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Energy consumption, thermal comfort, and indoor air quality in mosques: Impact of Covid-19 measures

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ABSTRACT

Restrictions have been imposed on the number of people, the duration of their stay and air conditioning operation in temples to limit the spread of the SARS-CoV-2 pandemic. This work studied how restrictions affected energy consumption, thermal comfort, and indoor air quality (IAQ) in mosques. Energy consumption data on lighting, heating and cooling before and during the pandemic were analyzed in six mosques of various sizes located in Yalova city, Turkey. The annual energy consumption for lighting was reduced during the pandemic in all mosques due to less usage, while the annual heating and cooling costs were raised in one mosque despite their restricted use. Besides, experiments were conducted to assess the effect of pandemic measures on thermal comfort and IAQ by measuring indoor temperature, relative humidity, air velocity, CO_2 and PM concentrations in a typical mosque. Keeping the windows open and limiting occupancy improved the IAQ. This was evidenced by the lower average CO_2 concentration during the pandemic (428 ± 40 ppm) than before the pandemic (661 ± 201 ppm). An acceptable thermal environment was achieved under pandemic measures at night during the summer period. Creating excellent conditions can be difficult without air conditioning even with open windows and prayers performed at night.

1. Introduction

The spread of SARS-CoV-2, which is a new type of coronavirus and was first seen in Wuhan city, China, on December 12, 2019, was determined by the World Health Organization (WHO) as a pandemic on March 11, 2020 (WHO, 2021). The high spread rate of the pandemic and the fatal consequences caused public health experts to focus on various measures to limit the incidence of Covid-19. Furthermore, states took various measures to minimize the rate of transmission of coronavirus (Gupta, 2021; Nižetić, 2020). In this process, especially measures and restrictions have emerged in the environments where people gather (Cowling and Aiello, 2021; Di Lorenzo and Di Trolio, 2020; Stoecklin, 2020). In this context, in Turkey as well as in other countries, the use of spaces with a high density of people, including mosques, was completely restricted or temporarily suspended.

The mosques are visited five times a day throughout the year in partial occupancy. However, they reach full occupancy at noon on Fridays, at morning time on two Eid days a year, on religious nights such as Kandil nights, and especially for Tarawih prayers during night prayers in Ramadan. The behavior and actions of the congregation members in mosques differ from those performed in other large-volume structures (theatre, gymnasium, library, shopping center, etc.). Therefore, energy consumption, thermal comfort, and indoor air quality (IAQ) in these buildings are also different (Yüksel et al., 2020).

The reduction in the occupancy during the pandemic is expected to affect the IAQ (Abouleish, 2021; Agarwal, 2021; Elsaid and Ahmed, 2021). Furthermore, most mosques are ventilated naturally by open windows due to the pandemic, which can affect the thermal comfort of the occupants. It can also affect IAQ, both positively by diluting the indoor pollutants and negatively by infiltration of outdoor air pollution.

1.1. *Coronavirus in Turkey*

In Turkey, the first coronavirus case was seen on March 11, 2020. After the first case, there was a rapid increase in the number of daily cases due to super emitters. Turkey's daily case numbers for approximately 2 years are shown in Fig. 1. Four peaks were observed at different

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Abbreviations

CFD	Computational fluid dynamics
D	Data logger (temperature and relative humidity measuring device)
FM	Fatih Mosque
GM	Güneyköy Mosque
HM	Hacı Hasan Sert Mosque
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
YM	Yalova Merkez Mosque
NHMRC	National Health and Medical Research Council
NOHSC	National Occupational Health and Safety Commission
P	Particulate matter meter
PM	Particulate matter
PM_{10}	Particulate matter, diameter ≤10 μm
$PM_{2.5}$	Particulate matter, diameter ≤2.5 μm
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
RM	Rüstempaşa Mosque
SM	Safran Köyü Mosque
T	Thermal comfort measuring device
TVOC	Total volatile organic compounds
WHO	World Health Organization

times of the year, where the daily number of cases increased significantly. With the implementation of the restrictions throughout the country, the daily number of cases dropped to 1000–2000 people on average, while the restrictions were gradually loosened due to the stagnation in the number of cases. In the autumn and winter months, the daily number of cases reached a peak value of 32137, and then it decreased to 10000 in February and March. A rapid increase occurred in April, peaking at 62797 people. During the country-wide closure, between April 29 and May 17, 2021, the average number of daily cases was reduced to around 6000. The number of cases started increasing again on July 7, 2021 and peaked at 33860. The number of cases started increasing again from the last week of December 2021 and reached the peak of 111157 in February 2022.

The effects of the Covid-19 pandemic on mosque attendance were observed in a short time since mosque worshipping was completely suspended on March 16, 2020. From May 29, 2020, mosques were open to congregation members for noon, afternoon, and Friday prayers following mask, distance, and hygiene rules. The congregation was allowed to worship together, under measures taken such as mask, distance, and hygiene at all prayer times on June 24, 2020 (Presidency of Religious Affairs, 2020a; Presidency of Religious Affairs, 2020b; Presidency of Religious Affairs, 2020c). As the distance of 1.5 should be maintained between prayers, the capacity of the mosques was reduced by about one-third. On the other hand, due to airborne transmission of coronavirus among people, the usage scenarios of HVAC (heating, ventilation, and air conditioning) systems were reconsidered. Since the effects of air conditioning systems on the spread rate of the disease in crowded places were not fully known, the use of these systems was suspended.

1.2. Research on coronavirus in the built environment

Scientists have started investigating the effects of Covid-19 and its environmental conditions on people since the spread of the coronavirus disease throughout the world (Majumder and Ray, 2021; Qarnain et al., 2020; Sikarwar et al., 2021). Faridi et al. (2020) collected samples from the rooms of patients with Covid-19 in Iran's largest hospital. No evidence of coronavirus presence was found in the samples taken from a distance of 2 m distance between patients' beds. Therefore, it was emphasized that a distance of at least 2 m should be kept from sick people. A review study by Azuma et al. (2020) concluded that the virus can remain on various porous or non-porous surfaces for days. Furthermore, it was determined that the aerosolized time of SARS-CoV-2 was from 1.5 to 3 h, depending on the temperature (19–23 °C) and relative humidity (40–88%) in the environment. Ahlawat et al. (2020) suggested an optimal level of relative humidity to reduce the spread of the pandemic and protect people's health, also considering the humidity for comfort conditions of 40–60%. Ismail et al. (2022) followed daily coronavirus cases and deaths for six months in six cities in Saudi Arabia and determined that the outdoor air temperature, relative humidity, and air pollution were among the factors that impacted Covid-19 spread. The number of cases increased as the temperature and relative humidity of the indoor air increased, and the number of cases and deaths was directly proportional to the outdoor air quality.

The effect of ventilation was generally evaluated in studies aimed at reducing the rate of transmission of coronavirus in the indoor environment. Some studies found that poor ventilation strategies promoted the transmission of Covid-19 (Correia et al., 2020). For example, Ascione et al. (2021) recommended using sensible heat recovery in the ventilation system of university buildings that were constantly fed fresh air for

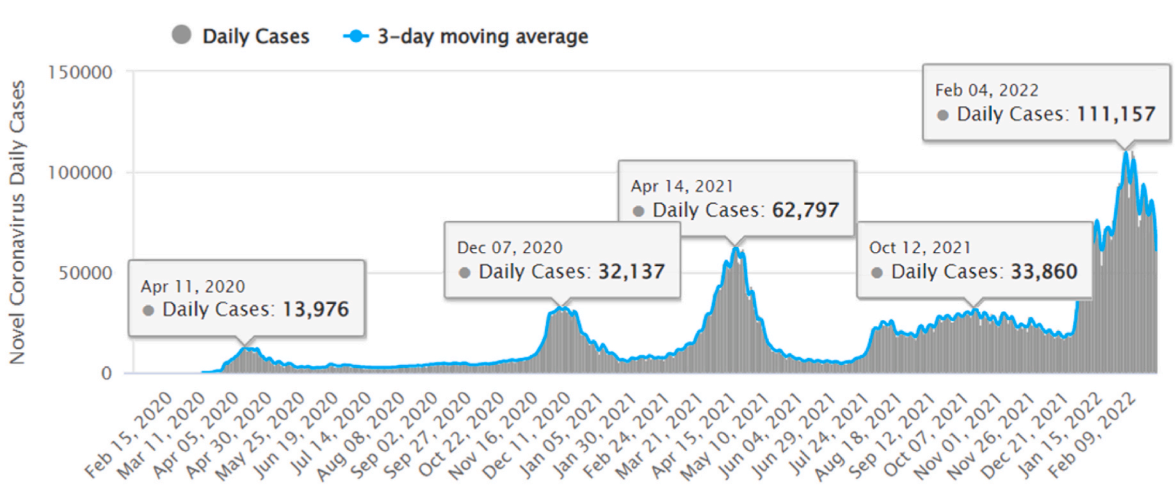


Fig. 1. Number of daily cases of Covid-19 infection in Turkey (Worldometers, 2021).

health reasons. Borro et al. (2021) researched the effects of air conditioners on the spread of coronavirus indoor environments applying a computational fluid dynamics (CFD) in a children's hospital and concluded that the use of HVAC systems with a double air flow rate in such environments contributed to the transport of indoor pollutants to remote points. However, the presence of exhaust ventilation at high flow rates reduced the concentrations of pollutants. On the other hand, Gil-Baez et al. (2021) investigated the effects of coronavirus on students' health in schools in a Mediterranean region. The measured concentration of CO_2 varied between 4110 and 5366 ppm, thus exceeding the limit of about 1000 ppm indoors (EN 16798- 1, 2019) recommended for a good IAQ. $PM_{2.5}$ (particulate matter, diameter ≤2.5 μm) and PM_{10} (particulate matter, diameter ≤10 μm) of 1.14–15.6 μg/m^3 and 2.04–34.86 μg/m^3 were below the recommended limits of 25 μg/m^3 (24h avg) and 50 μg/m^3 (24h avg) (WHO, 2000), respectively. However, the TVOC (total volatile organic compounds) values ranged between 206.99 and 589.71 μg/m^3, thus exceeding the recommended limit of 300 μg/m^3 (Yüksel et al., 2021) in some of the cases depending on the occupancy. In general, the mentioned studies highlight the need for sufficient ventilation.

Instructions on the use of natural or mechanical ventilation systems to reduce the spread of coronavirus and improve IAQ affect energy consumption in buildings. At the same time, opening windows and restrictions on air conditioning affect indoor thermal conditions. Thus, there is a relationship between Covid-19 and IAQ, thermal comfort, and energy consumption. To our knowledge, no study has been conducted on the effects of the Covid-19 pandemic measures on thermal comfort, IAQ, and energy consumption in mosques so far.

1.3. Research on energy consumption, thermal comfort, and IAQ in mosques

Al-Homoud et al. (2005) examined the energy use in mosques in a hot and humid climate depending on the area and the usage time. The share in total energy consumption was between 69% and 79% for air conditioners, between 17% and 27% for lighting, and between 2% and 9% for fans. Abdou et al. (2005) assessed 5-year energy bills of 5 mosques, with an average occupancy of 30% and 100%, and capacities ranging from 190 to 1319 people. The highest total annual energy consumption (163920 kWh, that is, approximately fourteen tons of crude oil) was recorded in the mosque with the highest congregation capacity (1319 people), where split air conditioners were used. Al Touma and Ouahrani (2017) concluded that most mosques in Qatar were insulated, examined energy savings measures that can be done in addition to insulation, and simulated the energy consumption of a sample mosque. Energy savings of 9.1% were achieved by adding insulation to the roof of a mosque with insulated walls, and 6.2% were saved when a shading apparatus was added to the roof. Al-Homoud (2009) interpreted the domes of mosques as areas where hot and stagnant air accumulates. The selection of an appropriate cooling system for the working area and its operation were stated to be the key points in reducing energy consumption.

Thermal comfort and energy use were monitored by annual measurements by Atmaca and Gedik, (2019) in a mosque that had two different HVAC systems. It was found that the entrance areas of the mosque had the lowest level of thermal comfort. It was recommended to compose an intermediate zone between the indoor and outdoor environment to ensure a homogeneous temperature distribution in the indoor environment and to operate the air conditioners differently for the Friday prayers due to the high temperature observed during the prayer. Ibrahim et al. (2014) investigated the thermal comfort conditions during daily prayers in a mosque in Malaysia with the help of measuring devices placed 1.5 m above the ground. Comfort conditions were not met due to the high indoor temperature. Kamar et al. (2019) examined the PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) indices in a mosque based on one-year field measurements. By increasing air speed through fans placed at 6 m above ground, the PMV and PPD indices could reportedly be reduced by up to 95% and 91%, respectively. Saeed (1996) studied thermal dissatisfaction during Friday prayers in a mosque in Saudi Arabia. Depending on the clothing insulation, a difference was observed between the data obtained by the PMV/PPD model and the actual mean vote obtained from the field survey of 12% (larger values were obtained with the field survey). Al-ajmi (2010) investigated the thermal comfort parameters in six mosques approximately the same size. The average PMV index ranged between 1.3 and 0.67, and the PPD index varied between 40.3 and 5.4%. Noman et al. (2016) analyzed changes in PMV and PPD indices under different ventilation conditions by performing a CFD analysis of airflow in a mosque. Under current conditions, the thermal comfort conditions were well above the limit values as defined by ASHRAE Standard 55 (ANSI/ASHRAE Standard 55-2017, 2017). It was determined that the PPD index could be reduced by up to 60% by placing an exhaust fan with a diameter of 56 cm on the wall facing the west side of the mosque.

Jaafar et al. (2017) evaluated IAQ and thermal comfort conditions through a CFD analysis. Indoor CO_2 concentration decreased from 1200 to 500 ppm by increasing the hourly ventilation rate in the mosque from 6 to 14. Ocak et al. (2012) evaluated the concentrations of CO_2 and particulate matter (investigated particle sizes: 0.5–1.0, 1.0–5.0 and > 5.0) in a mosque according to different cleaning programs. The cleaning (vacuuming) program consisted of three different scenarios: one week before the prayer, the day before the prayer, and on the day of the prayer. The level of CO_2 concentration indicated that the ventilation supply during worship was insufficient. The lowest concentration of particulate matter was obtained when vacuuming was performed one day before worship. Al-Dabbous et al. (2013) investigated the daily level of CO_2 concentration in a mosque in Kuwait at 5-min intervals. The level of CO_2 reached its peak (847.5 ppm) during worship. The maximum CO_2 concentration (approximately 1700 ppm) was obtained during the Friday worship time (noon) with full occupancy. It was suggested to provide fresh air in the mosque only during worships to save energy. Additionally, the total amount of volatile organic compounds was monitored in the mosque. It was found that these pollutants originate mainly from the outdoor environment. Yüksel et al., (2020) monitored CO_2 concentrations inside a mosque during the Tarawih prayer, which is one of the longest prayers. The CO_2 concentration reached 3750 ppm in the last worship period that lasted about 1 h, thus substantially exceeding the recommended limits.

All the studies mentioned above focus on energy consumption, thermal comfort, or IAQ in temples prior to the pandemic. This is, to the best knowledge of the authors, the first study to evaluate and compare the energy consumption, thermal comfort, and IAQ in mosques before and during the pandemic. The findings of this study are expected to provide a basis for measures to be taken, particularly for IAQ in mosques, the number of which are around 90000 in Turkey.

1.4. Aim of the study

All studies in the literature on mosques refer to the period before the Covid-19 pandemic or were conducted without special considerations of the pandemic. Investigating the effects of coronavirus measures on indoor environmental conditions and energy consumption in mosques is of significant importance in terms of assessing the current situation. In this context, this study aims to investigate the effect of pandemic measures on energy consumption, thermal comfort, and IAQ in temples and to compare the findings with those before the epidemic. As such, people can meet their social needs in a comfortable and healthy environment with less energy consumption during the pandemic, which is not certain when it will end. To do this, the electricity consumption bills arising from heating-cooling and lighting before and during the pandemic were analyzed, and the effects of the pandemic on energy consumption were evaluated. Furthermore, the impact of the Covid-19 pandemic on thermal comfort and IAQ was experimentally analyzed by examining key parameters of thermal comfort and air quality before and during the pandemic in a typical medium-sized mosque. The findings help provide recommendations on mosque operation during a pandemic to achieve a comfortable and healthy indoor environment and save energy.

2. Materials and methods

In the present study, electricity bills from six different mosques for the period before and during the pandemic were collected and analyzed. Furthermore, thermal comfort and IAQ parameters were measured before and during the pandemic in a typical medium-sized neighborhood mosque. The collected data served to evaluate the effects of Covid-19 disease on energy consumption, thermal comfort, and IAQ parameters in mosques, which differ in terms of usage patterns and times compared to other large structures.

2.1. Mosque selection and billing methodology

Mosques can differ from each other in terms of features such as indoor volumes and historical value, although they all serve the same purpose. Therefore, the mosques selected for this study were classified in terms of size, location, and historical context. Six mosques of different types commonly encountered throughout Turkey were chosen (Table 1). All mosques are located in or close to Yalova, Turkey, which has a warm and humid climate. In this way, it was ensured that the climatic conditions and outdoor parameters were nearly identical for each mosque.

The Yalova Merkez Mosque (Table 1) with the two thousand one hundred people capacity has a larger congregation capacity than the other mosques due to its central location in the bazaar area. The Fatih Mosque is a large neighborhood mosque, filled with the people of the region at worship times. Its volume and congregation capacity are higher compared to the other neighborhood mosques. Hacı Hasan Sert and Rüstempaşa Mosques are located in ordinary neighborhoods such as the Fatih Mosque, but they represent medium- and small-scale volumes, respectively. This means that the Hacı Hasan Sert Mosque has a smaller congregation capacity than the Fatih Mosque, and the Rüstempaşa Mosque has a smaller congregation capacity than the Hacı Hasan Sert Mosque. The Rüstempaşa Mosque also differs from the other mosques by its use. There is no congregational worship, except for Friday prayers. The Güneyköy Mosque is a historic mosque that contains historical structures. The main feature that distinguishes this mosque, which is far from the city center, is the material of the walls. The walls are made of cut stone, while in the other mosques they are made of bricks. Finally, the Safran Köyü Mosque located in Safran Village is a representative of mosques located in rural areas with low population density. It should be noted that there is no insulation on any of the walls of the aforementioned mosques.

The electricity bills were collected for all the mosques. The total energy consumption, cost of energy, and unit energy price were stated in the bills. Monthly energy consumption data on lighting and heating-cooling was collected for the period between June 2018 and December 2021. The data was obtained from the Uludağ Electricity Distribution Company (Uludağ Electricity Distribution Company, 2020). There are two energy meters in each mosque, one records the consumption for lighting and the other consumption for heating-cooling systems. Electricity was the only energy carrier for both lighting and heating-cooling systems. Consumption data was provided separately for lighting and heating and cooling. For some months, consumption data was not available because the meters could not be read due to curfews caused by the pandemic. To evaluate the effect of the pandemic on energy consumption, the annual data on electricity consumption were compared before (March 2019 to March 2020) and during (March 2020 to March 2021) the pandemic.

2.2. Methodology of thermal comfort and IAQ measurements

Parameters affecting thermal comfort and IAQ were measured before and during the pandemic in the medium-sized Hacı Hasan Sert Mosque (Table 2). The mosque had two Regal RAC 50 type air conditioners, each with a nominal cooling capacity of 13.25 kW, located on the inner surface of the wall facing the members of the congregation, and two fans with a diameter of 0.8 m positioned on the right and left outer wall at a height of 3 m from the floor. The study during the pandemic was conducted in June 2020. The new data recorded during the pandemic (Case 4) were compared with those reported by Yüksel et al., (2020) which conducted measurements for the Tarawih prayer in the same mosque in 2018 before the pandemic (Cases 1 to 3) to evaluate the effects of the pandemic on the quality of the indoor environment. Experiments before and during the pandemic were carried out in the same month (June) and at the same time (between 22^{00}-23^{30}), ensuring that the climatic conditions were similar. On the other hand, the fact that the Tarawih prayer could not be performed due to pandemic control measures caused measurements to be made in the night prayer instead of the Tarawih prayer. This caused occupancy to drop from 40% to 10% and reduced the duration of stay in the mosque by 35 min, compared to the case before the pandemic. In the new measurements, as before the pandemic, the congregation members began to enter the mosque within 10 min before the prayer time and quickly left (approximately within 5 min) after the prayer was completed. This behavior of congregation members was the same both before and during the pandemic. On the other hand, the use of air conditioners and fans was prohibited during the pandemic. Differences in use and occupancy were considered part of the effects of the pandemic on thermal comfort and IAQ. To minimize the difference in seasonal meteorological conditions, the new measurements were made in June, as in the reference study (Yüksel et al., 2020). The general thermal sensation of people was investigated using Fanger's PMV and PPD model (EN 7730-2005, 2005; Fanger, 1970). The parameters to calculate the PMV and PPD values were determined from the corresponding tables in the relevant standards (Al-Dabbous et al., 2013; Kamar et al., 2019). Taking into account the types of clothing that depended on the climatic conditions (short-sleeve shirts, pants) and moderate activity during worship (standing, praying), the metabolic rate, the clothing insulation, and the effective mechanical power were assumed to be 1.6 met, 0.57 clo, and 0 W/m^2, respectively, as in the reference study (Yüksel et al., 2020). Other parameters to calculate PMV and PPD values and examine thermal comfort, such as air temperature, relative humidity, and air velocity, were obtained experimentally.

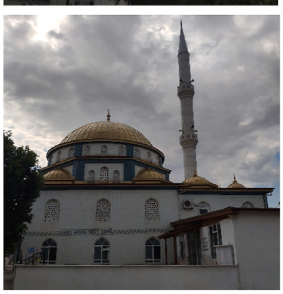
Indoor air velocity, air temperature, relative humidity, CO_2, $PM_{2.5}$, PM_{10} concentrations, and outdoor temperature and relative humidity were measured at 1-min intervals. TESTO-480 and PCE-MPC20 instruments were used to measure air velocity, CO_2 concentration, and PM concentrations. The TESTO-480 device measuring indoor air velocity and CO_2 concentration had an uncertainty of ± 0.03 m/s and ± 50 ppm. The PCE-MPC20 device used to monitor the concentration of $PM_{2.5}$ and PM_{10} had a resolution of 1 μg/m^3 resolution. Ten TESTO-174H devices recorded temperature and relative humidity (Fig. 2), one in the outdoor environment and nine in the indoor environment. Data loggers that collected indoor and outdoor air temperature and relative humidity data had an uncertainty of ± 0.5 °C and ± 3%.

3. Results and discussion

3.1. Effect of Covid-19 measures on energy consumption

In this section, energy consumption data between June 2018 and December 2021, obtained from the energy distribution company for the six mosques, were evaluated. It should be noted that the data before March 2020 represent the pre-pandemic period while the data after March 2020 represent the pandemic period since the first coronavirus case was seen in March 2020 and subsequently worshipping in mosques

Table 1
Information about the mosques studied.

	Name	Type of Mosque (Width × Length)	Mosque Capacity	Mosque Capacity during Pandemic	Abbreviation
	Yalova Merkez Mosque	Central Mosque (27 m × 21 m)	2100	700	YM
	Fatih Mosque	Large-Scale Neighborhood Mosque (21 m × 17 m)	1350	450	FM
	Hacı Hasan Sert Mosque	Medium Sized Neighborhood Mosque (12 m × 11 m)	465	155	HM
	Rüstempaşa Mosque	Small Scale Neighborhood Mosque (8 m × 6 m)	60	20	RM
	Güneyköy Mosque	Historical Mosque (11 m × 9 m)	120	40	GM

(continued on next page)

Table 1 (*continued*)

	Name	Type of Mosque (Width × Length)	Mosque Capacity	Mosque Capacity during Pandemic	Abbreviation
	Safran Köyü Mosque	Village Mosque (18 m × 15 m)	600	200	SM

Table 2
Cases studied before and during the pandemic.

	Cases	Occupancy	Windows	Fans	Air-Conditioners	Date
Before Pandemic	Case 1a	40% (22^{15}-23^{15})	Open (22^{15}-23^{15})	Turned on (22^{30}-23^{15})	Turned off	June 11, 2018
	Case 1b	100% (22^{15}-23^{15})	Open (22^{15}-23^{15})	Turned on (22^{30}-23^{15})	Turned off	June 10, 2018
	Case 2	40% (22^{15}-23^{15})	Closed	Turned off	Turned on (22^{15}–22^{45})	June 13, 2018
	Case 3	40% (22^{15}-23^{15})	Closed	Turned on	Turned on (22^{30}–23^{15})	June 09, 2018
During Pandemic	Case 4	10% (22^{35}-23^{00})	Open (22^{35}-23^{00})	Turned off	Turned off	June 22, 2021

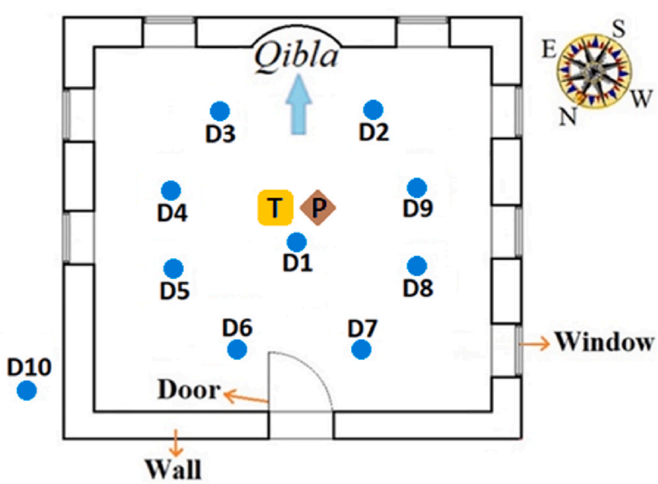


Fig. 2. Location of devices in the reference study and the present study ("T" – Testo-480, "P" – PCE-MPC20, "D1-9" – indoor data loggers, "D10" – outdoor data logger).

was suspended. The amount of energy consumed was examined separately for lighting and heating-cooling. The data on energy consumption during pandemic were recorded from March 2020 to March 2021, when control measures were in force. In the graphics, the mosques were indicated using the abbreviations defined in Table 1.

3.1.1. *Energy consumption for lighting*

The amount of energy consumption for lighting between 2018 and 2021 is shown in Fig. 3 for the Yalova Merkez Mosque together with the other mosques. It is seen that a higher amount of energy was consumed in the Yalova Merkez Mosque in the summer months of 2019 (the year before the pandemic) compared to other months. Energy consumption in April, May, and June 2020 (the first months of the pandemic period in which the measures vary) was 975, 817 and 617 kWh, respectively, while they were 6480, 2767 and 5687 kWh in 2019. This was substantially less than in the same months in previous years due to the suspended use of mosques after March 2020. However, in year 2021, with the loosening of the pandemic measures, an increase of 239, 105, and 256 kWh in energy consumption was observed compared to year 2020, was observed in April, May, and June, respectively. The average energy consumption data of the Yalova Merkez Mosque for the years 2019, 2020 and 2021 were 4997, 1406 and 1538 kWh, respectively.

The energy consumption of Fatih Mosque, which is a large neighborhood mosque, was minimal in May 2021 (125 kWh, during the pandemic) and maximal in April 2020 (583 kWh, during the pandemic). Energy consumption at the Fatih Mosque increased in the first months of the pandemic compared to previous years (2018, 2019). It was 583 and 312 kWh in April and May 2020, respectively, when the pandemic process was effective, while it was 214 and 296 kWh in the same months of 2019. This means that more energy was consumed, although the mosque was used less in the first months of the pandemic. Less energy was consumed between June and November 2020 (during the pandemic) compared to the previous year. The high consumption in the first two months of the pandemic was attributed to the lighting operation of the staff and congregation members. The lighting system was regularly turned off by members of the Fatih Mosque congregation due to the active use of the mosque before the pandemic. It is assumed that the lighting system was left on for long periods during the pandemic when the mosque was not actively used. Turning off lights in the evening when the mosque is not in use and providing local lighting instead of illuminating the entire volume, except for prayer times, should be considered as an energy-efficient lighting strategy.

In the Hacı Hasan Sert Mosque, which is a medium-sized neighborhood mosque, the minimum energy consumption for lighting was 41 kWh in September 2021, and the maximum was 264 kWh in March 2021 (during the pandemic). Consumption data between April and June 2020 could not be obtained because the distribution company did not record it. However, the energy consumption for lighting was 138 kWh in March 2020, when the pandemic started, whereas it was 171 kWh in the same month of 2019 before the pandemic. This showed that energy consumption in the mosque decreased, as expected. In the Rüstempaşa Mosque, consumption data in the first year of the pandemic period could not be obtained because it was not recorded. Therefore, comparisons

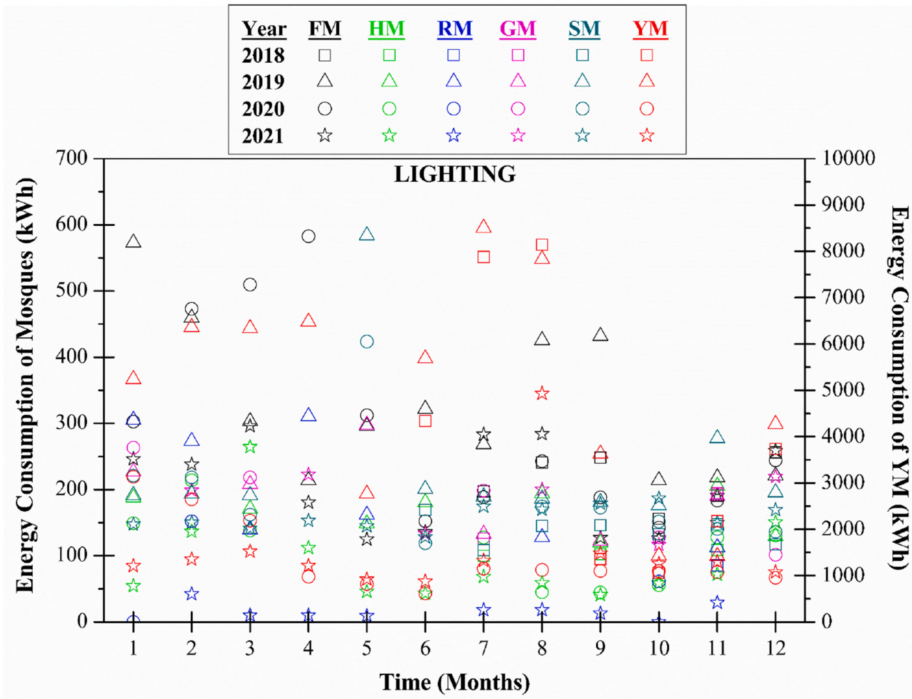


Fig. 3. Energy consumption for lighting in the Yalova Merkez Mosque and other mosques.

were made between 2019 and 2021. The energy consumption for the year 2021, when the pandemic was in force, decreased compared to 2019.

In the Güneyköy Mosque, which represents historical mosques, the distribution company did not check the energy consumption monthly, since its use was suspended due to restoration. Similar to the Rüstempaşa Mosque, worship was suspended except for Friday prayers. The available data indicated an energy consumption of 126, 133 and 199 kWh in July 2018, 2019 and 2020, respectively, for this mosque. The increase despite the pandemic was caused by the fact that the electricity distribution company used the average of the data recorded before the pandemic to predict consumption during the pandemic.

For the Safran Köyü mosque, which is a village mosque, the minimum and maximum energy consumption was obtained in July 2018 (108 kWh) and May 2019 (584 kWh), respectively. Taking into account the effect of the pandemic, energy consumption was 30 and 161 kWh lower in March and May 2020 (the first months of the pandemic), respectively, compared to the same months of 2019 (before the pandemic). Furthermore, in 2021, energy consumption was lower than in 2019 in all months except for April and October.

To compare the energy consumption for lighting before and during the pandemic, the total annual energy consumption of the mosques is summarized in Table 3. According to the research conducted by Atmaca and Gedik (2019) in a large traditional mosque (1015 m^2 floor area) with a capacity of 1256 people before the pandemic, the energy consumption from lighting was 46 kWh/m^2 in 2017. When this result was compared to other mosques, it was found to be higher than other mosques except Yalova Merkez Mosque. Annual electricity consumption was 51 kWh/m^2 higher than the reference study (Atmaca and Gedik, 2019), as the lighting systems in the Yalova Merkez Mosque were operated continuously.

The energy consumption for lighting decreased in all mosques compared to the pre-pandemic values due to the reduced usage of the mosques, especially in evenings when lighting was needed. The energy consumption for lighting may be further reduced by using motion sensors and energy-saving lighting systems in all mosques, especially in the Yalova Central Mosque.

Table 3
Total annual electricity consumption of mosques for lighting before and during pandemic.

Mosques (Floor Area)	Consumption for Lighting Systems			
	Before Pandemic (From March 2019 to March 2020)		During Pandemic (From March 2020 to March 2021)	
	kWh	kWh/m^2	kWh	kWh/m^2
Marmara Theology Mosque[a] (Atmaca and Gedik, 2019) (1005m^2)	46082.6	45.9	–	–
Yalova Merkez Mosque (YM) (567m^2)	54139.6	96.5	13648.9	24.1
Fatih Mosque (FM) (357m^2)	3690	10.3	3230.8	9.1
Hacı Hasan Sert Mosque (HM) (132m^2)	1512.7	11.5	859.6	6.5
Rüstempaşa Mosque (RM) (48m^2)	1004.6	20.9	103.5	2.2
Güneyköy Mosque (GM) (99m^2)	1215	12.3	844.3	8.5
Safran Köyü Mosque (SM) (270m^2)	2621.6	9.7	1777.5	6.6

[a] The results of the reference study (Atmaca and Gedik, 2019) refer to the year 2017.

3.1.2. *Energy consumption for heating and cooling*

The energy consumption for heating-cooling is shown in Fig. 4 for the Yalova Merkez Mosque and the other mosques. Comparison of the monthly data given in Fig. 4 was not possible due to the lack of data in some mosques. Therefore, the effects of the pandemic on electricity consumption for heating-cooling in various types of mosques were evaluated by examining the annual total consumption data before and during the pandemic given in Table 4.

The maximum and minimum energy consumption for heating-cooling for the Yalova Merkez Mosque were registered in January 2020 (before pandemic and the control measures), and May 2021 (during pandemic). While energy consumption in the mosque generally

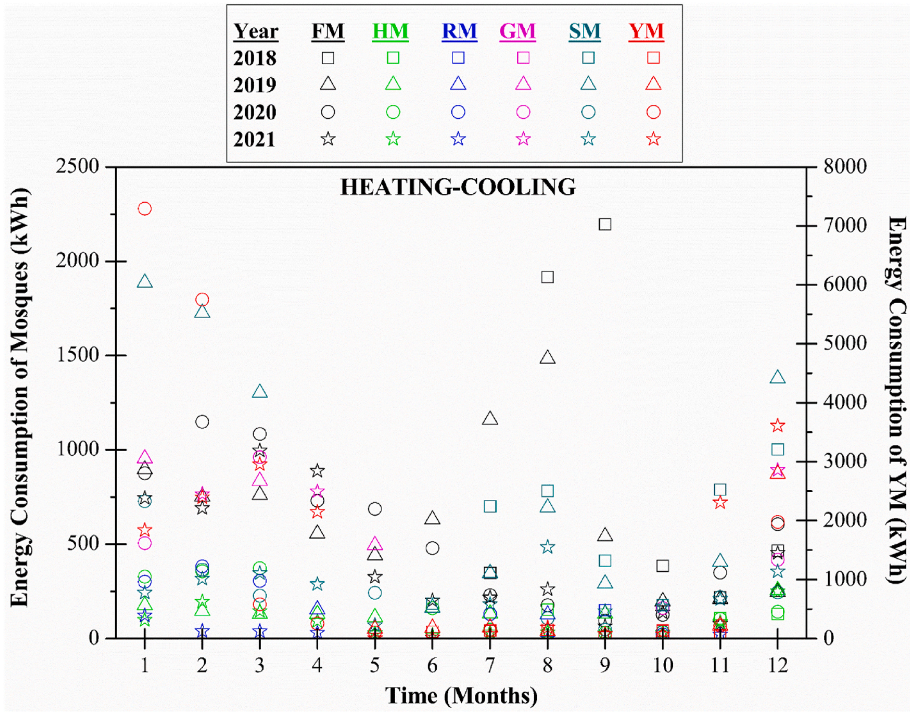


Fig. 4. The amount of energy consumption caused by heating-cooling systems in the Yalova Merkez Mosque and other mosques.

Table 4
Total annual electricity consumptions for heating-cooling in mosques.

Mosques (Floor Area)	Consumption for Heating-Cooling Systems			
	Before Pandemic (From March 2019 to March 2020)		During Pandemic (From March 2020 to March 2021)	
	kWh	kWh/ m^2	kWh	kWh/ m^2
Marmara Theology Mosque[a] (Atmaca and Gedik, 2019) (1005m^2)	47737.2	47.5	–	–
Yalova Merkez Mosque (YM) (567m^2)	16719.6	29.5	10970.8	19.4
Fatih Mosque (FM) (357m^2)	8252.2	23.1	6000.1	16.8
Hacı Hasan Sert Mosque (HM) (132m^2)	1581.6	12	1216.8	9.2
Rüstempaşa Mosque (RM) (48m^2)	966.5	20.1	621.2	12.9
Güneyköy Mosque (GM) (99m^2)	1835.7	18.5	2305.7	23.2
Safran Köyü Mosque (SM) (270m^2)	5674	21	1685.4	6.2

[a] The results of the reference study (Atmaca and Gedik, 2019) belong to the year 2017.

decreased due to the effect of the pandemic, consumption was almost the same (1 kWh difference) in November 2019 and 2020. Furthermore, considering the data for 2021, the energy consumption was lower than before the pandemic, except for August, November, and December.

The energy consumption for heating-cooling in March, April, May, November, and December 2020 (during pandemic) was higher than in 2019 (before pandemic) in the Fatih Mosque. Electricity consumption in 2021 was lower than in 2019 in all months except March (234 kWh difference), April (332 difference), and December (206 kWh difference). In addition to these months of 2021, higher energy consumption was observed in 2020 in February, May, and November compared to 2019. The lowest and highest energy consumption in the mosque was determined in September 2021 and 2018 (66 and 2196 kWh).

On the other hand, the Safran Köyü Mosque had lower energy consumption during the pandemic (2020) than before the pandemic (2019). In this village mosque, 227 kWh of energy was consumed in March 2020, when the first case was seen, and 1302 kWh of energy was consumed in March 2019. The energy consumption in the same month in 2021 was 346 kWh. The largest difference between monthly data during and before the pandemic occurred between January 2019 and 2021 (1644 kWh).

For Hacı Hasan Sert Mosque, the data on energy consumption from heating-cooling before and during the pandemic were limited. Energy consumption during the pandemic decreased by 85 kWh (July), 101 kWh (September) and 115 kWh (December) in 2020 compared to 2019. In 2021, a decrease occurred in January (78 kWh), April (38 kWh), July (100 kWh) September (104 kWh), and December (7 kWh) compared to the pre-pandemic period. However, energy consumption in February and March 2021 increased by 48 and 15 kWh, respectively.

Monthly evaluations for the Güneyköy Mosque could not be made, except for March, since the electricity distribution company did not make billing pay bills and the use of the mosque was suspended in some months. Similarly, due to the lack of data for the Rüstempaşa Mosque, comparisons could only be made between April and August 2019 and 2021. In March, the first month of the pandemic, the energy consumption from heating for the Güneyköy Mosque increased by 126 kWh, compared to the pre-pandemic period. In April and August 2019 and 2021, the reduction in energy consumption for the Rüstempaşa Mosque during the epidemic was 123 kWh (April) and 127 kW (August). A more detailed examination of these mosques was conducted in Table 4.

The Safran Köyü Mosque was one of the mosques in which monthly consumption in 2020 and 2021 was less than before the pandemic. Energy consumption decreased by 586, 243, 186, and 1133 kWh in August, September, November, and December 2020 compared to the previous year. For the same months of 2021, reductions of 210, 147, 197, and 1023 kWh were observed, respectively.

However, the increase in energy consumption for heating-cooling during the pandemic in some mosques for a few months implied that air conditioning systems were used in these mosques despite the prohibition of their use. In these mosques, the congregation untimely turned on the air conditioning systems while worship was continuing. Additionally, in the first months of the pandemic (Table 4), the energy distribution company predicted the billing according to the average of previous years. For this reason, energy consumption was recorded even in mosques where almost no consumption was made. Although the authors requested details of the billing policy of the energy distribution company, it was not shared due to confidentiality of information. Therefore, it could not be clearly determined which parameter caused the increase in energy consumption in which mosques. However, in general, it was estimated that the increase in energy consumption in mosques during the pandemic was caused by the use of air conditioning systems or incorrect billing by the energy distribution company.

The total energy consumption of the Marmara Theology Mosque, Istanbul (Turkey), with a floor area of 1005 m^2, was reported to be 47.5 kWh/m^2 in 2017 before the pandemic (Table 4) (Atmaca and Gedik, 2019). Energy consumption in the reference study (Atmaca and Gedik, 2019) was higher than that of the mosques considered in this study. This suggests that the energy consumption in mosques was reasonable; however, the consumption could be reduced with the help of insulation applications as the mosques were not insulated. During the pandemic, the heating-cooling systems in the Güneyköy Mosque, whose energy consumption increased compared to before the pandemic, were adjusted by the mosque staff according to the outdoor air temperature. Managing the HVAC systems with an automation system integrated with outdoor temperature, changes in the number of congregations, and prayer times in this mosque, as well as other mosques, can help reduce energy consumption.

3.2. Effect of Covid-19 measures on thermal comfort and IAQ in mosques

Indoor air temperature, relative humidity, air velocity and CO_2 concentration data were measured during the pandemic and compared with the data reported by Yüksel et al., (2020) to evaluate the effect of pandemic measures on thermal comfort and IAQ. Furthermore, $PM_{2.5}$ and PM_{10} concentrations in the mosque were monitored during the pandemic and compared with several standards on IAQ.

3.2.1. Air temperature

Fig. 5 shows the outdoor and indoor air temperatures before and during the pandemic. The fluctuation between the maximum and minimum outdoor air temperature was 4.7, 1.6, 4.5, and 3.9 °C in Case 1a, Case 1b, Case 2 and Case 3 (before the pandemic), respectively. The difference recorded was only 1.1 °C in the measurement carried out during the pandemic (Case 4). Similarly, the difference between the maximum and minimum indoor air temperature was 0.4, 1.2, 1.3, 0.7 before the pandemic (Case 1a, Case 1b, Case 2, and Case 3) while it was 0.3 °C during the pandemic (Case 4). This was partially caused by a lower prayer duration in Case 4.

In cases with open windows (Case 1a, Case 1b, and Case 4), the minimum indoor air temperatures were 26.2, 26.3, and 24.2 °C, while the maximum temperatures were 26.6, 27.6, and 24.6 °C, respectively. This shows that during the pandemic (Case 4), the indoor air temperature did not change significantly during worship. This contrasts with Cases 2 and 3 before the pandemic when the indoor air temperature dropped despite the higher occupancy (40%) due to the air conditioning and the small influence of outdoor climatic conditions (windows closed). The reasons for the low temperature difference in Case 4 were reduced occupancy (only 10%, i.e., low heat gains), low variation in the outdoor air temperature, and turning off the air conditioners. These findings imply that the effects of the pandemic measures were a reduction in internal temperature fluctuation (low occupancy and air conditioning turned off) and a greater dependence on outdoor climatic conditions (windows open).

3.2.2. Relative humidity

Fig. 6 shows the relative humidity data measured simultaneously with the outdoor and indoor air temperatures (Fig. 5). The highest outdoor (82%) and indoor (67%) relative humidity was observed in Case 4 (during the pandemic). The humidity production of the people was small due to low occupancy (10%). Furthermore, the ratios of average indoor and outdoor relative humidity for Case 1a, Case 1b, and Case 4 with open windows were 0.86, 0.88, and 0.84, respectively. These data show that outdoor air humidity was the main factor that affected the indoor air humidity in cases when the windows were open. Reducing the

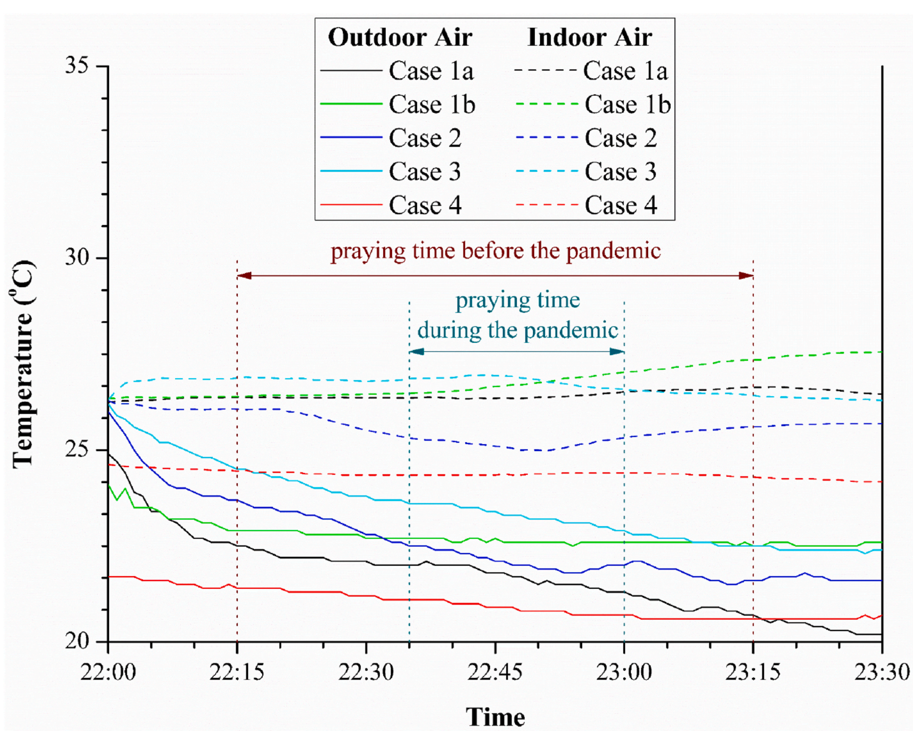


Fig. 5. Outdoor and indoor air temperatures before (Cases 1–3) (Yüksel et al., 2020) and during the pandemic (Case 4).

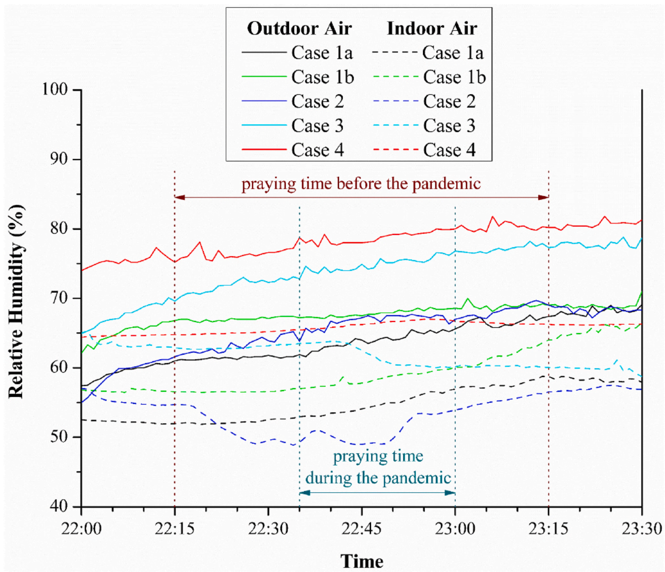


Fig. 6. Outdoor and indoor relative humidity before (Cases 1–3) (Yüksel et al., 2020) and during the pandemic (Case 4).

number of congregation members affected indoor air humidity to a lesser extent.

3.2.3. Air velocity

Fig. 7 shows the air velocity measured before and during the pandemic. The highest air velocity (2.2 m/s) was obtained in Case 1a, with the windows open and the fans on. The average air velocity was 0.11, 0.25, 0.17 and 0.31 m/s in Cases 1a, 1b, 2 and 3 (before the pandemic), respectively. In Case 4, the average was around 0.1 m/s, considerably less than in all other cases except for Case 1b. This decrease is attributed to the combined effect of turning off fans and air conditioners and reducing the number of people in the mosque. The maximum air velocity in Case 4 was 0.4 m/s, probably caused by a momentary movement of the occupants close to the sensor. These data indicate that pandemic measures (turning off fans and air conditioners, reducing occupancy) led to less air movement. This may result in a lower rate of transmission of the coronavirus, a lower risk of draught, and a warmer overall thermal sensation.

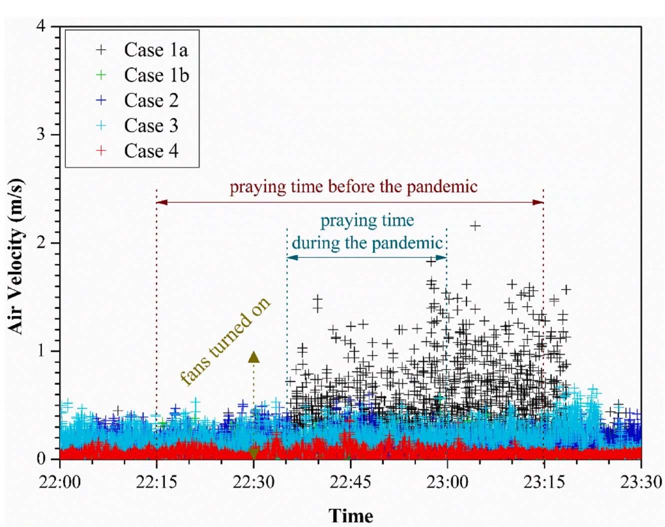


Fig. 7. Indoor air velocity before (Cases 1–3) (Yüksel et al., 2020) and during the pandemic (Case 4).

3.2.4. PMV and PPD indices

The maximum, minimum and average thermal comfort data obtained at the time of worship before (Yüksel et al., 2020) and during the coronavirus pandemic are given in Table 5. Before the pandemic, the best thermal conditions were achieved in Case 2 with the air conditioning on and the windows closed. PMV and PPD were 0.63 and 13%, respectively. The highest PMV and PPD values (1.3 and 40%) were found in Case 1a with air conditioners off, fans on, and windows open. In both cases, occupancy was 40% and outdoor air temperature was similar. This shows the important effect of air conditioning on thermal comfort in the mosque. During the pandemic period (Case 4), the PMV and PPD values were 0.82 and 19%, respectively, indicating acceptable, but not excellent thermal conditions. This was caused by the relatively high room temperature and relative humidity while having a low air velocity. The air conditioning was turned off. The room temperature was high despite the open windows and low occupancy (i.e. low heat gains). This shows that (1) acceptable thermal conditions can be achieved during the pandemic even with air conditioning off providing those prayers are performed during night hours, (2) excellent thermal conditions can be difficult to achieve without air conditioning, even when the windows are open, and prayers are performed during nights. These findings refer to the conditions of the summer period.

3.2.5. CO_2 concentration

CO_2 concentration is a good indicator of adequacy of the indoor ventilation rate in spaces where occupants and their activities are the main sources of pollution. It is generally recommended to keep the concentration below 1000 ppm to prevent irritation due to bio effluents (Ascione et al., 2021; Daisey et al., 2003). CO_2 concentration data recorded during the pandemic (Case 4) were compared with the findings presented in Ref (Yüksel et al., 2020). that was used as a reference (Fig. 8). The reference study (Yüksel et al., 2020) demonstrated that CO_2 concentration can reach significant levels during prayer in mosques. In

Table 5
Thermal comfort parameters in Hacı Hasan Sert Mosque before (Yüksel et al., 2020) and during the pandemic.

		Before Pandemic (2019) (Yüksel et al., 2020)				During Pandemic (2020)
Cases (Occupancy, %)		Case 1a (40%)	Case 1b (100%)	Case 2 (40%)	Case 3 (40%)	Case 4 (10%)
Outdoor Air Temperature (°C)	Max	24.9	24.1	26	26.2	21.7
	Min	20.2	22.5	21.5	22.3	20.6
	Avg.	22.6 ± 0.8	21.9 ± 1.5	22.2 ± 1.5	23.3 ± 0.7	20.9 ± 0.4
Indoor Air Temperature (°C)	Max	26.64	27.56	26.28	26.96	24.63
	Min	26.24	26.34	24.98	26.29	24.18
	Avg.	26.7 ± 0.3	26.4 ± 0.1	25.3 ± 0.2	26.7 ± 0.2	24.4 ± 0.1
MRT (°C)	Avg.	28.3 ± 0.5	26.6 ± 0.3	24.4 ± 0.8	25.3 ± 0.3	25.6 ± 0.9
Outdoor Air Relative Humidity (%)	Max	69.1	71	69.7	78.8	81.8
	Min	57.4	62.1	55	64.9	74
	Avg.	68.1 ± 2	64.0 ± 5	66.3 ± 4	74.7 ± 3	78.3 ± 2
Indoor Air Relative Humidity (%)	Max	58.8	66.5	57.5	65.3	67
	Min	51.8	56.4	48.9	58.7	64.4
	Avg.	58 ± 2	55 ± 2	52 ± 3	61 ± 1	66 ± 1
Air Velocity (m/s)	Max	2.2	0.6	0.6	0.7	0.4
	Min	0	0	0	0	0
	Avg.	0.11 ± 0.06	0.25 ± 0.29	0.17 ± 0.08	0.31 ± 0.24	0.1 ± 0.03
PMV[a] **(–)**	Avg.	1.3	0.9	0.63	0.85	0.82
PPD[a] **(%)**	Avg.	40	23	13	20	19

[a] PMV and PPD were obtained from the mean data. The evaluation intervals were 22^{35}-23^{00} for Case 4 and 22^{30}-23^{15} for other cases.

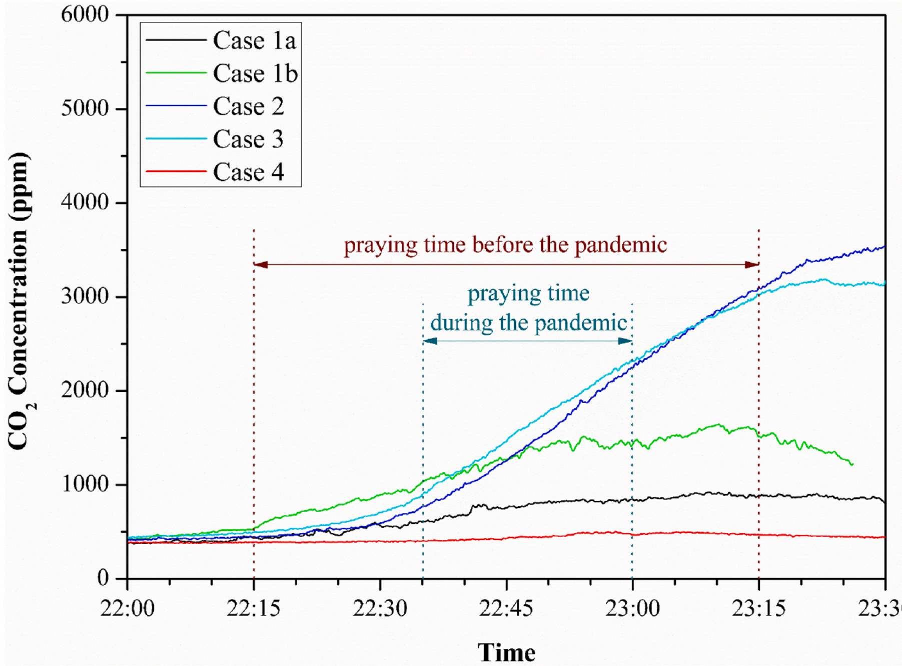


Fig. 8. Indoor CO_2 concentration before (Cases 1–3) (Yüksel et al., 2020) and during the pandemic (Case 4).

Case 2, where the occupancy rate was 40% and the worship time was 1 h, the CO_2 concentration gradually increased from the initial 410 ppm at the start of the prayer to 3541 ppm at the end of the prayer. The same trend was observed in Case 3 under the same conditions as in Case 2, but the windows closed. In Case 1a (40%), the increase in CO_2 concentration was less dramatic compared to Cases 2 and 3, although the occupancy was the same. The difference was related to natural ventilation through opening windows. The average CO_2 concentration in Case 4 (during the pandemic) with open windows and 10% occupancy was 428 ± 40 ppm compared to the 661 ± 201 ppm in Case 1a with open windows but a higher occupancy of 40% (Table 6). The maximum CO_2 concentrations were 922 and 504 ppm in Case 1a and Case 4, respectively. Compared to Cases 1 to 3, Case 4 had a shorter worship time by ~25 min. Since human respiration was the primary source of CO_2 in the indoor environment (Algarni et al., 2021), occupancy, natural ventilation, and a two-fold reduction in the worship time compared to the period before the pandemic directly affected the CO_2 levels in the mosque. This illustrates the positive effect of pandemic measures on IAQ. Keeping the windows open all the time and limiting occupancy during the pandemic reduced the deterioration of the IAQ. Therefore, these pandemic measures are likely to limit exposure to coronavirus as well as other pathogens.

3.2.6. Particulate matter $PM_{2.5}$ and PM_{10}

One of the factors that affects IAQ and human health is the amount of particulate matter in the indoor air. The concentration of particulate matter in inhaled air has gained more importance during the pandemic. Depending on the use of masks, the pollutants in inhaled air are attached to the masks and therefore increase in pollutants causes an increase in death rates caused by Covid-19. According to (Saravanan et al., 2020) and (Le et al., 2020), the concentration of pollutants in the outdoor environment decreased due to the decrease in traffic density during the pandemic. This points to the possibility that the increase in indoor pollutant concentrations will decrease as a result of the use of windows. Wu et al. (2020) reported that an increase of 1 μg/m^3 in $PM_{2.5}$ concentration caused a 15% increase in deaths from SARS-CoV-2. For this reason, the results for Case 4 are presented and discussed here because it may be useful to examine particle concentrations as one of the important IAQ parameters during the pandemic. Data on particulate matter (PM) are only available for Case 4 (during the pandemic) as no measurements were performed before the pandemic.

Fig. 9 shows the concentration of PM in the indoor environment during worship in Case 4. The mean concentrations of $PM_{2.5}$ and PM_{10} in the mosque were measured 26.4 and 74.9 μm/m^3. During the same observation period (22^{00}-23^{30}), the mean outdoor PM concentrations retrieved from the Yalova Air Quality Monitoring Station (40° 39′ 44″ N, 29° 17’ 47” E) were 13 and 69 μm/m^3 for $PM_{2.5}$ and PM_{10} (Republic of Turkey, 2021). That is, the indoor fine particulate matter ($PM_{2.5}$) was higher than those in the outdoor, while the coarse particulate matter (PM_{10}) was in a comparable level. The maximum concentrations of $PM_{2.5}$ and PM_{10} in the mosque measured reached 55 and 125 μm/m^3, and the minimum concentrations recorded were 18 and 48 μm/m^3 (23^{00}-23^{15}), respectively. While there were no significant differences in $PM_{2.5}$ concentrations at the start and end of the prayer, PM_{10} concentrations slightly increased at the end. The reason for the slightly elevated concentration of PM_{10} could be the resuspension of the dust particles that were deposited on the carpets into the air by the congregation members walking or praying. Since fine particles diffuse through the inner part of the carpet, it could not be resuspended as much as coarse particles.

Table 6
CO_2 concentration in Hacı Hasan Sert Mosque before (Yüksel et al., 2020) and during the pandemic.

		Before Pandemic (2019) (Yüksel et al., 2020)				During Pandemic (2020)
Cases (Occupancy, %)		Case 1a (40%)	Case 1b (100%)	Case 2 (40%)	Case 3 (40%)	Case 4 (10%)
CO_2 Concentration (ppm)	Max	922	1644	3541	3190	504
	Min	362	392	410	432	375
	Avg.	661 ± 201	1041 ± 427	1519 ± 1127	1547 ± 1044	428 ± 40

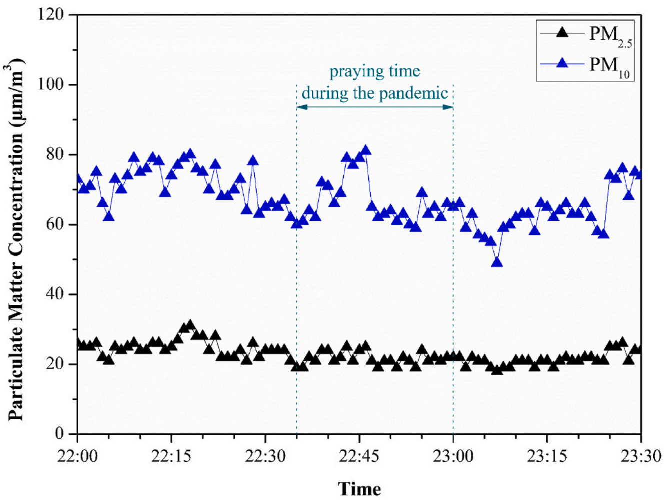


Fig. 9. Indoor $PM_{2.5}$ and PM_{10} concentration during pandemic (Case 4).

The 24 h avg limit concentrations of $PM_{2.5}$ and PM_{10} declared by the World Health Organization (WHO) are 25 µm/m^3 and 50 µm/m^3 (WHO, 2000) while Health Canada (Health Canada, 1989) and the State of Washington recommend a short-term concentration (1 h) of $PM_{2.5}$ below 100 µm/m^3 (Federal–Provincial Advisory Committee, 1989; Le, 2020; Wu et al., 2020). Furthermore, the National Health and Medical Research Council (NHMRC) (NHMRC, 1996) and the National Occupational Health and Safety Commission (NOHSC) (NOHSC, 1995) have a 1-h average guideline value of 90 µm/m^3 for PM_{10}. Since there are no IAQ standards or guidelines available yet for worship building, it can be compared with all relevant IAQ standards. In this study, the average measured concentrations (90 min) of $PM_{2.5}$ and PM_{10} were 26.4 and 74.9 µm/m^3, exceeding the daily limit concentrations recommended by the WHO. This indicates that if the congregation stays in the mosque throughout the day under the conditions that occur at the time of prayer, they will be exposed to high levels of pollutants. However, the presence of the congregation in the mosque for about half an hour and five times on ordinary days ensures that the exposure to the pollutants should be relatively low. On the other hand, the average values were lower than the 1-h average guideline values of Health Canada, State of Washington. NHMRC and NOHSC. Because the presence of droplets from the people's mouths is one of the sources of PM indoors, wearing protective masks is one of the factors that affect the PM concentration. According to (Mimura et al., 2021), $PM_{2.5}$ concentrations increase by ~7% and 30% of initial values when people speak with a mask and without a mask, respectively. Similar to $PM_{2.5}$ concentrations, PM_{10} levels increase by ~6% and 28%. These results indicate that PM concentrations decrease dramatically when masks are worn. In addition to the effect of the mask, it is likely that reducing occupancy and cleaning the floor more frequently caused a reduction in PM levels during the pandemic.

No significant correlation was found between the measured CO_2 and PM concentrations ($r = 0.62$, $p < 0.05$ for $PM_{2.5}$ and $r = 0.62$ $p < 0.05$ for PM_{10}). This indicates that CO_2 and PM originated partially from different sources. Although occupants were the main source of CO_2 indoors, Fig. 9 shows that occupancy was not the main reason for the variation in PM levels. On the other hand, the correlation between $PM_{2.5}$ and PM_{10} was strong ($r = 0.85$), indicating that most of PM could be emitted by the same sources. Changes in PM concentrations outside prayer times suggest that dust particles in the indoor environment could be affected by air movement due to open windows. Studies conducted by Gupta and David Cheong (2007), Goyal and Kumar (2013), Li et al. (2017), Sahu and Gurjar (2021) and Riley et al. (2002) in different microenvironments found that the indoor to outdoor PM ratios were higher in naturally ventilated rooms than in mechanically ventilated rooms. This evidenced the impact of outdoor air intake on indoor PM concentrations in naturally ventilated indoors and consequently on IAQ.

4. Conclusion

The effect of pandemic measures such as restriction of access to mosques, reduced occupancy, opening windows, and restricted use of mechanical ventilation and air conditioning on energy consumption, thermal comfort, and IAQ was studied. Energy consumption for lighting and heating-cooling was analyzed for six representative mosques. Thermal comfort and IAQ parameters such as air temperature, relative humidity, air velocity and CO_2, $PM_{2.5}$ and PM_{10} concentrations were recorded in a typical mosque. The findings are relevant for mosques located in similar climatic regions and having similar physical characteristics. The main conclusions that can be drawn are as follows:

- Annual electricity consumption for lighting decreased in all mosques during the pandemic compared to the pre-pandemic period. However, monthly consumption increased in some months in all mosques except for Yalova Merkez and Rüstempaşa Mosques. This was explained by leaving the lighting system on for long periods when the mosque was not actively used. Turning off the lights when the mosque is not in use and using local lighting systems with motion sensors, except for prayer times, should be considered.
- Annual electricity consumption for heating and cooling decreased in all mosques except for the Güneyköy Mosque during the pandemic. However, the monthly consumption increased in some months in all mosques except for Safran Köyü and Rüstempaşa Mosques. This was partially attributed to the billing methodology based on the averages of previous years, and to the use of air conditioning or fans during prayers despite prohibition. The use of solar assisted heat pumps could help reduce the need for electricity from public grid.
- The indoor air temperature varied only slightly during prayer as a result of pandemic measures. Therefore, the effects of pandemic measures were a reduction in variation of the indoor air temperature due to low occupancy (10%) and the air conditioning turned off, and greater dependence on climatic conditions due to the opening of the windows.
- Acceptable thermal environment was attained under pandemic measures in the summer period. This conclusion refers to prayers performed at night without solar radiation and outdoor air below room temperature. Excellent thermal conditions can be difficult to achieve without air conditioning even with open windows and prayers performed at night.
- Pandemic measures, such as turning off fans and air conditioners and reducing occupancy, led to less air movement in the center of the mosque. This may result in a lower rate of transmission of the coronavirus, a lower risk of draught, but also a warmer overall thermal sensation, which may not be desirable under summer conditions.
- Keeping the windows open all the time and limiting occupancy during the pandemic improved IAQ as expressed by CO_2 concentration. The average concentrations (90 min) of $PM_{2.5}$ and PM_{10} measured during the pandemic were 26.4 and 74.9 µm/m^3. This exceeded the daily limits recommended by the WHO, (2000) but was lower than the 1-h average guideline values of Health Canada, the State of Washington, NHMRC, (1996), and NOHSC, (1995).
- Future investigations should focus on the effects of pandemic measures in all seasons through annual assessments of temples of various sizes and be aided by numerical simulations to directly determine the impact of various pandemic measures. Moreover, future studies should be directed towards passive measures such as reducing heat losses and leaks and equipment assisted with renewable and clean energy sources such as solar energy. Studies should consider the implementation of smart automation systems to minimize the energy need for lighting and HVAC system.

CRediT authorship contribution statement

Ahmet Yüksel: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Müslüm Arıcı:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Michal Krajčík:** Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Mihriban Civan:** Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Hasan Karabay:** Methodology, Formal analysis, Writing – review & editing, Supervision.

Declaration of competing interest

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

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