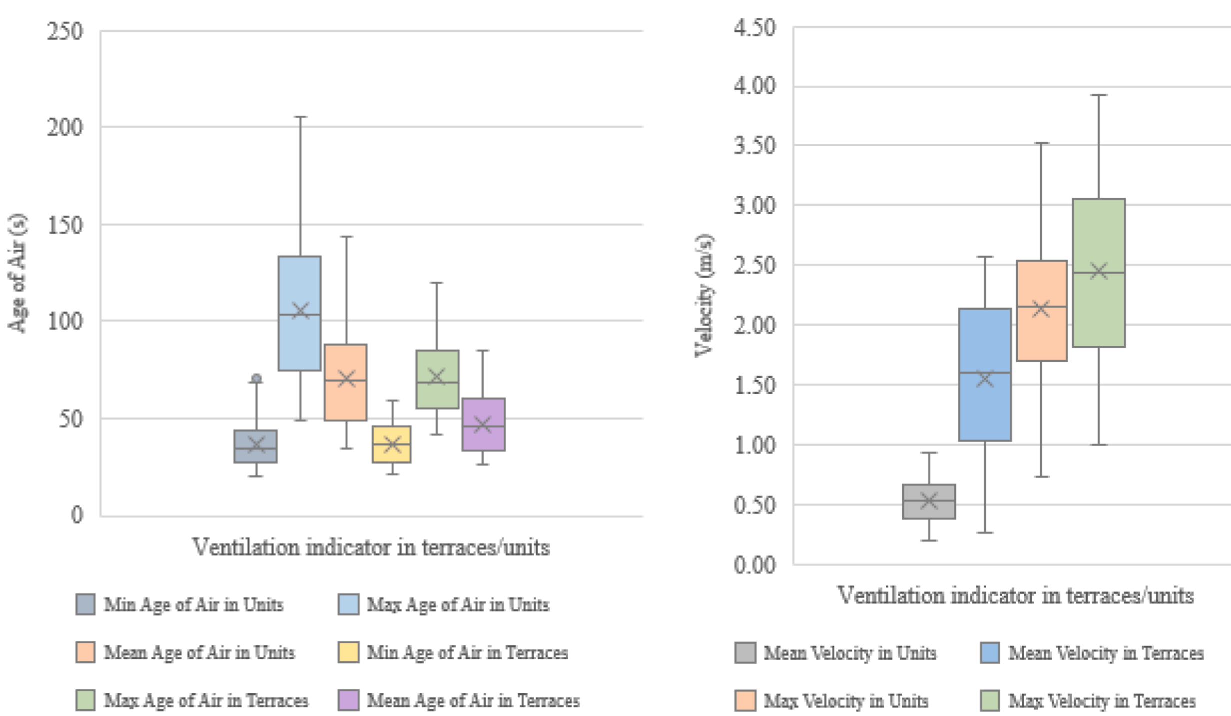


Fig. 9. Boxplots for ten data groups.

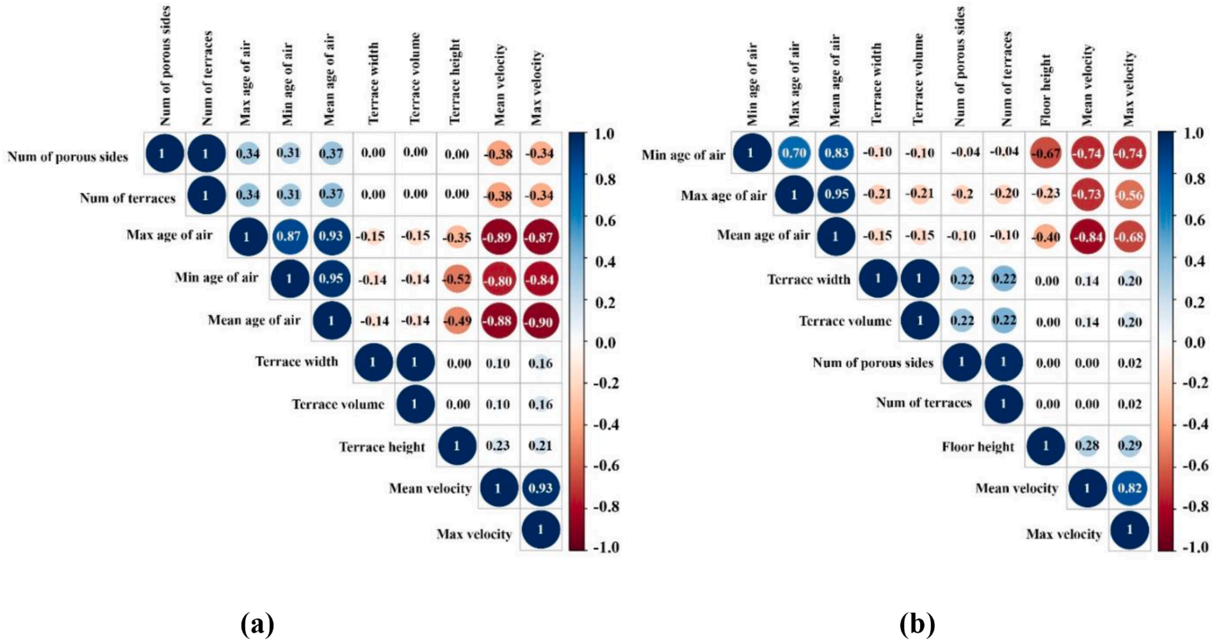


Fig. 10. Corrplots with Pearson's correlation coefficient for: a) residential units, b) terraces.

Table. 3
The significance Spearman correlation coefficient between datasets in units and terraces (P-Value).

Mean age of air	Max age of air	Min age of air	Max velocity	Mean velocity	
Units					
0.63	**0.00**	0.46	0.60	0.90	Num of porous sides
0.63	**0.00**	0.46	0.60	0.90	Num of terraces
0.07	**0.00**	0.65	**0.00**	0.13	Terrace width
0.00	**0.00**	**0.00**	**0.00**	**0.00**	Floor height
0.00	**0.00**	0.16	**0.04**	0.19	Terrace volume
Terraces					
Mean age of air	Max age of air	Min age of air	Max velocity	Mean velocity	
0.00	**0.00**	**0.00**	**0.00**	**0.00**	Num of porous sides
0.00	**0.00**	**0.00**	**0.00**	**0.00**	Num of terraces
0.04	**0.02**	**0.04**	**0.02**	0.13	Terrace width
0.00	**0.00**	**0.00**	**0.00**	**0.00**	Floor height
0.04	**0.02**	**0.04**	**0.02**	0.13	Terrace volume

results were compared in two stages. First, the measured values for mentioned variables are compared in models with the identical terrace **width and different number of porous sides**. Then, comparing the averaged values for each variable within the units, the semi-outdoor spaces, and the central courtyard determined the effect of the number of porous sides on natural ventilation.

In the first phase of this study, the effects of porous sidewalls on internal ventilation are investigated. The obtained results are presented in the normalized wind profiles of the models (Fig. 11), in numerical diagrams (Figs. 12-13), and in graphical contours (Fig. 15) to compare the performance of the models. The results show that for the models with identical terrace widths, the double-sided terrace buildings have better performance than the other groups. However, for a terrace width of 1 m, the models with single-sided terraces perform better than other porous buildings (Fig. 11).

The averaged values for mean and maximum air velocity inside the units showed that the implementation of porosity in solid buildings does not play an effective role in increasing the flow velocity inside the units. The results show that solid and double-sided models have similar performance in terms of average air velocity inside the housing units. However, the porous lateral and single-sided models show weaker performance than the base model, with average velocity reductions of 3.7 and 4.63 percent, respectively. Creating ambient porosity in buildings with courtyards can improve the level of maximum flow velocity within units. In this regard, double-sided terraces indicated the best performance by increasing the maximum flow velocity up to 8.45% (Fig. *11*).

On the other hand, achieved values for correlation and significant coefficients (r_s = 0, 0.02, p=0.9, 0.6>0.05) confirm the negligible relationship between the number of porous sides and mean/maximum velocity in units (Fig. *10*a, Table. 3).

In this phase of research, the effect of porous sidewalls on airspeed in terraces and courtyards is evaluated. The findings reveal that for the models with identical terrace width and different number of porous sidewalls, the single models have the best performance in terms of mean and maximum air speed in terraces. However, an opposite behavior was observed in the central courtyards. In the models with similar terrace width, an increment in the number of peripheral porous sides leads to an increase of the mean and maximum air velocity in the courtyards (Fig. *11*).

According to Fig. *11*, there is a monotonic decrease in mean and maximum velocity in terraces with an increase in porous sides. In this context, the inclusion of porosity in the sidewalls reduced the mean and maximum velocities in terraces by 36.76% and 25.41%, respectively, compared to the single-sided model. At the same time, the introduction of porosity in the solid model leads to an improvement in the ventilation performance in the courtyards. The increment in mean and maximum air velocities by 57.62% and 25.26%, respectively, compared to the base model, substantiates this claim (Fig. *11*).

Achieved values for Spearman's correlation coefficient (r_s = -0.38, -0.34) indicated a reverse monotonic relationship between numbers of porous sides and mean/ maximum velocity in terraces, respectively. The significant Spearman correlation coefficient value of 0.0 confirms a robust negative correlation between the two variables (Fig. *10*b, Table. 3).

Achieved numerical results indicate that there is an inverse relationship between the number of porous sides and the age of air in units.

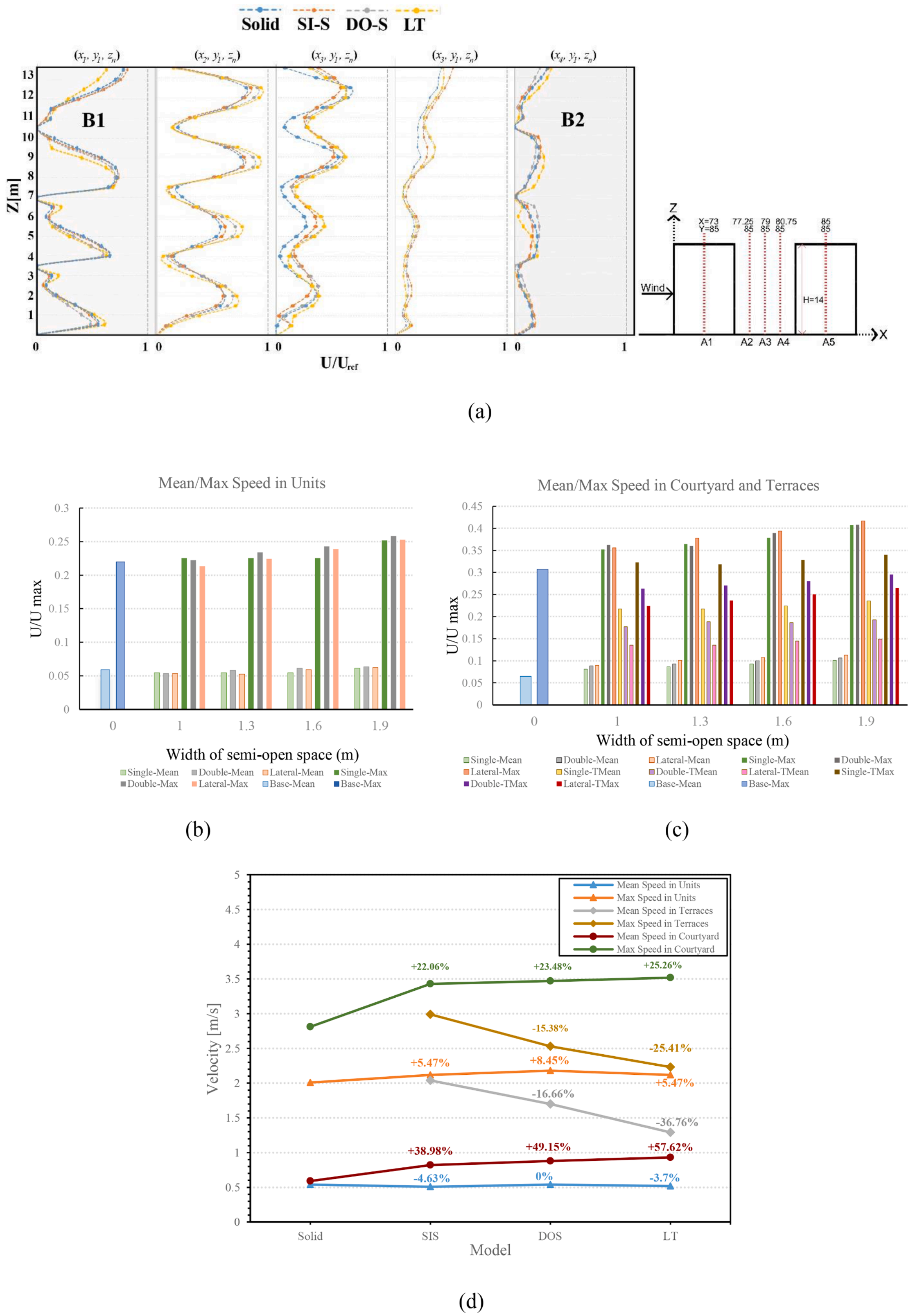


Fig. 11. a) Normalized mean wind profiles in four models with identical terrace width and a different number of porous sides ($U_{ref} = 2.43\ ms^{-1}$), b) Mean and maximum airspeed within the units, c) terraces, and courtyard in the models with identical terrace width, and a different number of porous sides, d) Averaged values of mean and maximum velocity within the units, terraces, and courtyard in the models with a different number of porous sides.

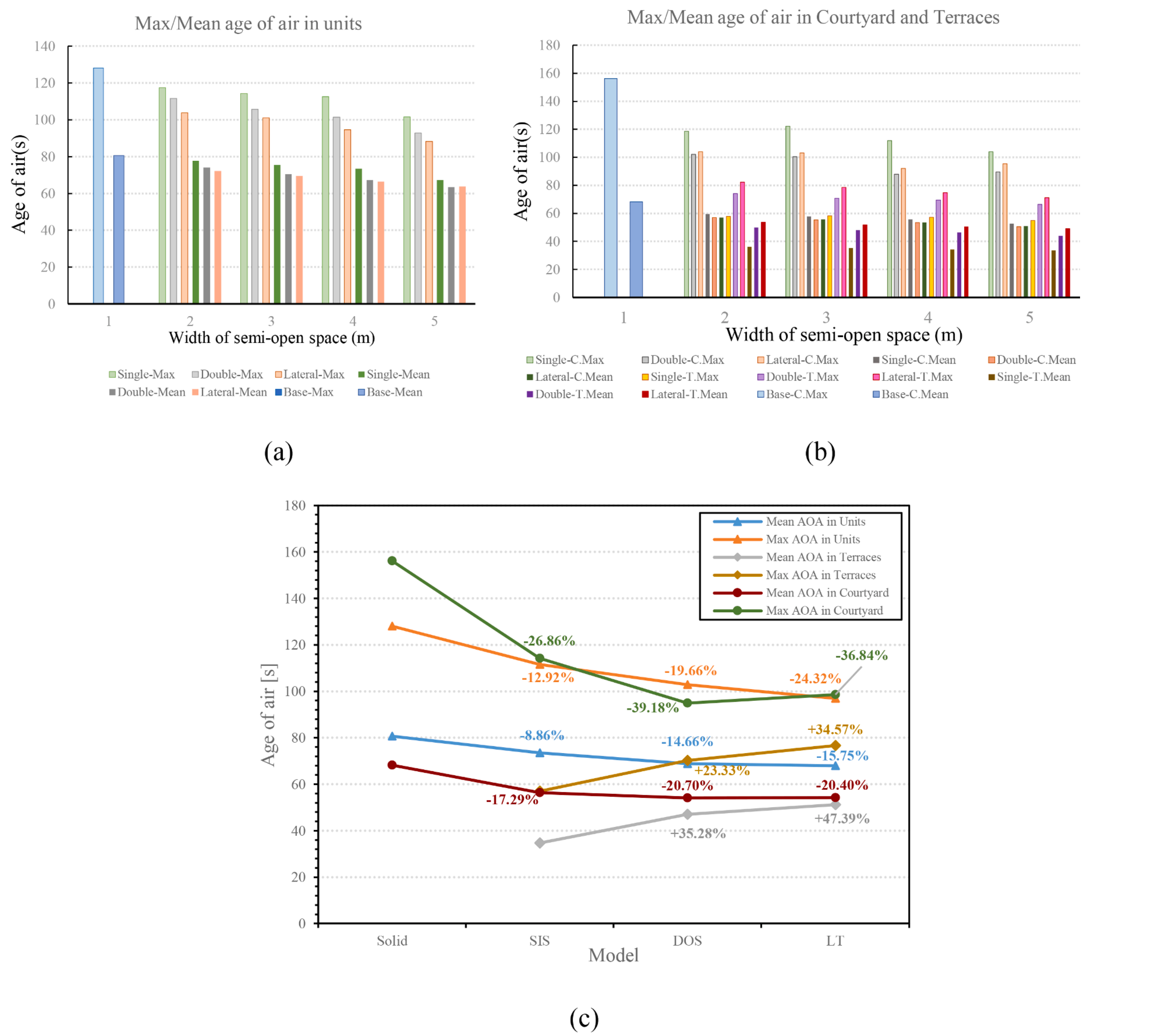


Fig. 12. a) Mean and maximum age of air within the units, b) terraces, and courtyard in the models with identical terrace width and different numbers of porous sides, c) Averaged values of the mean and maximum age of air within the units, terraces, and courtyard in the models with the different number of porous sides.

In other words, in the cases with similar terrace width, an increase of porous sides leads to lower values of age of air, which means high ventilation efficiency (Fig. 12).

A cursory glance at Fig. 12b reveals the negative relationship between the age of air and the number of porous sides. As shown in Fig. 12b, a significant difference in mean and maximum values between the lateral and base model was observed. The data provide preliminary evidence that this model enhances ventilation performance by decreasing the mean and maximum age of air up to 15.75% and 24.32%, respectively (Fig. 12b).

According to the analysis, the minimum, mean, and maximum age of air were correlated negatively with the number of porous sides. However, the results yielded no significant relationship between the minimum, mean, and maximum age of air and number of porous sides (Fig. 10a, Table. 3).

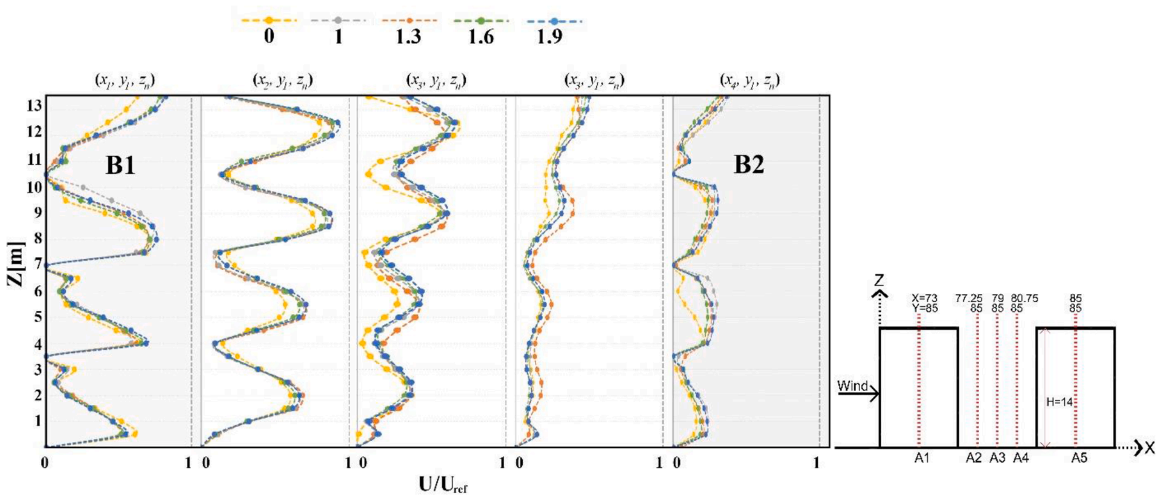
It can be inferred from Fig. 12b that in the models with identical terrace width, double-sided models indicate the best ventilation performance in courtyards. As shown in Fig. 12b, a significant difference in mean and maximum values was observed between the solid case and porous buildings. The results yielded some interesting findings. Despite the courtyards, by increasing the number of porous sides, the age of air values follows an ascending path in the terraces, which means the lower potential of natural ventilation (Fig. 12b).

The data provide convincing evidence of a strong association between the number of porous sides and the age of air values (Fig. 12c). Among the several cases, double-sided models indicated the best ventilation performance in courtyards, since the maximum and mean age of air in these models is decreased by 39.18%, and 20.70%, respectively. Lateral and single-sided models are placed in the next priorities. However, by introducing the lateral porous sides, achieved values for the mean and maximum age of air in terraces increases by 47.39%, and 34.57%, respectively.

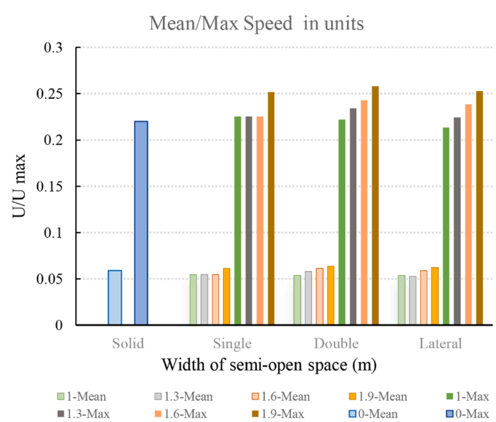
Our findings provide strong evidence that there is a positive correlation and statistically significant relationship between the age of air in terraces and numbers of porous sides (Fig. 10b, Table. 3).

5.3. *Width of semi-outdoor spaces*

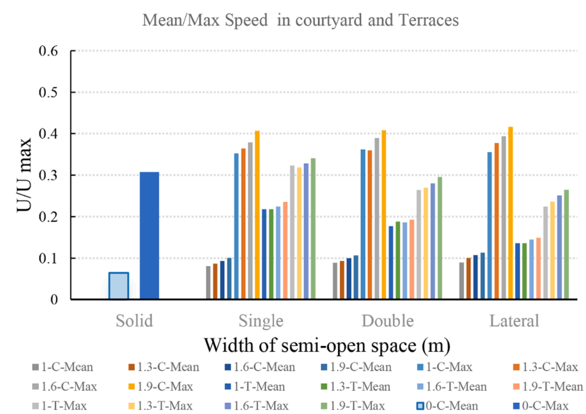
The second phase of this study is to determine the effects of terrace width on the efficiency of natural ventilation. The achieved results are illustrated in the normalized wind profiles (Fig. 13), in numerical diagrams (*Fig. 14*), and in graphical contours (*Fig. 15*) to compare the



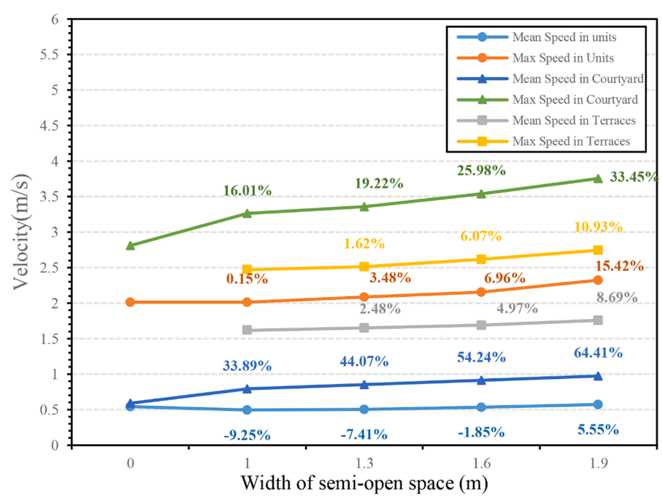
(a)



(b)



(c)



(d)

Fig. 13. a) Normalized mean wind profiles in four models with identical porous sides and different terrace widths ($U_{ref} = 2.43\ ms^{-1}$). b) Mean and maximum airspeed within the units, c) terraces, and courtyard in the models with identical porous sides, and different terrace width of, d) Averaged values of mean and maximum velocity within the units, terraces, and courtyard in the models with identical porous sides, and different terrace widths.

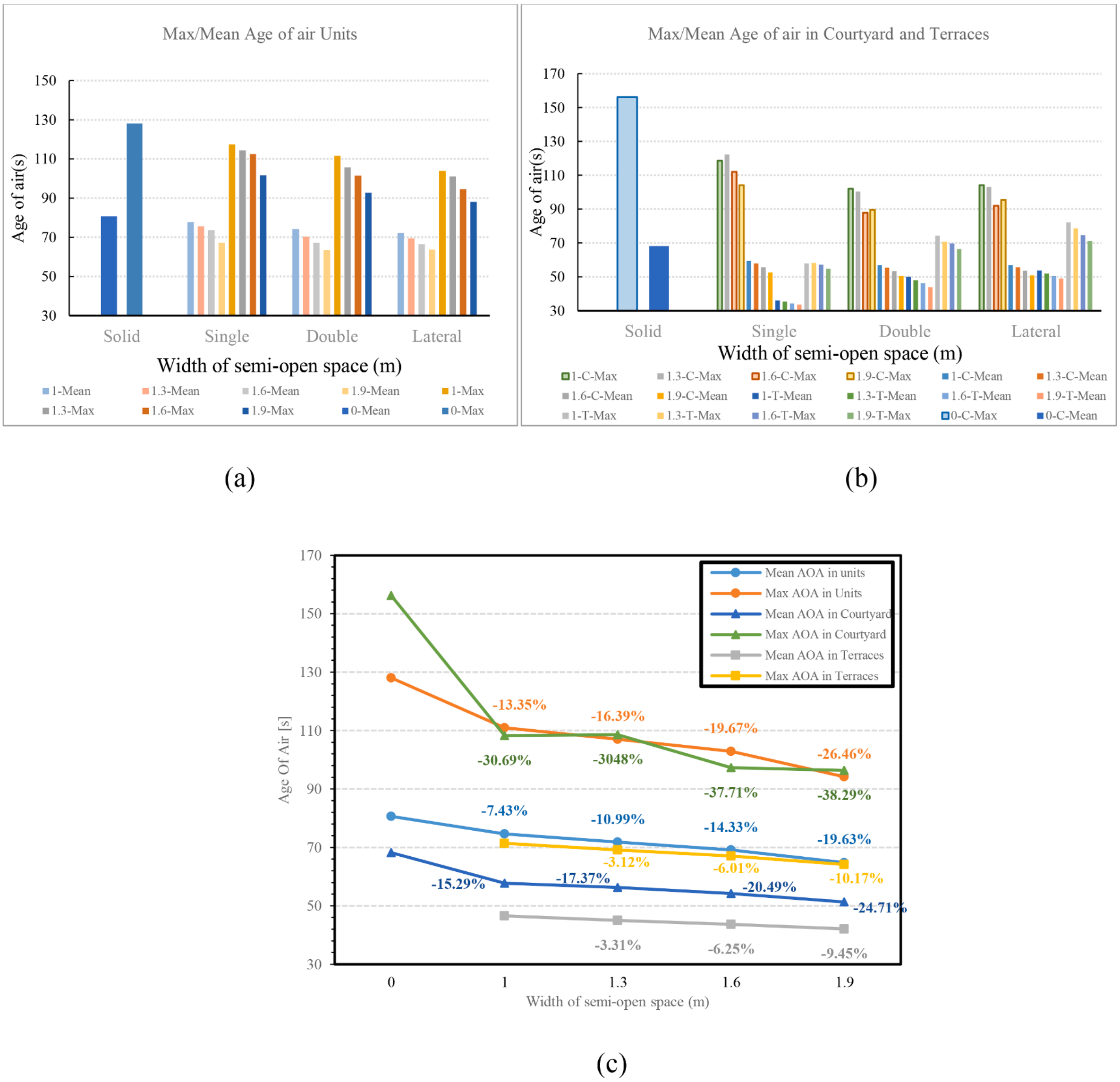


Fig. 14. a) Mean and maximum age of air within the units, b) terraces, and courtyard in the models with identical porous sides, and different terrace width, c) Averaged values of the mean and maximum age of air within the units, terraces, and courtyard in the models with identical porous sides, and different terrace width.

performance of the models. The analysis of the results consists of two steps: First, the ventilation indicators were compared in the models with identical porous sides and different terrace widths. Then, the mean numerical values of the models with different terrace width were determined.

The data provide convincing evidence for the claim that increasing the terrace width has a positive effect on natural ventilation. It can be inferred from Fig. 13b that in the models with double-sided and lateral group, increasing the terrace width leave a positive effect on the mean and maximum velocity in units. The results yielded no significant effect of terrace width on mean/maximum air velocity in single-sided models. Fig. 13d provides evidence of a positive relationship between the width of terraces and the maximum speed within the units. However, creating a terrace and increasing its width is not considered an effective solution to improve the mean flow velocity within the units. Since, it was found that the average internal flow velocity of the models with terrace width 1-1.3, and 1.6 is lower than that of the solid model. It can be claimed that only in the case of 1.9-meter terraces, a significant difference (5.55% and 15.42%) with the base model was observed.

Our findings indicated that the correlation between mean velocity in units and terrace width was positive and statistically insignificant (r_s = 0.14, Sig= 0.13). However, a positive and statistically significant correlation was obtained between internal maximum air velocity and terrace width (r_s = 0.2, Sig= 0.0) (Fig. *10*a, Table. 3).

The values obtained for the average and maximum velocity on the terraces and courtyards are in line with the results from the first stage. A general conclusion emerging from the Fig. 13c is that for the models with similar porous sides, increasing the terrace width improves the air velocity in courtyards. For mean/maximum velocity in terraces, no significant pattern was recognized. However, the models with 1.9-meter terrace width indicated the best performance in all groups.

Fig. 13d indicates a monotonic positive relationship between terrace width and mean/maximum velocity in courtyards. The increase of terrace width from 1 to 1.9 meters leads to mean and maximum velocity growth in courtyards by 33.89-64.40%, and 16.42-33.45% respectively.

According to the results, the correlation between terrace width and mean velocity in terraces was positive and insignificant (r_s = 0.1, Sig=0.13). However, a positive and statistically significant correlation was observed between terrace width and maximum velocity in terraces (r_s = 0.16, Sig=0.02) (Fig. *10*b, Table. 3).

This study used quantitative techniques to analyze the relationship between terrace width and the age of air. An inverse relationship

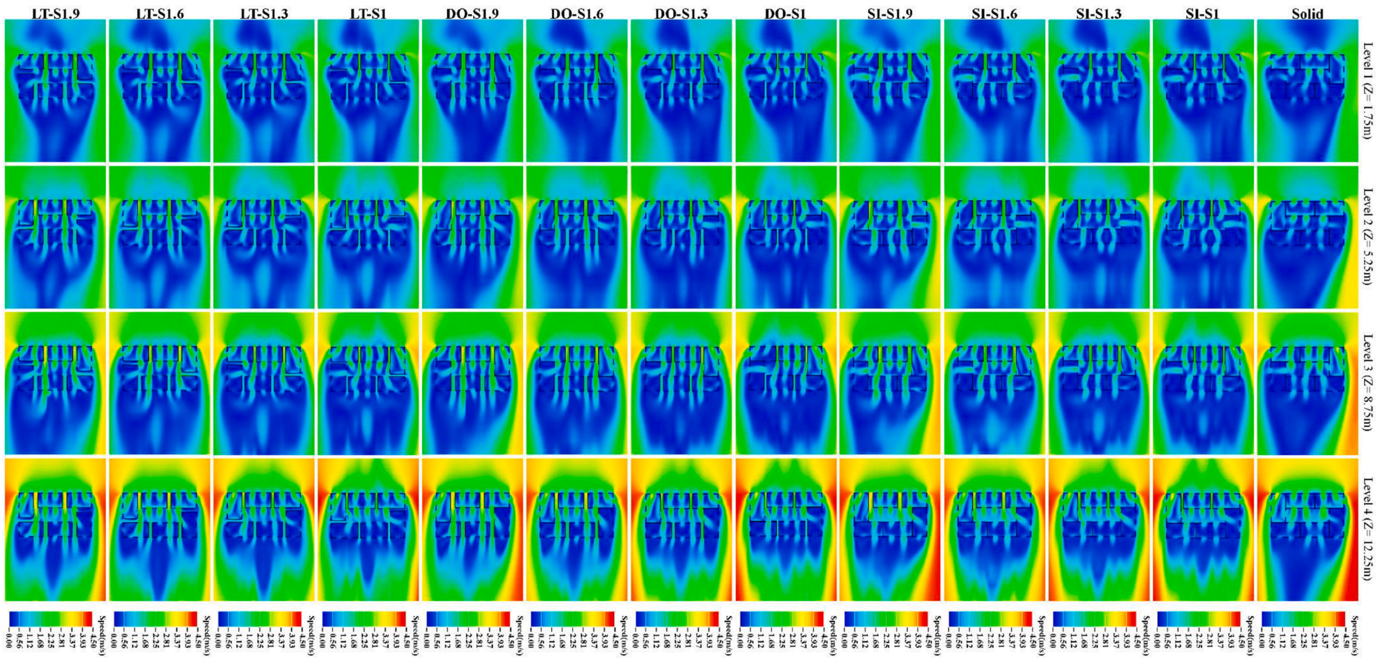


Fig. 15. Velocity contours of research models on three plane cuts.

between terrace width and age of air value in units was observed. These data provide evidence of a link between terrace width and the age of air in units (*Fig. 14*a).

According to *Fig. 14*c, the mean age of air char follows a descending process. By increasing the terrace width up to 1.9 meters, the mean and maximum age of air in units decreases by -20 and -26%, respectively. The data provide preliminary evidence that the models with wider terraces enhances ventilation performance in units.

According to the analysis, minimum, mean, and maximum age of air were correlated negatively with the width of terraces. However, the results yielded no significant relationship between the minimum/mean age of air and terrace width (Fig. 14a Table. 3). A significant correlation was obtained between the maximum age of air in units and terrace width (Sig= 0.0).

As presented in *Fig. 14*b, in the models with similar porous sides, the age of air values indicated a reverse relationship with terrace width. However, a significant pattern was not recognized for maximum age of air in courtyards.

The data provide convincing evidence of a strong association between the terrace width and age of air values in courtyards and terraces (*Fig. 14*c). By increasing the terrace width, the mean and maximum age of air in courtyard, indicated a decrease up to -20% and -38%, respectively. The decreased value of mean and maximum age of air by -9 and -10% in terraces means an enhanced ventilation potential in porous buildings with wider terraces.

Our findings provide strong evidence that there is a positive correlation and statistically significant relationship between the age of air in terraces and the number of porous sides (Fig. 10b, Table. 3).

6. Discussion

The emergence of COVID-19 proved the significant role of homes in pursuing numerous aspects of life and the current homes' inefficiency in addressing these targets. The combination of modern apartment buildings, private double-oriented terraces, and traditional courtyard buildings generates a new generation of buildings to match up with foundational standards for post-COVID era.

In this study, the buildings with different porosity rates were simulated, and compared to the solid case. Ventilation indicators such as air velocity and age of air were used to evaluate the efficiency of buildings in maintaining occupant health and mitigating post-COVID conditions. In this context, age of air values were measured as the best determinants of health status and IAQ in the research models.

According to the results, the implementation of permeability is a practical solution to enhance the performance of a courtyard building. Investigations proved the considerable role of porosity implementation on improving the ventilation performance. In this regard, increasing the number of terraces leaves a positive trace on courtyard and indoor ventilation. The significant coefficient between maximum age of air and terrace numbers prove the effectiveness of porosity on indoor ventilation and IAQ. Considerable reduction of age of air values means regularly exchanged air, less spread of respiratory droplets, and improved IAQ. However, numerical results and significant correlations proved the negative effect of porosity on terrace ventilation.

By increasing the terrace width, recorded values for indoor, terrace and courtyard air velocity indicated a rise. However, this relationship is not significant in most of the cases. Meanwhile, the decreased values of mean and maximum age of air in units, terraces and courtyards reveal enhanced ventilation potential in porous buildings with wider terraces. According to results, double-sided porous buildings are introduced as the most efficient and balanced model while providing acceptable air velocity in the units, terraces, and courtyards simultaneously. The results confirm the hypothesis that increasing the number of terraces leads to improved indoor and courtyard ventilation, and provide convincing evidence against the hypothesis that increasing the number of terraces is consistent with terrace ventilation. The data provide theoretical support for the hypothesis that there is an association between terrace width and indoor, terrace and courtyard ventilation.

The results of this study support the findings of previous studies on the significance of building configuration and presence of semi-outdoor spaces on ventilation performance. Our findings are consistent with prior studies that have reported the presence of building facade geometrical details such as balconies may introduce a high level of complexity in the airflow (Montazeri & Blocken, 2013; Kahsay et al., 2019; Zheng et al., 2020). Although our results challenge the conclusions of some investigations claiming that balconies are ineffective for natural ventilation (Mohammadi et al., 2010), and may even reduce the effectiveness of indoor airflow in single-sided naturally ventilated apartment buildings (Mohamedi et al., 2009), or double-sided ventilated buildings (Omrani et al., 2017), they are consistent with previous studies that have demonstrated the contribution of semi-outdoor spaces and balconies to indoor ventilation (Saadatjoo et al., 2021; Saadatjoo et al., 2021; Gamero-Salinas et al., 2022; Muhsin et al., 2017). While our results are consistent with these studies, we also observed some different patterns in terrace velocity, possibly due to building typology and terrace location. In recent research (Saadatjoo et al., 2021) , a positive relationship was observed between the number of terraces (porosity ratio) and the mean/maximum air velocity in terraces. In contrast, this research indicated a negative and significant relationship between the air velocity in the terraces and the number of terraces. These divergent findings are due to the diverse performance of porosity in different types of buildings (apartment buildings and courtyard building). This research also conformed the assertion of former investigations regarding the positive role of terrace link to surroundings on ventilation performance (Ok et al., 2008). In addition, this study proved the influence of number and dimension of semi-outdoor spaces on internal flow pattern and ventilation performance that is in accordance with the achievements of previous studies (Hirano et al., 2006; Saadatjoo et al., 2021; Saadatjoo et al., 2018; Izadyar et al., 2020). While the current study proved the positive effect of terrace width on interior and semi-outdoor velocity, Izadyar and his colleagues focused on balcony depth and demonstrated that the balconies with 35 and 30% depth ratio have the highest Indoor Air Velocity (Izadyar et al., 2020).

It is important to mention the main limitations of this study.

(1) Only one flow direction was considered in this study, normal to the main facade. Further studies need to be conducted with other prevailing wind speeds and directions.
(2) In this study, residential blocks were considered in small dimensions due to the time-consuming simulation process. The obtained values for airflow rate and similar indicators are not realistic in this situation. To measure the airflow and air exchange rate, further studies must be conducted with real block dimensions.

It should be noted that the focus of this work was explicitly on the ventilation performance of semi-outdoor spaces in courtyard buildings. This concept can be applied to the upcoming design process as an efficient design solution. Future studies may include energy performance analysis of these buildings, which are quite important in the context of a changing climate. Meanwhile, the impact of semi-outdoor spaces on other aspects of performance such as building acoustics and daylighting could be the subject of future studies.

7. Conclusion

This study presents a systematic evaluation of the influence semi-outdoor space on the natural ventilation performance in courtyard buildings. The CFD simulations, validated with wind-tunnel measurements, are employed.

According to the investigations, introducing porosity in courtyard buildings increases the maximum internal air velocity. However, this relationship is not significant. In terms of mean and maximum air velocity inside the units, the double-sided model indicated better behavior compared to the single-sided and lateral models. Furthermore, a negative and significant relationship was observed between the air velocity in the terraces and the number of terraces. At the same time, a positive correlation was observed between the air velocity in the courtyard and the number of terraces. Accordingly, double-sided models are introduced as the balanced model that provide acceptable air velocity in units, terraces and courtyards simultaneously.

It can be inferred from the simulations that increasing the number of porous sides decreases the internal mean and maximum ages of air by -15.75 and -24.32%, which means improved ventilation performance. This correlation is strong and significant. From this point of view, lateral models topped the list, followed by double-sided and single-sided models. Meanwhile, increasing the number of terraces left a negative trace on semi-outdoor ventilation. The strong and significant relationship between the age of air in terraces and the number of terraces proves this claim. From this point of view, single-sided models record the best performance, followed by double-sided and lateral models. Considering the recorded values for the age of air in courtyards, double-sided models topped the group. While, the lateral and single-sided models stood second and third, respectively. Hence, regarding the air permanency in indoor and semi-outdoor spaces, Double-sided model is introduced as the best option.

Increasing the width of the terrace does not have a positive effect on the internal mean velocity, However, it increases the maximum speed. As the width of the terraces increases, the flow velocity within the semi-outdoor spaces experience a rise. This relationship is positive and not significant. In this context, the efficient models are according to their width (1.9, 1.6, 1.3, and 1 meter).

Increasing the width of the terrace reduces the mean and maximum age of the air in the units by -20 and -26%, respectively. This relationship between these two variables is strong and significant. The models with a terrace width of 1.9 meters topped the list, whereas the 1-meter models indicated the worst performance. Furthermore, by increasing the terrace width, the mean and maximum age of the air in the courtyard, indicated a decrease up to -20% and -38%, respectively. The decreased value of mean and maximum age of air by -9 and -10% in terraces means an enhanced ventilation potential in porous buildings with wider terraces. The relationship between these two variables is strong and significant. So the terrace width of 1.9 meters is introduced as the most efficient value to cover the ventilation needs.

Overall, double-sided models are introduced as the balanced model that provides acceptable air velocity in units, terraces and courtyards simultaneously. Meanwhile, investigations proved that increasing the width of the terrace leaves a direct effect on buildings' ventilation performance.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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References

Abdelhady, M. I. M. (2021). Numerical simulation for the geometrical courtyard parameters affecting the indoor natural ventilation, case study in Sur, Oman. *Journal of Xi'an University of Architecture & Technology, 13*(3), 1–15.

Afshari, R. (2020). Indoor air quality and severity of COVID-19: Where communicable and non-communicable preventive measures meet. *Asia Pacific Journal of Medical Toxicology, 9*(1), 1–2. https://doi.org/10.22038/apjmt.2020.15312

Agarwal, N., Meena, C. S., Raj, B. P., Saini, L., Kumar, A., Gopalakrishnan, N., Kumar, A., Balam, N. B., Alam, T., Kapoor, N. R., & Aggarwal, V. (2021). Indoor air quality improvement in COVID-19 pandemic: Review. *Sustainable Cities and Society, 70*, Article 102942. https://doi.org/10.1016/j.scs.2021.102942

Ai, Z. T., Mak, C. M., Niu, J. L., Li, Z. R., & Zhou, Q. (2011). The effect of balconies on ventilation performance of low-rise buildings. *Indoor and Built Environment, 20*(6), 649–660. https://doi.org/10.1177/1420326X11409457

Akbari, P., Yazdanfar, S.-A., Hosseini, S.-B., & Norouzian-Maleki, S. (2021). Housing and mental health during outbreak of COVID-19. *Journal of Building Engineering, 43*, Article 102919. https://doi.org/10.1016/j.jobe.2021.102919

Ali Abd Al-Hameed, K. (2022). Spearman's correlation coefficient in statistical analysis. *International Journal of Nonlinear Analysis and Applications, 13*(1), 3249–3255. https://doi.org/10.22075/ijnaa.2022.6079

Ali, N. (2020). Role of vitamin D in preventing of COVID-19 infection, progression and severity. *Journal of Infection and Public Health, 13*(10), 1373–1380. https://doi.org/10.1016/j.jiph.2020.06.021

Allam, Z., & Jones, D. S. (2020). Pandemic stricken cities on lockdown. Where are our planning and design professionals [now, then and into the future]? *Land Use Policy, 97*, Article 104805. https://doi.org/10.1016/j.landusepol.2020.104805

Allard, F., & Santamouris, M. (1998). *Natural Ventilation in Buildings: A Design Handbook (BEST (Buildings Energy and Solar Technology))*. Earthscan Publications Ltd.

Allocca, C., Chen, Q., & Glicksman, L. R. (2003). Design analysis of single-sided natural ventilation. *Energy and Buildings, 35*(8), 785–795. https://doi.org/10.1016/S0378-7788(02)00239-6

Almhafdy, A., Ibrahim, N., Ahmad, S., & Yahya, J. (2015). Thermal performance analysis of courtyards in a hot humid climate using computational fluid dynamics CFD method. *Procedia - Social and Behavioral Sciences, 170*, 474–483. https://doi.org/10.1016/j.sbspro.2015.01.012

Asfour, O. S. (2010). Prediction of wind environment in different grouping patterns of housing blocks. *Energy and Buildings, 42*(11), 2061–2069. https://doi.org/10.1016/j.enbuild.2010.06.015

Asyary, A., & Veruswati, M. (2020). Sunlight exposure increased Covid-19 recovery rates: A study in the central pandemic area of Indonesia. *The Science of the Total Environment, 729*, Article 139016. https://doi.org/10.1016/j.scitotenv.2020.139016

Awada, M., Becerik-Gerber, B., Hoque, S., O'Neill, Z., Pedrielli, G., Wen, J., & Wu, T. (2021). Ten questions concerning occupant health in buildings during normal operations and extreme events including the COVID-19 pandemic. *Building and Environment, 188*, Article 107480. https://doi.org/10.1016/j.buildenv.2020.107480

Awada, M., Becerik-Gerber, B., White, E., Hoque, S., O'Neill, Z., Pedrielli, G., Wen, J., & Wu, T. (2022). Occupant health in buildings: Impact of the COVID-19 pandemic on the opinions of building professionals and implications on research. *Building and Environment, 207*, Article 108440. https://doi.org/10.1016/j.buildenv.2021.108440

Baetke, F., Werner, H., & Wengle, H. (1990). Numerical simulation of turbulent flow over surface-mounted obstacles with sharp edges and corners. *Journal of Wind Engineering and Industrial Aerodynamics, 35*, 129–147. https://doi.org/10.1016/0167-6105(90)90213-V

Bangalee, M. Z. I., Lin, S. Y., & Miau, J. J. (2012). *Wind driven natural ventilation through multiple windows of a building : A computational approach, 45* pp. 317–325). https://doi.org/10.1016/j.enbuild.2011.11.025

Bartzis, J. G., Vlachogiannis, D., & Sfetsos, T. (2004). Thematic area 5: best practice advice for environmental flows. *The QNET-CFD Network Newsletter, 2*, 34–39.

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014). Auditory and non-auditory effects of noise on health. *Lancet (London, England), 383*(9925), 1325–1332. https://doi.org/10.1016/S0140-6736(13)61613-X

Basner, M., Müller, U., & Elmenhorst, E.-M. (2011). Single and combined effects of air, road, and rail traffic noise on sleep and recuperation. *Sleep, 34*(1), 11–23. https://doi.org/10.1093/sleep/34.1.11

Bazant, M. Z., & Bush, J. W. M. (2021). A guideline to limit indoor airborne transmission of COVID-19. *Proceedings of the National Academy of Sciences of the United States of America*, (17), 118. https://doi.org/10.1073/pnas.2018995118

Berkovic, S., & Yezioro, A. (2017). *Study of thermal comfort in courtyards in a hot arid climate*. https://doi.org/10.1016/j.solener.2012.01.010. *May 2012*.

Bhattacharyya, S., Gesteland, P. H., Korgenski, K., Bjørnstad, O. N., & Adler, F. R. (2015). Cross-immunity between strains explains the dynamical pattern of paramyxoviruses. In *Proceedings of the national academy of sciences of the United States of America* (pp. 13396–13400). https://doi.org/10.1073/pnas.1516698112. *112*(43).

Bhikhoo, N., Hashemi, A., & Cruickshank, H. (2017). Improving thermal comfort of low-income housing in thailand through passive design strategies. *Sustainability*. https://doi.org/10.3390/su9081440. Vol. 9, Issue 8.

Bokel, R. (2007). *The effect of window position and window size on the energy demand for heating, cooling and electric lighting*.

Bornehag, C. G., Sundell, J., Hägerhed-Engman, L., & Sigsgaard, T. (2005). Association between ventilation rates in 390 Swedish homes and allergic symptoms in children. *Indoor Air, 15*(4), 275–280. https://doi.org/10.1111/j.1600-0668.2005.00372.x

Buratti, C., & Palladino, D. (2020). Mean age of air in natural ventilated buildings: Experimental evaluation and CO2 prediction by artificial neural networks. *Applied Sciences (Switzerland), 10*(5), 1–22. https://doi.org/10.3390/app10051730

Burns, A. C., Saxena, R., Vetter, C., Phillips, A. J. K., Lane, J. M., & Cain, S. W. (2021). Time spent in outdoor light is associated with mood, sleep, and circadian rhythm-related outcomes: A cross-sectional and longitudinal study in over 400,000 UK Biobank participants. *Journal of Affective Disorders, 295*, 347–352. https://doi.org/10.1016/j.jad.2021.08.056

Chai, T., & Draxler, R. (2014). Root mean square error (RMSE) or mean absolute error (MAE)? *Geosci. Model Dev., 7*. https://doi.org/10.5194/gmdd-7-1525-2014

Che, W., Ding, J., & Li, L. (2022). Airflow deflectors of external windowsto induce ventilation: Towards COVID-19 prevention and control. *Sustainable Cities and Society, 77*, Article 103548. https://doi.org/10.1016/j.scs.2021.103548

Chen, C., Chen, P., Chen, J., & Su, T. (2021). Recommendations for ventilation of indoor spaces to reduce COVID-19 transmission. *Journal of the Formosan Medical Association, 120*(12), 2055–2060. https://doi.org/10.1016/j.jfma.2021.08.007

Chen, J., & Clarke, K. C. (2020). Indoor cartography. *Cartography and Geographic Information Science, 47*(2), 95–109. https://doi.org/10.1080/15230406.2019.1619482

Chen, S., Oliva, P., & Zhang, P. (2019). *The effect of air pollution on migration : Evidence from China* (p. 230).

Cheung, C., & Leung, K. (2011). Neighborhood homogeneity and cohesion in sustainable community development. *Habitat International, 35*(4), 564–572. https://doi.org/10.1016/j.habitatint.2011.03.004

Coma, J., Pérez, G., de Gracia, A., Burés, S., Urrestarazu, M., & Cabeza, L. F. (2017). Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades. *Building and Environment, 111*, 228–237. https://doi.org/10.1016/j.buildenv.2016.11.014

Cui, D. J., Mak, C. M., & Niu, J. L. (2013). Effect of balconies and upper–lower vents on ventilation and indoor air quality in a wind-induced, naturally ventilated building. *Building Services Engineering Research and Technology, 35*(4), 393–407. https://doi.org/10.1177/0143624413499353

Dadras, M., Shafri, H., Shafri, M., Ahmad, N., Pradhan, B., & Safarpour, S. (2014). A combined fuzzy MCDM approach for identifying the suitable lands for Urban development: An example from bandar ABBS, Iran. *Journal of Urban and Environmental Engineering, 8*, 11–27. https://doi.org/10.4090/juee.2014.v8n1.011027

Díaz, J., Antonio-López-Bueno, J., Culqui, D., Asensio, C., Sánchez-Martínez, G., & Linares, C. (2021). Does exposure to noise pollution influence the incidence and severity of COVID-19? *Environmental Research, 195*, Article 110766. https://doi.org/10.1016/j.envres.2021.110766

Dunnett, N., & Kingsbury, N. (2008). *Planting green roofs and living walls hardcover*. Timber Press.

El-Tanbouly, R., Hassan, Z., & El-Messeiry, S. (2021). The role of indoor plants in air purification and human health in the context of COVID-19 pandemic: A proposal for a novel line of inquiry. *Frontiers in Molecular Biosciences, 8*, Article 709395. https://doi.org/10.3389/fmolb.2021.709395

Elrayies, G. M. (2022). Prophylactic architecture: Formulating the concept of pandemic-resilient homes. In *Buildings, 12*. https://doi.org/10.3390/buildings12070927

Evans, G. W. (2003). The built environment and mental health. *Journal of Urban Health : Bulletin of the New York Academy of Medicine, 80*(4), 536–555. https://doi.org/10.1093/jurban/jtg063

Farea, T. G., Ossen, D. R., Alkaff, S., & Kotani, H. (2015). CFD modeling for natural ventilation in a lightwell connected to outdoor through horizontal voids. *Energy and Buildings, 86*, 502–513. https://doi.org/10.1016/j.enbuild.2014.10.030

Franke, J., & Baklanov, A. (2007). *Best practice guideline for the CFD simulation of flows in the urban environment: COST action 732 quality assurance and improvement of microscale meteorological models*.

Gamero-Salinas, J., Kishnani, N., Monge-Barrio, A., López-Fidalgo, J., & Sánchez-Ostiz, A. (2021a). Evaluation of thermal comfort and building form attributes in different semi-outdoor environments in a high-density tropical setting. *Building and Environment, 205*. https://doi.org/10.1016/j.buildenv.2021.108255

Gamero-Salinas, J., Kishnani, N., Monge-Barrio, A., López-Fidalgo, J., & Sánchez-Ostiz, A. (2021b). The influence of building form variables on the environmental performance of semi-outdoor spaces. A study in mid-rise and high-rise buildings of Singapore. *Energy and Buildings, 230*, Article 110544. https://doi.org/10.1016/j.enbuild.2020.110544

Gamero-Salinas, J., Kishnani, N., Sánchez-Ostiz, A., Monge-Barrio, A., & Benitez, E. (2022). Porosity, openness, and exposure: Identification of underlying factors associated with semi-outdoor spaces' thermal performance and clustering in tropical high-density Singapore. *Energy and Buildings, 272*, Article 112339. https://doi.org/10.1016/j.enbuild.2022.112339

Ghasemi, M., Kandar, M. Z., & Noroozi, M. (2015). Investigating the effect of well geometry on the daylight performance in the adjoining spaces of vertical top-lit atrium buildings. *Indoor and Built Environment, 25*(6), 934–948. https://doi.org/10.1177/1420326X15589121

Group, W. H. O., Sleigh, A., Clements-Croome, D., & Member, P. (2009). *Natural ventilation for infection control in health care settings*.

Hamouche, S. (2020). COVID-19 and employees' mental health: stressors, moderators and agenda for organizational actions. *Emerald Open Research, 2*(15). https://doi.org/10.35241/emeraldopenres.13550.1

Hao, S., Yu, C., Xu, Y., & Song, Y. (2019). The effects of courtyards on the thermal performance of a vernacular house in a hot-summer and cold-winter climate. *Energies*, (6), 12. https://doi.org/10.3390/en12061042

Hariri, M. T. R., Najaf Khosravi, S., & Saadatjoo, P (2016). The impact of high-rise building form on climatic comfort at the pedestrian level. *Journal of Architecture and Urban Planning, 9*(17), 61–77.

Health Ontario, P. (2022). *COVID-19 Transmission through Short and Long-Range Respiratory Particles* (pp. 1–48). *February*.

Healthonics. (2019). *Health Benefits of Sunlight*. https://www.healthonics.healthcare/health-benefits-sunlight/?__cf_chl_tk=x1IdmHGajNwkEXbbwUleFFU3pv20cLQLF55NqjnN6FI-1665255771-0-gaNycGzNCOU.

Heinsohn, R. J., & Cimbala, J. M. (2003). *Indoor Air Quality Engineering , Environmental Health and Control of Indoor Pollutants*. CRC Press. https://doi.org/10.1201/9780203911693

Heiselberg, P. (2004). Natural ventilation design. *International Journal of Ventilation, 2* (4), 295–312. https://doi.org/10.1080/14733315.2004.11683674

Hirano, T., Kato, S., Murakami, S., Ikaga, T., & Shiraishi, Y. (2006). A study on a porous residential building model in hot and humid regions: Part 1—the natural ventilation performance and the cooling load reduction effect of the building model. *Building and Environment, 41*(1), 21–32. https://doi.org/10.1016/j.buildenv.2005.01.018

Holick, M. F. (2004). Sunlight and vitamin D for bone health and prevention of autoimmune diseases, cancers, and cardiovascular disease. *The American Journal of Clinical Nutrition, 80*(6), 1678S–1688S. https://doi.org/10.1093/ajcn/80.6.1678S. Suppl.

Hwang, R.-L., & Lin, T. P. (2007). Thermal comfort requirements for occupants of semi-outdoor and outdoor environments in hot-humid regions. *Architectural Science Review, 50*, 60–67. https://doi.org/10.3763/asre.2007.5043

Izadyar, N., Miller, W., Rismanchi, B., & Garcia-Hansen, V. (2020). A numerical investigation of balcony geometry impact on single-sided natural ventilation and thermal comfort. *Building and Environment, 177*, Article 106847. https://doi.org/10.1016/j.buildenv.2020.106847

Jiang, Y., Alexander, D., Jenkins, H., Arthur, R., & Chen, Q. (2003). *Natural Ventilation in Buildings : Measurement in a Wind Tunnel and Numerical Simulation with Large Eddy Simulation, 91* pp. 331–353).

Kahsay, M. T., Bitsuamlak, G. T., & Tariku, F. (2019). CFD simulation of external CHTC on a high-rise building with and without façade appurtenances. *Building and Environment, 165*, Article 106350. https://doi.org/10.1016/j.buildenv.2019.106350

Konidari, A., & Fedeski, M. (2014). *The adaptation of the "porous residential building model" to hot dry climates*.

Korman, M., Tkachev, V., Reis, C., Komada, Y., Kitamura, S., Gubin, D., Kumar, V., & Roenneberg, T. (2022). Outdoor daylight exposure and longer sleep promote wellbeing under COVID-19 mandated restrictions. *Journal of Sleep Research, 31*(2), e13471. https://doi.org/10.1111/jsr.13471

Lewis, D. (2022). Why the WHO took two years to say COVID is airborne. *Nature, 604* (7904), 26–31. https://doi.org/10.1038/d41586-022-00925-7

Liu, J., Wyver, S., & Chutiyami, M. (2022). Impacts of COVID-19 restrictions on young children's outdoor activity: A systematic review. *Children (Basel), 9*(10), 1564. https://doi.org/10.3390/children9101564

Liu, T., He, L., Yu, W., Freudenreich, T, & Lin, X. (2022). Effect of green plants on individuals' mental stress during the COVID-19 pandemic: A preliminary study. *International Journal of Environmental Research and Public Health., 19*(20), 13541. https://doi.org/10.3390/ijerph192013541

Shen, J., Kong, M., Dong, B., Birnkrant, M. J., & Zhang, J. (2021). A systematic approach to estimating the effectiveness of multi-scale IAQ strategies for reducing the risk of airborne infection of SARS-CoV-2. *Building and Environment, 200*, Article 107926. https://doi.org/10.1016/j.buildenv.2021.107926

Felkner, J., & Chatzi, E. (2014a). Effect of Structure and Morphology on Natural Ventilation Potentials, Comfort, and Energy Use in Tall Buildings. Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a Changing World.

Liston, K. (n.d.). *The Future of Home Design—During and after COVID-19*. https://www.remodeling.hw.net/%0Abusiness/design/the-future-of-home-design-during-and-after-covid-19_o.

Loomis, D., Grosse, Y., Lauby-Secretan, B., El Ghissassi, F., Bouvard, V., Benbrahim-Tallaa, L., Guha, N., Baan, R., Mattock, H., & Straif, K. (2013). The carcinogenicity of outdoor air pollution. In *The Lancet. Oncology, 14* pp. 1262–1263). https://doi.org/10.1016/s1470-2045(13)70487-x

López-Cabeza, V. P., Rivera-Gómez, C., Roa-Fernández, J., Hernandez-Valencia, M., & Herrera-Limones, R. (2023). Effect of thermal inertia and natural ventilation on user comfort in courtyards under warm summer conditions. *Building and Environment, 228*, Article 109812. https://doi.org/10.1016/j.buildenv.2022.109812

Mahdavi, A., & Najaf Khosravi, S. (2020). Acoustical and airflow considerations concerning double-layered façades with openings for natural ventilation. *E3S Web of Conferences, 172*, 1–5. https://doi.org/10.1051/e3sconf/202017224002

Majeed, M. N., Mustafa, F. A., & Husein, H. A. (2019). *Impact of Building Typology on Daylight Optimization Using Building Information Modeling : Apartments in Erbil City as a Case Study, 6* pp. 187–201). https://doi.org/10.15627/jd.2019.17

Massey, F. J. (1951). The Kolmogorov-Smirnov test for goodness of fit. *Journal of the American Statistical Association, 46*(253), 68. https://doi.org/10.2307/2280095

Meiss, A., Feijó-Muñoz, J., & García-Fuentes, M. A. (2013). Age-of-the-air in rooms according to the environmental condition of temperature: A case study. *Energy and Buildings, 67*, 88–96. https://doi.org/10.1016/j.enbuild.2013.08.016

Meo, S. A., Abukhalaf, A. A., Alomar, A. A., AlMutairi, F. J., Usmani, A. M., & Klonoff, D. C. (2020). Impact of lockdown on COVID-19 prevalence and mortality during 2020 pandemic: observational analysis of 27 countries. *European Journal of Medical Research, 25*(1), 56. https://doi.org/10.1186/s40001-020-00456-9

Mohamedi, M. F., Prasad, D., King, S., & Hirota, K. (2009). The impact of balconies on wind induced ventilation of singlesided naturally ventilated multi-storey apartment. In *PLEA2009 - 26th conference on passive and low energy architecture. Quebec City, Canada*.

Mohammadi, A., Mohd Tahir, M., Usman, I., Goh, N., & Che-Ani, A. (2010). *The Effect of Balcony to Enhance the Natural Ventilation of Terrace Houses in the Tropical Climate of Malaysia*.

Mohammed, M., Bulama, K., Usman, A., Modu, M., Bukar, A., Lawan, A., & Habib, G. (2020). Psychosocial perception of the effects of harmattan dust on the environment and health of building occupants in Maiduguri, Nigeria. *Facilities, ahead-of-p*. https://doi.org/10.1108/F-05-2019-0060

Molina-Sabio, M., & Rodríguez-Reinoso, F. (2004). Role of chemical activation in the development of carbon porosity. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 241*(1), 15–25. https://doi.org/10.1016/j.colsurfa.2004.04.007

Montazeri, H., & Blocken, B. (2013). CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: Validation and sensitivity analysis. *Building and Environment, 60*, 137–149. https://doi.org/10.1016/j.buildenv.2012.11.012

Moonen, P., Dorer, V., & Carmeliet, J. (2011). Evaluation of the ventilation potential of courtyards and urban street canyons using RANS and LES. *Journal of Wind Engineering and Industrial Aerodynamics, 99*(4), 414–423. https://doi.org/10.1016/j.jweia.2010.12.012

Morawska, L., Tang, J. W., Bahnfleth, W., Bluyssen, P. M., Boerstra, A., Buonanno, G., Cao, J., Dancer, S., Floto, A., Franchimon, F., Haworth, C., Hogeling, J., Isaxon, C., Jimenez, J. L., Kurnitski, J., Li, Y., Loomans, M., Marks, G., Marr, L. C., & Yao, M. (2020). How can airborne transmission of COVID-19 indoors be minimised? *Environment International, 142*, Article 105832. https://doi.org/10.1016/j.envint.2020.105832

Motamedi, H., Shirzadi, M., Tominaga, Y., & Mirzaei, P. A. (2022). CFD modeling of airborne pathogen transmission of COVID-19 in confined spaces under different ventilation strategies. *Sustainable Cities and Society, 76*, Article 103397. https://doi.org/10.1016/j.scs.2021.103397. July 2021.

Mozaffari Ghadikolaei, F., Ossen, D. R., & Mohamed, M. F. (2020). Effects of wing wall at the balcony on the natural ventilation performance in medium-rise residential buildings. *Journal of Building Engineering, 31*, Article 101316. https://doi.org/10.1016/j.jobe.2020.101316. July 2019.

Muhammad, J. S., Siddiqui, R., & Khan, N. A. (2022). SARS-CoV-2: Can sunlight exposure reduce the risk of developing severe consequences of COVID-19? *Computational Biology and Chemistry, 96*, Article 107602. https://doi.org/10.1016/j.compbiolchem.2021.107602

Muhsin, F., Yusoff, W. F. M., Mohamed, M. F., & Sapian, A. R. (2017). CFD modeling of natural ventilation in a void connected to the living units of multi-storey housing for thermal comfort. *Energy and Buildings, 144*, 1–16. https://doi.org/10.1016/j.enbuild.2017.03.035

Najaf Khosravi, S., & Mahdavi, A (2021). A CFD-based parametric thermal performance analysis of supply air ventilated windows. *Energies, 14*(9). https://doi.org/10.3390/en14092420

Najaf Khosravi, S., Saadatjoo, P., Mahdavinejad, M., & Amindeldar, S (2016). The effect of roof details on natural ventilation efficiency in isolated single buildings. *PLEA 2016 - cities, buildings, people: Towards regenerative environments*.

Nikghadam, N. (2015). Climatic patterns of functional spaces in vernacular houses of Bushehr (by Grounded Theory). *The Monthly Scientific Journal of Bagh-e Nazar, 12* (32), 77–90.

Ok, V., Yasa, E., & Özgunler, M. (2008). An experimental study of the effects of surface openings on air flow caused by wind in courtyard buildings. *Architectural Science Review, 51*(3), 263–268. https://doi.org/10.3763/asre.2008.5131

Omrani, S., Garcia-Hansen, V., Capra, B. R., & Drogemuller, R. (2017). On the effect of provision of balconies on natural ventilation and thermal comfort in high-rise residential buildings. *Building and Environment, 123*, 504–516. https://doi.org/10.1016/j.buildenv.2017.07.016

Pellow, J., Solomon, E. M., & Barnard, C. N. (2011). Complementary and alternative medical therapies for children with attention-deficit/hyperactivity disorder (ADHD). *Alternative Medicine Review, 16*(4), 323–337.

Perini, K., Ottelé, M., Haas, E. M., & Raiteri, R. (2013). Vertical greening systems, a process tree for green façades and living walls. *Urban Ecosystems, 16*(2), 265–277. https://doi.org/10.1007/s11252-012-0262-3

Pirrera, S., De Valck, E., & Cluydts, R. (2010). Nocturnal road traffic noise: A review on its assessment and consequences on sleep and health. *Environment International, 36* (5), 492–498. https://doi.org/10.1016/j.envint.2010.03.007

Plano, S. A., Casiraghi, L. P., Moro, P. G., Paladino, N., Golombek, D. A., & Chiesa, J. J. (2017). Circadian and metabolic effects of light: Implications in weight homeostasis and health. *Frontiers in Neurology*. https://doi.org/10.3389/fneur.2017.00558. Vol. 8OCT.

Prianto, E., & Depecker, P. (2002). Characteristic of airflow as the effect of balcony, opening design and internal division on indoor velocity: A case study of traditional dwelling in urban living quarter in tropical humid region. *Energy and Buildings, 34* (4), 401–409. https://doi.org/10.1016/S0378-7788(01)00124-4

Rajapaksha, I., Nagai, H., & Okumiya, M. (2003). A ventilated courtyard as a passive cooling strategy in the warm humid tropics. *Renewable Energy, 28*(11), 1755–1778. https://doi.org/10.1016/S0960-1481(03)00012-0

Rao, S. P. (2015). Impacts of orientation on daylighting in high-rise office buildings in Malaysia. *Journal of Design and Built Environment, 15*(2), 29–38. *December 2015, 15*.

Ren, C., Xi, C., Wang, J., Feng, Z., Nasiri, F., Cao, S. J., & Haghighat, F. (2021). Mitigating COVID-19 infection disease transmission in indoor environment using physical barriers. *Sustainable Cities and Society, 74*, Article 103175. https://doi.org/10.1016/j.scs.2021.103175

Rodríguez-Algeciras, J., Tablada, A., Chaos-Yeras, M., De la Paz, G., & Matzarakis, A. (2018). Influence of aspect ratio and orientation on large courtyard thermal conditions in the historical centre of Camagüey-Cuba. *Renewable Energy, 125*, 840–856. https://doi.org/10.1016/j.renene.2018.01.082

Rose, L., Horrison, E., & Venkatachalam, Lavanya Jothi (2011). Influence of built form on the thermal comfort of outdoor urban spaces. In *The 5th International Conference of the International Forum on Urbanism (IFoU)*.

Roshan, G., Arab, M., & Klimenko, V. (2019). Modeling the impact of climate change on energy consumption and carbon dioxide emissions of buildings in Iran. *Journal of Environmental Health Science & Engineering, 17*(2), 889–906. https://doi.org/10.1007/s40201-019-00406-6

Rothan, H. A., & Byrareddy, S. N. (2020). The epidemiology and pathogenesis of coronavirus disease (COVID-19) outbreak. *Journal of Autoimmunity, 109*, Article 102433. https://doi.org/10.1016/j.jaut.2020.102433

Saadatjoo, P., Mahdavinejad, M., Najaf Khosravi, S., & Kaveh, N. (2016). Effect of courtyard proportion on natural ventilation efficiency. *International Journal of Advances in Mechanical and Civil Engineering, 3*(5), 92–97.

Saadatjoo, P., Mahdavinejad, M., & Zarkesh, A. (2019). *Porosity Rendering in High-Performance Architecture : Wind-Driven Natural Ventilation and Porosity Distribution Patterns, 12* pp. 73–87). https://doi.org/10.22034/AAUD.2019.89057

Saadatjoo, P., Mahdavinejad, M., & Zhang, G. (2018). A study on terraced apartments and their natural ventilation performance in hot and humid regions. *Building Simulation, 11*(2), 359–372. https://doi.org/10.1007/s12273-017-0407-7

Saadatjoo, P., Mahdavinejad, M., Zhang, G., & Vali, K. (2021). Influence of permeability ratio on wind-driven ventilation and cooling load of mid-rise buildings. *Sustainable Cities and Society, 70*, Article 102894. https://doi.org/10.1016/j.scs.2021.102894

Saligheh, E., & Saadatjoo, P. (2020). Impact of central courtyard proportions on passive cooling potential in hot and humid regions (case study: single-story buildings in Bandar Abbas). *Naqshejahan-Basic Studies and New Technologies of Architecture and Planning, 10*(2), 137–152.

Sarai, M., & Moayedfar, S. (2008). Socioeconomic items of sustainable urban development in Arid Areas, Ardakan City. *Journal of Geographical Researches*, 90.

Schwartz, S. (2019). *How Unhealthy Air Quality Can Trigger Mental Health Issues*. https://ecohappinessproject.com/unhealthy-air-quality/.

Sharmand. (2008). *Revision of the Comprehensive Strategic Plan of Bandar Abbas*.

Shetabivash, H. (2015). Investigation of opening position and shape on the natural cross ventilation. *Energy and Buildings, 93*, 1–15. https://doi.org/10.1016/j.enbuild.2014.12.053

Shojaei, A., & Salari, P. (2021). COVID-19 and the “Stay at home” recommendation: An ethnographic study. *Journal of Education and Health Promotion, 10*(62). https://doi.org/10.4103/jehp.jehp_910_20

Spagnolo, J., & de Dear, R. (2003). A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Building and Environment, 38*(5), 721–738. https://doi.org/10.1016/S0360-1323(02)00209-3

Stanley, M. (2022). *Noise Pollution. National Geographic*. https://education.nationalgeographic.org/resource/noise-pollution.

Stoiljkovic, B. (2022). Social cohesion and neighbor interactions within multifamily apartment buildings: Challenges of COVID-19 and directions of action. *Sustainability, 14*, 738. https://doi.org/10.3390/su14020738

Szyszkowicz, M., Rowe, B. H., & Colman, I. (2009). Air pollution and daily emergency department visits for depression. *International Journal of Occupational Medicine and Environmental Health, 22*(4), 355–362. https://doi.org/10.2478/v10001-009-0031-6

Tablada de la Torre, A. E., Blocken, B., Carmeliet, J., De Troyer, F., & Verschure, H. (2005). The influence of courtyard geometry on air flow and thermal comfort: CFD and thermal comfort simulations. In *Proceedings of the 22nd Conference on Passive and Low Energy Architecture* (p. 1).

Tanabe, S., & Takewaki, I. (2020). Role of ventilation in the control of the Covid-19 infection: Emergency presidential discourse. *The society of heating, air-conditioning and sanitary engineers of Japan (SHASE)* (pp. 1–6).

Tokazhanov, G., Tleuken, A., Guney, M., Turkyilmaz, A., & Karaca, F. (2020). How is COVID-19 experience transforming sustainability requirements of residential buildings? A review. *Sustainability, 12*(20). https://doi.org/10.3390/su12208732

Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M., & Shirasawa, T. (2008). AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of Wind Engineering and Industrial Aerodynamics, 96*(10–11), 1749–1761. https://doi.org/10.1016/j.jweia.2008.02.058

Toris-Guitron, M. G., Esparza-López, C. J., Luna-León, A., & Pozo, C. E. (2022). Evaluation of the thermal performance of traditional courtyard houses in a warm humid climate: Colima, Mexico. *Heritage Science, 10*(1), 187. https://doi.org/10.1186/s40494-022-00820-4

Van Buggenhout, S., Zerihun Desta, T., Van Brecht, A., Vranken, E., Quanten, S., Van Malcot, W., & Berckmans, D. (2006). Data-based mechanistic modelling approach to determine the age of air in a ventilated space. *Building and Environment, 41*(5), 557–567. https://doi.org/10.1016/j.buildenv.2005.02.029

Van Dijken, F., & Roerstra, A. (2021). Implications of COVID-19 pandemic for application of natural ventilation. *REHVA Journal*, 58–63. *June*.

Wang, X., Gard, W., Borska, H., Ursem, B., & van de Kuilen, J. W. G. (2020). Vertical greenery systems: From plants to trees with self-growing interconnections. *European Journal of Wood and Wood Products, 78*(5), 1031–1043. https://doi.org/10.1007/s00107-020-01583-0

Watkins, G., Tarnopolsky, A., & Jenkins, L. M. (1981). Aircraft noise and mental health: II. Use of medicines and health care services. *Psychological Medicine, 11*(1), 155–168. https://doi.org/10.1017/s003329170005337x

Wei, Z., Van Le, Q., Peng, W., Yang, Y., Yang, H., Gu, H., Lam, S. S., & Sonne, C. (2021). A review on phytoremediation of contaminants in air, water and soil. *Journal of Hazardous Materials, 403*, Article 123658. https://doi.org/10.1016/j.jhazmat.2020.123658

Wong, N. H., Kwang Tan, A. Y., Tan, P. Y., Chiang, K., & Wong, N. C. (2010). Acoustics evaluation of vertical greenery systems for building walls. *Building and Environment, 45*(2), 411–420. https://doi.org/10.1016/j.buildenv.2009.06.017

Wu, Y., Kang, J., Lau, S., Xie, H., & Liu, F. (2022). Soundscape, well-being and mental health during/after the COVID-19 pandemic. *Frontiers in psychology*. https://www.frontiersin.org/research-topics/38469/soundscape-well-being-and-mental-health-duringafter-the-covid-19-pandemic#overview.

Xu, X., Luo, F., Wang, W., Hong, T., & Fu, X. (2018). Performance-based evaluation of courtyard design in China’s cold-winter hot-summer climate regions. *Sustainability (Switzerland)*, (11), 10. https://doi.org/10.3390/su10113950

Yang, L., Liu, X., Qian, F., & Niu, S. (2020). Research on the wind environment and air quality of parallel courtyards in a university campus. *Sustainable Cities and Society, 56*, Article 102019. https://doi.org/10.1016/j.scs.2020.102019

Zabolbbasi, F., Pourasgarian, A., & Sisipour, M. (2007). Investigating the climatic condition of Hormozgan Province. *National Climatology Center Bulletin*, 27–28.

Zhang, J. (2020). Integrating IAQ control strategies to reduce the risk of asymptomatic SARS CoV-2 infections in classrooms and open plan offices. *Science and Technology for the Built Environment*, 1013–1018. https://doi.org/10.1080/23744731.2020.1794499

Zheng, X., Montazeri, H., & Blocken, B. (2020). CFD simulations of wind flow and mean surface pressure for buildings with balconies: Comparison of RANS and LES. *Building and Environment, 173*, Article 106747. https://doi.org/10.1016/j.buildenv.2020.106747