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THERMAL COMFORT AND VENTILATION CONDITIONS IN HEALTHCARE FACILITIES - PART 1: AN ASSESSMENT OF INDOOR ENVIRONMENTAL QUALITY (IEQ)

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Abstract

Healthcare facilities provide a cure from the ailment while maintaining a clean environment. A high indoor environmental quality (IEQ) can improve the recovery process and create a pleasant working environment, while a poor IEQ causes nosocomial diseases that are harmful to the patients as well as the hospital staff. To assess the state of IEQ in selected local hospitals, the current study investigates critical IEQ parameters. Based on a detailed literature synthesis, three parameters are selected (temperature, relative humidity, and CO_2) for IEQ assessment in four local hospitals. Four different locations (emergency room, OT, ICU, and medical ward) in each hospital are considered with respect to the existing heating, ventilation, and air conditioning (HVAC) system. Data is recorded on a 5-min interval for 6 days uninterrupted and the mean hourly value for each location is calculated for 24 hours. Statistical analysis is performed to compare the day- and night-time IEQ trends. A significant difference is found in the day- and night-time observations for OTs, while random trends are noticed in emergency areas. The results show that occupancy rate, ambient thermal conditions, type of HVAC system, and building orientation are vital drivers of IEQ. In conclusion, design and retrofitting recommendations are provided.

Keywords: CO_2 concentration, healthcare facilities, HVAC system, indoor environmental quality, thermal comfort

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1. Introduction

Healthcare facilities must ensure better quality medical treatment and nursing care to the patients (Leung and Chan, 2006). To achieve these and other wellness standards, the accurate design of a healthcare facility is imperative (King et al., 2015). The design accuracy demands to ensure effective ventilation, air-conditioning, and air supply since they are at the core of the wellness standards of a healthcare facility (Yu et al., 2009). Their noncompliance results in an unhealthy, stale and poor ambiance which can cause indoor environmental pollution and result into exposure to hospital-associated infections (HAIs) (Baqi et al., 2009; Beggs et al., 2015; CDPH Report, 2016; Ishtiaq et al., 2017; Mohammadpour et al.,

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2017). A major factor in controlling the HAIs is the provision of good indoor environmental quality (IEQ) that can help in preventing hazardous viruses and bacteria to propel through air. Contrary to that, bad IEQ can cause sick building syndrome, fatigue, nausea, eye and skin irritation, and many other symptoms of discomfort (Leung and Chan, 2006; Mohammadpour et al., 2017). As the occupants and nature of services are different in hospitals, its environment also varies from a normal commercial or industrial building, demanding special architectural and mechanical design considerations. Therefore, the design guidelines for healthcare facilities by the World Health Organization (WHO) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) are very particular about physical and functional features of these buildings (ASHRAE Standard, 2007; WHO, 2016). Compliance with these guidelines can help achieve the standard levels of IEQ. In doing so, ASHRAE supports mechanical interventions such as ventilation for circulation of air which enhances the IEQ (ASHRAE Standard, 2007; Chen et al., 1992).

Adequate ventilation rate is an indication of a healthy air-conditioning system in any building. In summers, ventilation is considered to be a low-cost remedy, used since ages, for air-conditioning when the outdoor comfort conditions are better than the indoor conditions. Due to this, the variation in indoor temperature and relative humidity through occupancy rates remains minimal (Blondeau et al., 2002). Certainly, a ventilation system plays a significant role in controlling the comfort conditions, not only in summers but also in winters. The synergy of the heating and ventilation systems is responsible for maintaining thermal comfort, failing which can cause significant occupant discomfort (Mumovic et al., 2009).

Various factors affect the IEQ such as temperature, moisture, precipitation, amount of chemicals, and pollutants in the air and the quality of outdoor air imported to the indoor environment. On the other hand, carbon dioxide (CO_2) is the basic indicator for building ventilation rates, effecting comfort and performance (Bakó-Biró et al., 2012; Ng et al., 2011; Turanjanin et al., 2014). For example, it can negatively affect the human decision-making capabilities; at 2500 ppm or lower, this performance becomes marginal and in some cases even dysfunctional (Satish et al., 2011; Seppänen et al., 1999). Thus, these IEQ factors directly affect the occupants of a healthcare facility and are a measure of their satisfaction. Therefore, they should be controlled and monitored as a priority (El-Sharkawy and Noweir, 2014).

There exists sizeable research on building IEQ (Chao and Hu, 2004). For example, the indoor air quality of various public buildings has been broadly measured and analyzed (Annesi-Maesano et al., 2013; Asif et al., 2018b; Azizpour et al., 2013; Branco et al., 2015; Cartieaux et al., 2011; de Gennaro et al., 2014) and the acceptable thermal comfort level has been established (Khodakarami and Nasrollahi, 2012; Lomas and Giridharan, 2012; Pourshaghaghy and Omidvari, 2012). Also, most studies are carried out in cold climatic regions like the USA, Canada, UK, and other European countries (Candanedo and Feldheim, 2016; Kolarik et al., 2016; St-Jean et al., 2012; Wei et al., 2015). But there are limited studies on the collective and comparative analysis of thermal comfort and ventilation rates. It is quite rare to find a study comprehensively covering the aspects of indoor temperature, relative humidity, and CO_2 concentration in a complex facility like a hospital located in a hot and humid climate (Pourshaghaghy and Omidvari, 2012; Yau and Chew, 2009).

The context of investigation for the current study is Pakistan, which is a developing country and does not have proper air quality management schemes. This causes grave problems in the local healthcare sector. According to a local study, for a better healthcare facility environment, air quality can be determined by the particulate matter levels imparted by various indoor activities and infiltration from outdoor (Gulshan et al., 2015). A recent study shows that the indoor environmental quality in three local hospitals is affected by the visitors' occupancy level. It is concluded that the importance of HAIs in Pakistan is progressively increasing because of several reported cases of nosocomial infection caused by the contaminated air (Ishtiaq et al., 2017; Sudharsanam et al., 2008). Another survey was conducted in local hospitals to evaluate the present hygiene and environmental conditions. The findings reveal the poor practice of correct infection control. It is claimed that these findings are not particular to just the surveyed hospitals, but can be generalized for a majority of hospitals in the country (Baqi et al., 2009).

In light of the existing appalling state of practice, the main objectives of the current study are to identify the factors that affect the IEQ in terms of thermal comfort and ventilation quality and to analyze the present condition of IEQ in the selected healthcare facilities (Nardell, 2016). Building upon these objectives, the basic factors kept in mind are the type of (heating, ventilation, and air conditioning) HVAC system installed in the building and the effect of the number of occupants. Based on literature synthesis, selected indoor environmental quality parameters like indoor temperature, relative humidity, and CO_2 concentration are considered. The data is collected from four local hospitals with different ventilation systems using state of the art measurement devices. As a result, the level of IEQ for each hospital is measured and low performing hospitals are identified along with suggestions to improve their IEQ conditions. The hospital management can benefit from this study by paying attention to the indoor air quality which will ensure a comfortable atmosphere for the patients, attendants, and staff.

2. Literature review

A patient must not stay longer in a hospital, not only to reduce the hospitalization expenditure but also to avoid unnecessary exposure to HAIs (Capolongo et al., 2017; Graves et al., 2007). Since patients are already in a delicate condition due to suffering from an ailment, the chances of getting affected by more infections increase as they are vulnerable due to a deteriorated defense mechanism. Likewise, other occupants and users of healthcare facilities such as doctors, nurses, visitors, and other hospital staff are also exposed to the risk of developing life-threatening diseases (Capolongo et al., 2017). Also, since poor environmental conditions can lead to the high cost of energy consumption and low productivity, it is essential to provide comfortable conditions to the occupants to ensure health and sustainability (Asadi et al., 2017; Schellen et al., 2010). The role of design and operations of the built environment, where these individuals spend a considerable amount of time, in addressing health issues has been duly noted (Lee and Kim, 2008). In this regard, China has since long changed its legislation to maintain the indoor environmental quality of the buildings (Lai and Yik, 2007).

Research has highlighted the role of healthy buildings and their effectiveness towards better IEQ. A study on residential buildings demonstrated that measures can be taken to improve IEQ along with reducing energy consumption (Noris et al., 2013). Also, a thermo-graphic investigation showed that significant amounts of energy can be saved by improving the building envelope and providing effective insulation (Buonomano et al., 2014). Further, a comprehensive assessment of existing retrofit strategies in three healthcare buildings found that construction activities directly impact the patients and their wellbeing during retrofits (Mohammadpour et al., 2017).

2.1. IEQ Factors

The indoor environment is made up of five main factors: comfortable temperature, indoor air quality, acoustic control, odor control, and optical comfort (Abbaszadeh et al., 2006; Angelova, 2016; Asadi et al., 2017). These factors are both compounding in their nature and interconnected in their function. The compounding can be explained by the fact that comfortable temperature consists of temperature and relative humidity. The interconnectedness can be explained by the fact that temperature, relative humidity, CO_2, and the number of occupants significantly influence the indoor air quality of a healthcare facility (Beggs et al., 2015; Wan et al., 2011). Further, fungal particles are also considered as a vigorous contaminant in a healthcare environment, and their concentration increases mostly during the construction or restoration works (Sarıca et al., 2002; Sautour et al., 2007). Lastly, the interconnected factor of indoor air quality is assessed through various other factors such as carbon monoxide (CO), total volatile compounds (TVOCs), aldehydes (-CHO), ozone (O_3), particulate matters (PM 1, PM 2.5, PM 10), radon gas (Rn), nitrous oxide (N_2O) and airborne microbial contaminants (Leung and Chan, 2006, Morawska et al., 1998; Nordström et al., 1999).

However, the entire assessment of IEQ is based on the direct measurement of its factors and parameters (ASHRAE Standard, 2010). But this is an arduous task due to a large number of factors and parameters under the constraints of time and resources. Therefore, to reach to the most significant and largely contributing factors, a detailed desk exercise was carried out. In this process, following a methodology with similar objectives, literature was retrieved using keywords such as 'indoor environmental quality', 'indoor air quality', 'healthcare buildings and indoor environment' (Ullah et al., 2016). As a result, 18 research papers published between the years 2000-2017 were retrieved and used for identifying and synthesizing the IEQ factors. A total of 18 factors were identified from the selected papers and then a two-step content analysis was performed for shortlisting (Siddiqui et al., 2016). In the first step, the frequency of appearance of a factor in all the papers under consideration was counted and accumulated. In the second step, a qualitative score on the scale of high (H), medium (M) and low (L) was allotted to each factor after carefully analyzing its contextual significance in each paper it has appeared in. This qualitative score was then converted to a semi-quantitative scale (H=5, M=3, and L=1). Finally, as shown in Table 1, the literature score was calculated using (Eq. 1) which was then normalized and used to highlight the significance of all the identified factors and shortlist the most significant ones.

$$Literature\ Score = Qualitative\ \ Score\ x \left(\frac{Frequency}{Total\ No.\, of\ \ Papers} \right) \tag{1}$$

As a result, the top three factors, accounting for almost 40% of the overall score, are selected. These are relative humidity (RH), temperature (T), and carbon dioxide (CO_2). These factors are considered for data collection and analysis. Remarkably, the selected factors have almost the same frequency of appearance in the literature. On average, they appear in 68.5% (12.33 out of 18) of the reviewed literature. But what is more striking is that none of them have been given high contextual importance on average. Therefore, their qualitative score is 3. And interestingly the only factor to receive an average high contextual importance is fungi. This infers that in the literature, most of the IEQ factors are contextually treated on the same scale and most studies have found relative humidity, temperature, and CO_2 concentration as representative factors of indoor environmental quality. Therefore, selecting them for data collection will provide a very large picture of the real situation which can be considered typical as well as demonstrative of IEQ of the healthcare building stock.

3. Research methodology

This study is conducted following a structured and formal methodology as shown in Fig. 1. The entire process is divided into three stages which are explained in the subsequent sections.

3.1. Stage I

This stage outlines the genesis of the entire study and deals with some fundamental aspects that include the selection of the topic along with the formulation of the problem statement and research objectives. Background knowledge was gathered from the published articles to identify the gap in current research. Different aspects of requirement, basic advantages, application, and reasons for selecting this topic were addressed at this stage.

After completing the introduction phase, a detailed literature review was conducted to reveal the importance of IEQ especially in the healthcare facilities and how they can be improved. Through the detailed study of the selected articles, 18 factors of IEQ were identified (Hasnain et al., 2018).

Table 1. Literature analysis of IEQ factors

#	*Parameter*	*Frequency*	*Qualitative Score*	*Literature Score*	*Cumulative Score (%)*
1	Relative humidity	13	3	0.139	13.9%
2	Temperature	12	3	0.129	26.8%
3	Carbon dioxide	12	3	0.129	39.7%
4	Total volatile organic compounds	10	3	0.107	50.4%
5	Particulate matter 10	8	3	0.086	59.0%
6	Aldehydes	7	3	0.075	66.5%
7	Airborne bacteria count	6	3	0.064	72.9%
8	Particulate matter 2.5	6	3	0.064	79.3%
9	Fungi	3	5	0.054	84.7%
10	Ozone	3	3	0.032	87.9%
11	Nitrogen dioxide	7	1	0.025	90.4%
12	Carbon monoxide	6	1	0.021	92.5%
13	Particulate matter 1	2	3	0.021	94.6%
14	Radon	2	3	0.021	96.7%
15	Sulphur dioxide	4	1	0.014	98.1%
16	Nitric Oxide	1	3	0.011	99.2%
17	Bio aerosols contaminants	1	1	0.004	99.6%
18	Lead	1	1	0.004	100.0%

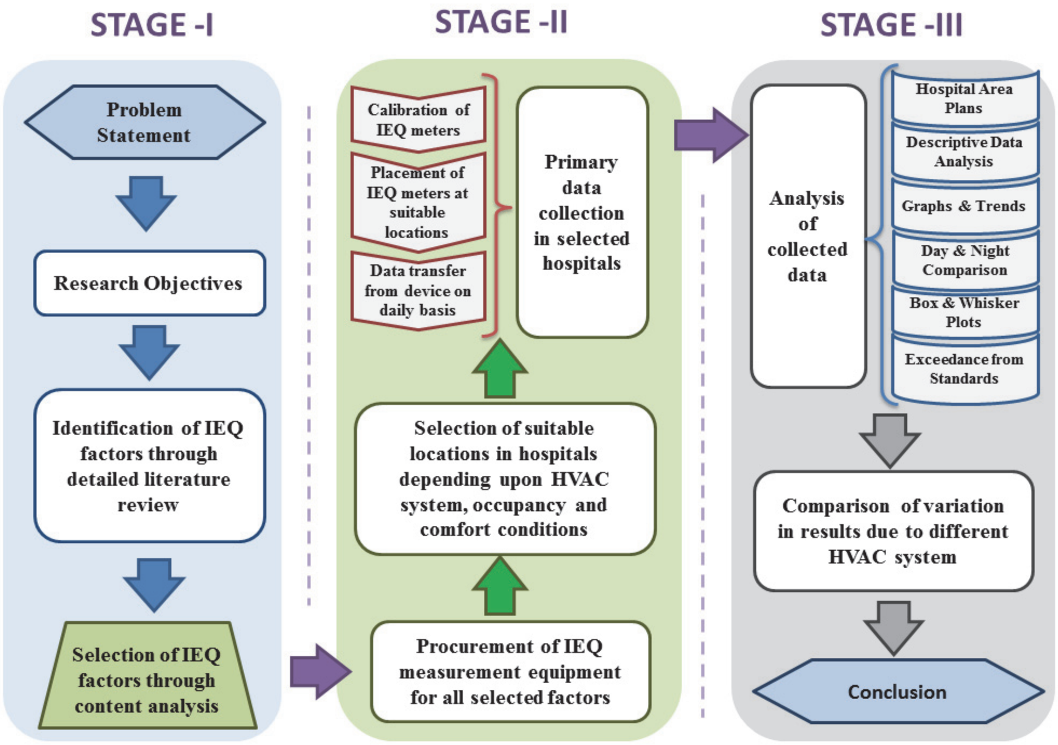


Fig. 1. Research methodology

The identified factors were evaluated through content analysis and the top three factors were selected, as previously explained. These selected factors form the basis for the collection and analysis of primary data in this study.

3.2. Stage II

This stage involves planning, preparing, and collecting primary data to achieve the study objectives. As reported in past studies, researchers have collected data through interviews and questionnaire surveys from the hospital occupants to evaluate the comfort conditions (Azizpour et al., 2013; Hellgren et al., 2011). But to enhance the reliability of findings, this study used primary data for which a two-step collection process was designed. In the first step, the most suitable equipment for the measurement of selected IEQ factors was identified. As part of this, various IEQ meters were reviewed after a market survey and evaluation of the technical specifications. The best suitable equipment was selected and its technical details are given in Table 2.

Table 2. Technical specifications of IEQ meter

Parameter	*Measuring Range*	*Accuracy*
T	0°C to 50° C	±0.8 °C
RH	10 to 90 %	±4% RH
CO_2	0 to 4000 ppm	±40 ppm(<1000ppm)

The second step was the assessment of the existing condition of the three selected IEQ factors. For this purpose, keeping in view the convenience of data collection and the possible variety of results, four different hospitals were selected. Three of them were semi-government hospitals with reserved rights of service while one was a public hospital. The number of hospitals was selected based on the sample size used in similar past research (Hellgren et al., 2011; Ishtiaq et al., 2017). Details of the selected hospitals for data collection are given in Table 3. To avoid any bias and unnecessary disclosure, hospital names are encoded.

All the selected hospitals are located in two major cities of Pakistan; the three semi-government hospitals (H2, H3, and H4) are situated in the subtropical climatic area of twin cities of Islamabad-Rawalpindi, consisting of the capital of the country. The fourth hospital (H1) is in Lahore, the second-largest city of the country and the capital of Punjab province. The climatic conditions for H1 were different from the rest as it is located in a semi-arid climatic zone (Mazhar et al., 2015; Sarfaraz et al., 2014).

After the selection of hospitals, four locations inside each hospital were indicated for the installation of IEQ meters. The locations were based on the occupancy, existing HVAC systems, and current comfort conditions (Asif et al., 2018a; Branco et al., 2015; Jung et al., 2015). These locations were:

a. Emergency room (ER), a most crowded and frequently used area.

b. Operation Theater (OT), a highly sterilized and isolated area.

c. Intensive care unit (ICU), a highly monitored and controlled area.

Medical ward (MW), where patients are kept for a relatively long period and attendants are allowed to visit.

3.2.1. Data collection

These steps were followed during the process of data collection:

a. To formalize the process, prior approvals were sought from the authorities at each hospital before the installation of IEQ meters.

b. The IEQ meters were calibrated for the outdoor atmosphere as per instructions by the manufacturer. If the calibration is not performed according to the instructions, the recorded values are not considered accurate or close to real-time data.

c. The meters were placed far away from the direct sources of HVAC, whether they were operational or not, and away from the entrance and exit point to avoid any direct influence of the outdoor environment on the measurements.

Table 3. Description of location of data collection

Hospital Code	*Total Beds*	*Department Name*	*Coordinates*	*Ventilation and Air-Conditioning type*	*Location*	*Location Codes*
Hospital 1 (H1)	3000	Accident and Emergency Department	31.57N,74.31E	Fans and natural ventilation	ER (L1)	H1L1
					OT (L2)	H1L2
					ICU (L3)	H1L3
					MW (L4)	H1L4
Hospital 2 (H2)	800	Institute of Cardiology	33.59N,73.04E	Split units, exhaust and ceiling fans	ER (L1)	H2L1
					OT (L2)	H2L2
					ICU (L3)	H2L3
					MW (L4)	H2L4
Hospital 3 (H3)	2500	Accident and Emergency Department	33.58N,73.04E	Split units, exhaust and ceiling fans	ER (L1)	H3L1
					OT (L2)	H3L2
					ICU (L3)	H3L3
		OT Complex			MW (L4)	H3L4
Hospital 4 (H4)	1200	Accident and Emergency Department	33.59N,73.04E	Central air-conditioning system	ER (L1)	H4L1
					OT (L2)	H4L2
					ICU (L3)	H4L3
					MW (L4)	H4L4

d. The data was collected for 6 days at each location, day and night, with data logging at an interval of 5 minutes (Asif et al., 2018b; Ferdyn-Grygierek, 2016; Sudharsanam et al., 2008). To represent the location according to their timeframe, suffixes 'N' and 'D' are used for night and day, respectively. For example, H1L1N represents the night-time data of Location 1 (ER) in Hospital 1.

e. The data was collected for 6 days at each location, day and night, with data logging at an interval of 5 minutes (Asif et al., 2018b; Ferdyn-Grygierek, 2016; Sudharsanam et al., 2008). To represent the location according to their timeframe, suffixes 'N' and 'D' are used for night and day, respectively. For example, H1L1N represents the night-time data of Location 1 (ER) in Hospital 1.

f. The recorded data was transferred daily from the IEQ meters to the external storage devices to confirm the safety of data from being deleted or corrupt. The data was organized in MS Excel with respect to the date and time.

g. The data was recorded in the months of September, October, and November of 2017 during which there is pleasant weather in the region and it does not require substantial use of air-conditioning. This was done particularly to avoid variation in data due to extreme weather conditions that warrant a substantial use of cooling or heating (Guerra-Santin and Tweed, 2015).

3.3. Stage III

This stage deals with individual and comparative analysis of gathered data. In doing so, several analyses were performed to determine the variation in the raw data. MS Excel was used to take the mean hourly values which were then generalized to an entire day, giving only one-day data for each location (Branco et al., 2015). The result of this study is discussed in the following pattern:

a. The architectural plans were drawn using specific computer tools and the difference of areas in location and existing HVAC systems were discussed.

b. The data was arranged and organized in this step. Average values for each location were calculated and minimum and maximum values for each parameter in each location were highlighted

c. These minimum and maximum values were then arranged in a graphical form for a better understanding of trends in the selected indoor parameters.

d. A comparison is made between the hourly means of the same locations in all hospitals extended to 24 hours for all the three factors separately. The comparison was made for the day and night variations in the values of parameters. For this purpose, the Wilcoxon sign test is performed using SPSS for both comparisons (Asif et al., 2018b).

e. Box and whisker plots were drawn to indicate the spread of data with the help of mean values, maximum values, and minimum values of indoor temperatures at each location.

f. To benchmark the state of environmental performance in the selected hospital, the percentage of exceedance from international standards is determined.

g. In the end, findings are discussed and conclusions are inferred to arrive at practical implications and recommendations for practitioners as well as researchers.

4. Result and discussion

4.1. Hospital area plans

Due to the unavailability of information, the architectural plans of hospital 1 and hospital 2 have been developed in AutoCAD 2014 using laser meter measurements, as shown in Fig. 2. All the layouts of the selected locations from each hospital are provided here to visualize the space allocation with respect to the number of beds. Hospital 1 has a spacious ER with 4 different bays and 7 beds in each bay. Despite such capacity, it is mostly overcrowded due to being a central public hospital. OT in H1 is not so spacious but remains frequently occupied due to being an unscheduled OT in the accident and emergency block. ICU and MW share a similar layout but have different occupancy levels since ICU is an entry restricted area. ER in H2 is divided into male and female areas with a high occupancy rate. The OT is situated in the pediatrics block and operates on a schedule, thus occupancy levels are consistent. Similarly, ICU is also situated in the pediatrics block and is slightly spacious than other ICUs. MW is normally ventilated and occupancy level is higher as compared to the number of beds.

In Fig. 3, the architectural plans of H3 and H4 are shown. The ERs of H2 and H3 are almost equal in size and occupancy rates. And so are their HVAC systems. The OTs in H2 and H3 are spacious but not adequately ventilated. The occupancy rate is inconsistent due to random sessions with medical students as these hospitals are part of medical schools and used as teaching hospitals. The ICUs are entry restricted and only the patients and staff are allowed. The MW in H4 is very spacious with adequate occupancy levels.

It is noticed that the area of ERs of H1 and H4 is almost the same but there are different occupancy levels and HVAC systems, causing higher CO_2 levels in the ER of H1. The OT in H2 is quite large and adequately ventilated. It operates on a schedule with limited occupancy rates. ICU and MW are also spacious and well ventilated and have a normal occupancy rate throughout the day.

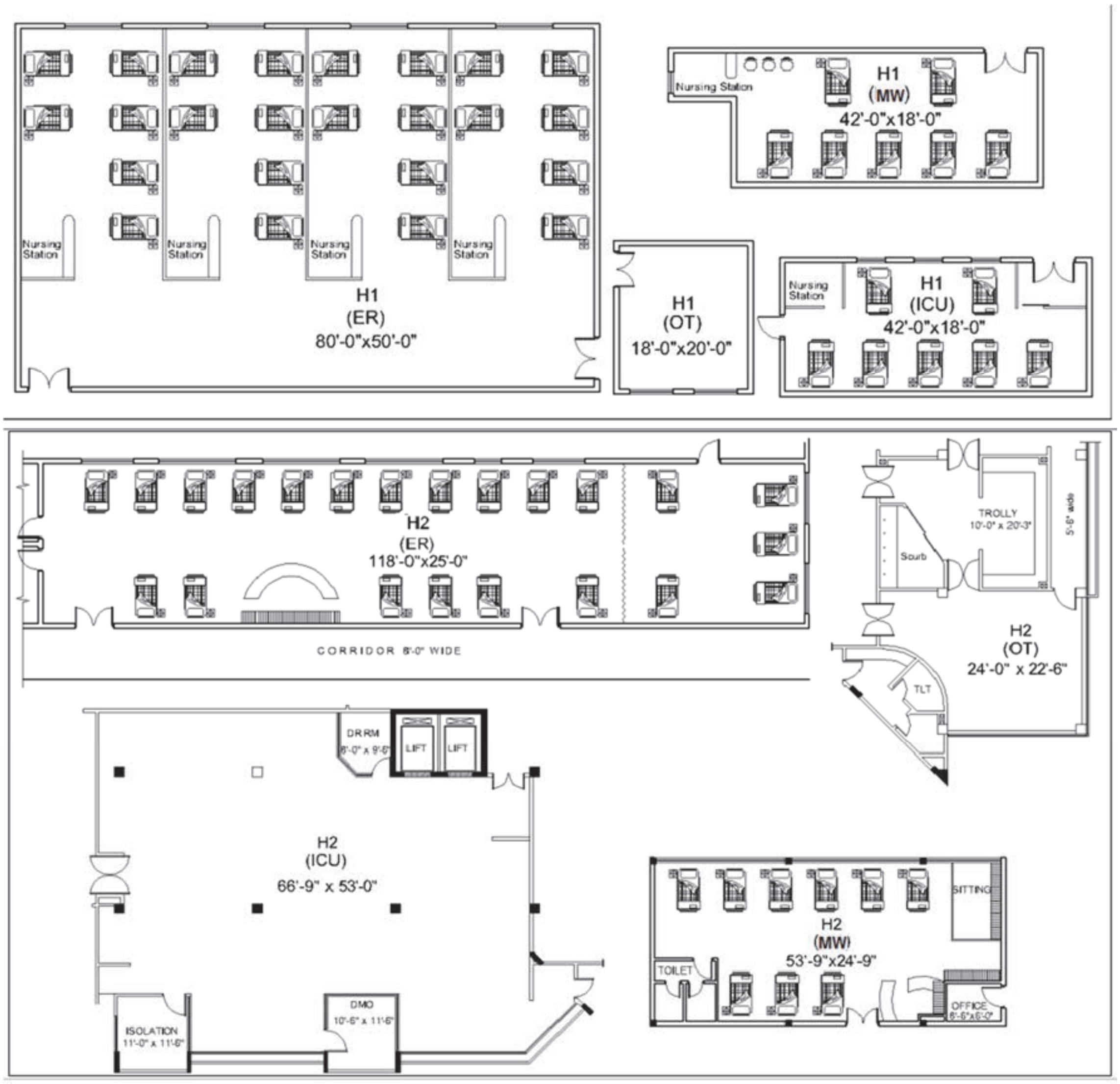


Fig. 2. Architectural layout plans of H1 and H2

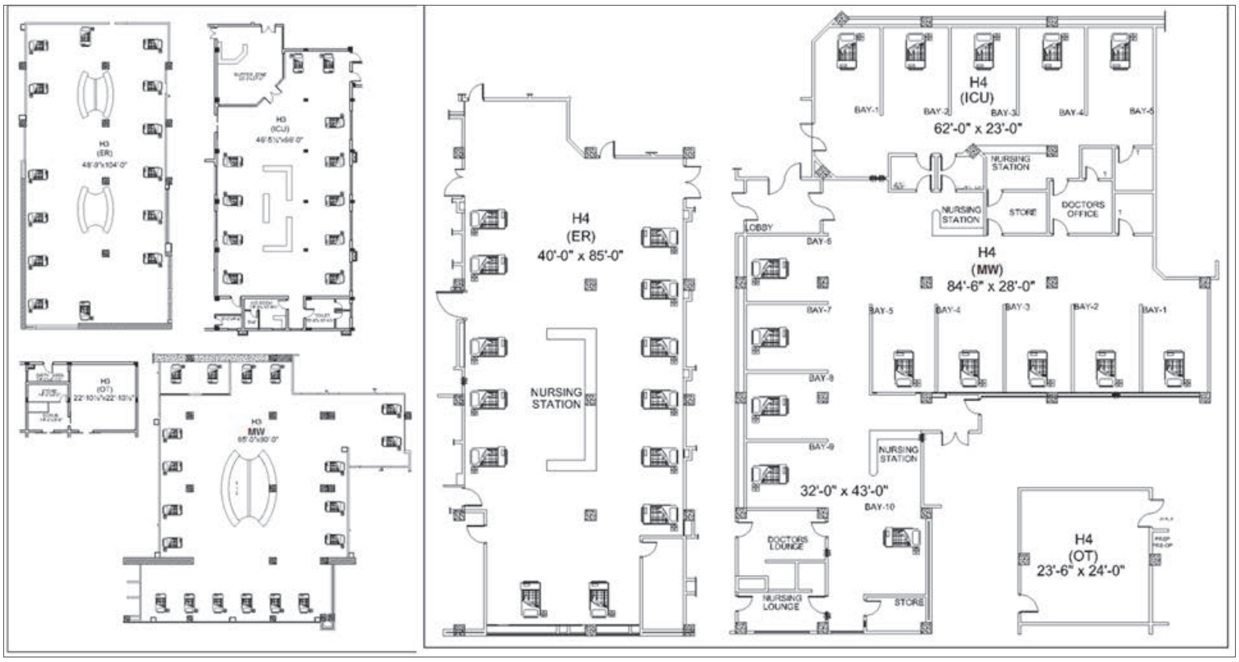


Fig. 3. Architectural layout plans of H3 and H4

4.2. Descriptive results

The minimum and maximum values of the parameters for each location have been summarized in Table 4 for the day- and night-time. The least indoor temperature (T) is recorded in H2L1N (21.5°C) and H3L3D (21.6°C) while the highest in H1L3N (26.8°C) and H1L1D (26.9°C). Similarly, the minimum value of relative humidity is observed in H1L4D and H2L2D (34.4%), while the maximum value is observed in H2L4N (58.4%). The minimum CO_2 level is measured in H2L2N (386ppm) and the maximum in H1L4D (2042ppm).

To illustrate the difference in day and night values of the measured parameters, the 24-hour data is divided into 12 hours. The first 12 hours after sunset (from 6:00 pm to 6:00 am) are considered as night-time, while the other 12 hours (from 6:00 am to 6:00 pm) are considered as day-time. The 12-hourly data of each parameter is plotted for each selected location and variations are observed. The difference in the values of T, RH, and CO_2 is because of the type of human activity, the orientation of a building, ambient temperature, occupancy level and the type of HVAC system (Asif et al., 2018b; Jung et al., 2015).

Although there is no fixed time of occupancy level in a hospital as it is a public place and data is recorded particularly in the emergency departments where occupancy level varies every hour, a peak time of 12:00 pm is indicated by the hospital authorities. Therefore, it is considered as the peak occupancy hour as reflected in the analysis.

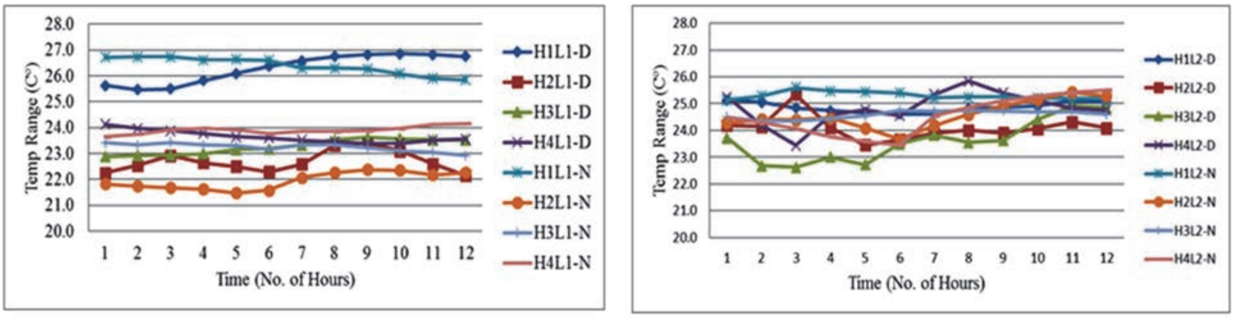
4.3. Graphs and trends

4.3.1. Indoor temperature

A graph is plotted between emergency rooms of each hospital with respect to day- and night-time. It can be observed in Fig. 4 Part (a), that H1L1N and H1L1D have the highest plotted values for T while H2L1D and H2L1N have the lowest values. It is seen that there is more fluctuation in the graph of H2L1, which indicates the instability in the temperature. Similarly, Fig. 4 Part (b), shows the variation of temperature in the OTs during the day- and night-time. H3L2D has the lowest temperature at the start of the day, but it gradually increases as the day progresses. The same trend is seen in other locations as well. H1L2N, H1L2D, and H3L2N do not show any sudden change in the temperature throughout the observation period.

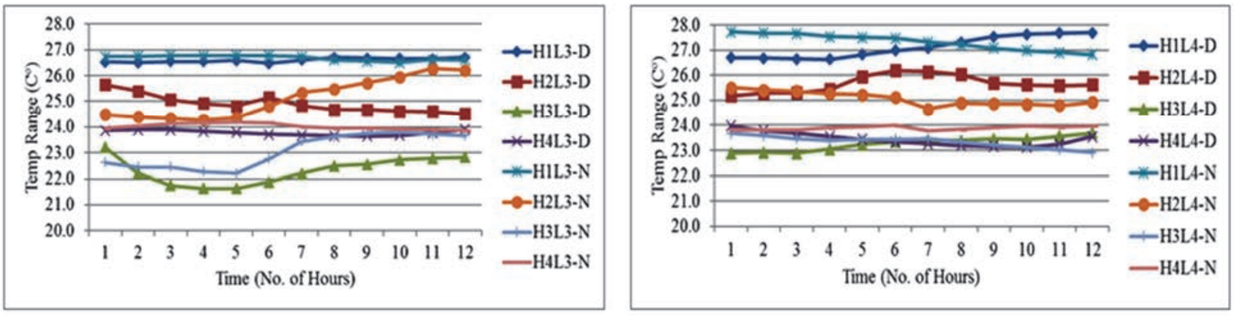
Table 4. Descriptive analysis of recorded data

Location	***No. of Hours***	***T***		***RH***		***CO_2***	
		Minimum	***Maximum***	***Minimum***	***Maximum***	***Minimum***	***Maximum***
H1L1N	12	25.9	26.7	36.5	43.2	1102	1601
H1L2N	12	25.1	25.6	49.7	55.4	1430	1991
H1L3N	12	26.5	**26.8**	45.3	48.1	1402	1794
H1L4N	12	26.8	27.7	34.7	43.8	919	1872
H2L1N	12	**21.5**	22.4	51.0	55.3	725	1210
H2L2N	12	23.7	25.4	35.5	47.4	**386**	445
H2L3N	12	24.3	26.3	49.3	55.6	620	821
H2L4N	12	24.7	25.5	51.3	**58.4**	815	1125
H3L1N	12	22.9	23.4	45.8	48.6	785	1090
H3L2N	12	24.4	24.7	45.6	47.3	869	945
H3L3N	12	22.2	23.8	48.2	53.4	770	830
H3L4N	12	22.9	23.7	46.1	49.4	519	798
H4L1N	12	23.7	24.2	39.3	44.6	470	636
H4L2N	12	23.5	25.5	41.3	47.1	466	499
H4L3N	12	23.9	24.2	43.9	47.9	488	553
H4L4N	12	23.8	24.0	41.3	47.1	476	537
H1L1D	12	25.5	**26.9**	36.5	44.4	1019	1976
H1L2D	12	24.6	25.1	50.4	53.2	1028	1744
H1L3D	12	26.5	26.7	43.6	47.0	1305	1629
H1L4D	12	26.6	27.7	**34.4**	46.5	933	**2042**
H2L1D	12	22.2	23.4	49.7	57.6	715	1223
H2L2D	12	23.5	25.4	**34.4**	42.7	407	518
H2L3D	12	24.5	25.7	46.5	51.2	608	836
H2L4D	12	25.2	26.2	50.8	57.2	786	1151
H3L1D	12	22.9	23.6	45.5	48.5	783	1021
H3L2D	12	22.6	24.9	45.5	54.4	855	1145
H3L3D	12	**21.6**	23.2	45.6	54.0	790	889
H3L4D	12	22.9	23.7	46.1	49.5	528	732
H4L1D	12	23.4	24.1	37.1	42.6	478	558
H4L2D	12	23.4	25.8	40.5	45.9	461	575
H4L3D	12	23.6	23.9	41.4	44.8	465	532
H4L4D	12	23.1	24.0	40.5	45.9	457	522



(a) Indoor temperatures in ERs

(b) Indoor temperatures in OTs



(c) Indoor temperatures in ICUs

(d) Indoor temperatures in MWs

Fig. 4. Indoor temperatures variations

The temperature trend in ICUs is shown in Fig. 4 Part (c). As the area remains isolated, a consistent trend is noticed in all the ICUs. The temperature remains constant for 24 hours in H1L3 and H4L3. However, H3L3 shows a little decrease in temperature during the early hours. H2L3D and H2L3N also show an increase in temperature around peak time. In Fig. 4 Part (d), mostly a linear temperature trend is noticed in medical wards. H1L1D and H1L1N show an increased curve at the peak hour of the day. On the other hand, H2L4D and H2L4N show a slight variation in the day-time but the overall temperature remains linear in other locations. This study shows that the temperature has not much variation in other locations but only in OTs. The reason behind these fluctuating values is the unplanned, abrupt, and large occupancy levels which is characteristic of its functional requirements.

4.3.2. Relative humidity

The trend of relative humidity is directly related to the indoor occupancy rates and ventilation system of a building (Asif et al., 2018b). It is observed in Fig. 5 Part (a) that the highest value of relative humidity is recorded in H2L1, where there is a notable increase during the peak time. This increment starts early in the morning and continues till the evening. It shows a slight rise in H3L1 during the night-time and the start of the day. H4L1N and H1L1D share almost the same graph, and the same is the case with H4L1D and H1L1N.

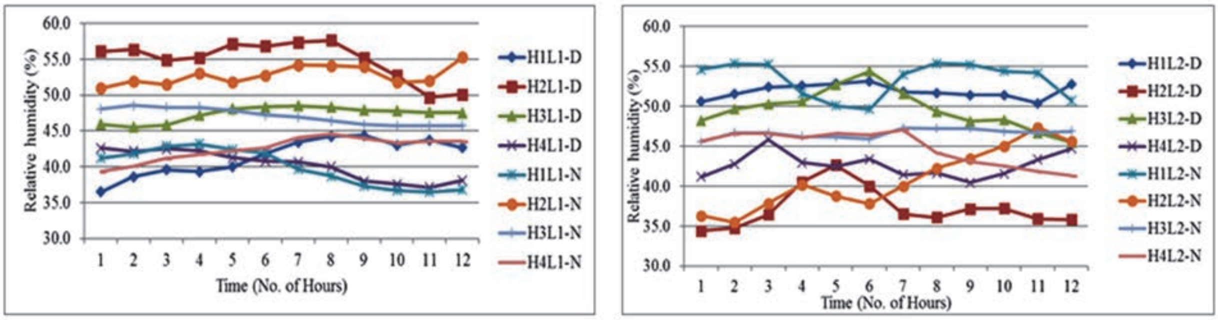
In Fig. 5 Part (b), OTs in all the hospitals show a random trend. For example, H2L2N has a sharp rise in relative humidity. It indicates the maximum occupancy during the night-time. H4L2D, H2L2D, H4L2D, H1L2N, and H3L2D also have fluctuating graphs. Only H3L2 shows a linear graph at night because it is a scheduled OT while others are casualty OTs with a mandate to operate on critically injured patients as and when required. It is evident from Fig. 5 Part (c) that ICUs also show an overall abrupt change of relative humidity levels; the most visible change is noticed in H3L3D and H3L3N. H2L3 shows increased relative humidity levels between the early morning and afternoon span. The graph of relative humidity levels in medical wards is vertically spread, which means there is a wide range of measured values.

Finally, in Fig. 5 Part (d), H1L4D, and H1L4N show a single peak graph. H3L4N and H3L4D also have a consistent graph with a slight rise at 12:00 pm. H2L4D, H2L4N, and H4L4N have random values. The graphs of OTs are the most converged and relative humidity is very well controlled there.

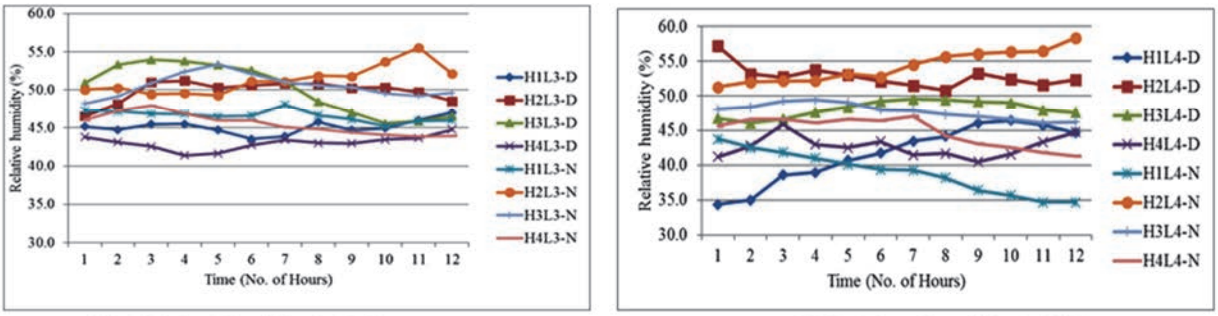
4.3.3. Carbon dioxide

As a universal indicator of indoor air quality, CO_2 indicates the presence of other indoor air pollutants and contaminants which lead to several signs of health risk (Branco et al., 2015). Hospitals are already full of health threats because most of the unhealthy and airborne diseases which affect the patients are present in the building (Capolongo et al., 2017). Like other parameters, CO_2 graphs are drawn for each location in the hospitals. Fig. 6 Part (a) shows that there is a visible change in CO_2 levels of H1L1D and H1L1N. Emergency rooms have the most unplanned occupant density as the flow of people is dependent upon the accident and casualty ratio. A high occupant density is observed in the wee hours of the night while the morning is not so crowded. H4L1 shows almost a linear graph of CO_2 with a slight rise in the evening time. As the OT of H1 has the maximum utilization, the CO_2 concentration is highest, particularly during the day-time but is observed to reduce during the night-time.

In Fig. 6 Part (b), H4L2N, H4L2D, H2L2N, and H2L2D share a consistent trend with the lowest recorded CO_2 concentration. Fig. 6 Part (c) shows that ICUs have very stable CO_2 levels in all the locations other than H1L3D and H1L3N. The CO_2 levels are highest during the morning time. It is visible in Fig. 6 Part (d) that medical wards are not monitored and controlled like ICUs, and the movement and occupancy are not regular. H1L4N and H1L4D have the highest CO_2 concentrations, especially in the evenings. Similarly, H2L4 and H3L4 show a comparable trend in days and nights. On the contrary, H4L4 shows the lowest and most stable readings in the observed medical wards.

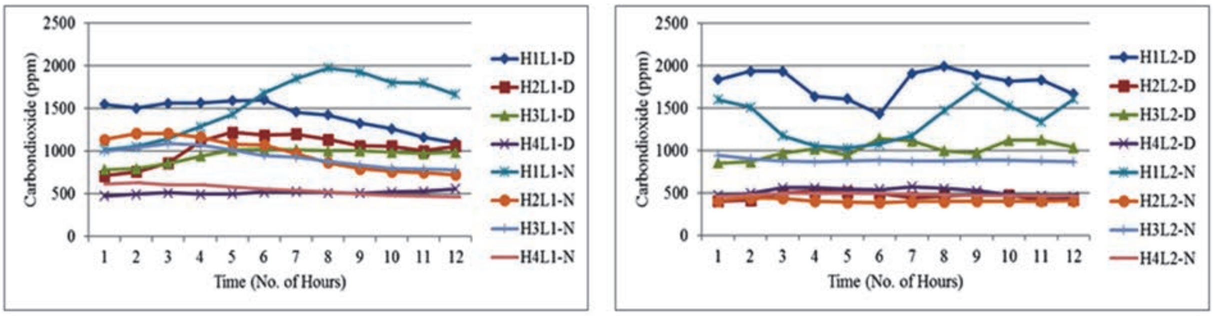


(a) Relative Humidity in ERs **(b)** Relative Humidity in OTs

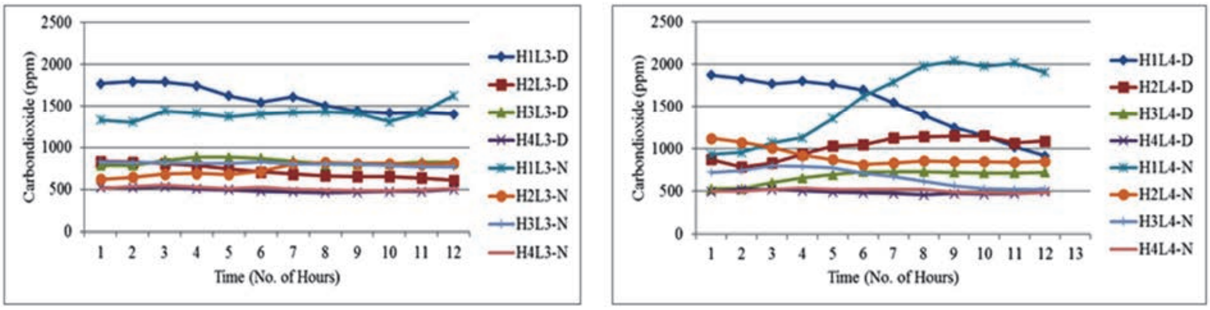


(c) Relative Humidity in ICUs **(d)** Relative Humidity in MWs

Fig. 5. Indoor relative humidity variations



(a) CO_2 in ERs **(b)** CO_2 in OTs



(c) CO_2 in ICUs **(d)** CO_2 in MWs

Fig. 6. Indoor CO_2 variations

4.4. Day and night comparison

4.4.1. Indoor temperature

Table 5 indicates the results of the Wilcoxon sign test performed to determine the variation in day- and night-time temperature values in all the locations. H1L1 shows no significant deviation ($p>0.05$) during the day- and night-time. Similarly, H1L3 and H1L4 also do not show any notable variation throughout the period. However, H1L2 shows a significant variation with the p-value 0.03 ($p<0.05$), suggesting a prominent difference in the day- and night-time temperatures in OTs. Similarly, H2L1, H2L2, and H2L4 show a significant difference with the p-values 0.003, 0.023, and 0.015, respectively ($p<0.05$) while H2L3 has no difference in day and night temperature values i.e. 0.432 ($p>0.05$). In H3, only H3L2 shows a significant difference with the p-value 0.005 ($p<0.05$) while other locations, H3L1, H3L3, and H3L4 indicate a similar behavior throughout the time with no variation in the indoor temperature. An opposite trend is noticed in H4 where only H4L2 has no significant difference with the p-value 0.099 ($p>0.05$) and the overnight trend in all other locations in H4 is different.

It is observed that L3 has the least variation in the day- and night-time temperatures. This implies that it has a consistent indoor temperature in ICUs due to a minimum outside movement. Most variations are observed in L2, pointing that OTs are mostly used in the day-time and the impact of high occupancy becomes effective on the indoor temperature.

4.4.2. Relative humidity

It is seen in Table 5 that a significant difference with the p-value 0.008 ($p<0.05$) is noted in H1L3D and H1L3N, while the other locations in H1 show similar trends in the p-values and no difference is noticed in the RH at day- and night-time. In H2 and H3, only OTs indicate a significant difference i.e. 0.041 and 0.005 respectively ($p<0.05$) in night and day values. In H4, only H4L1 has no significant difference, 0.060 ($p>0.05$), while for all other locations, night-time values are significantly different than the day-time values. H4L2, H4L3, and H4L4 have p-values 0.028, 0.005, and 0.028, respectively. An overall trend indicates that there is no difference observed in the emergency room in any of the hospitals.

4.4.3. Carbon dioxide

It is seen in Table 5 that there is no significant difference ($p>0.05$) in the day- and night-time observations of emergency rooms in all the hospitals as the p-values are 0.209, 0.695, 1.000 and 0.136 for H1L1, H2L1, H3L1, and H4L1, respectively. Contrary to that, OTs have the most irregular trends and significant difference ($p<0.05$) in night and day values as it is seen in all the hospitals, indicated by the p-values 0.002, 0.023, 0.008 and 0.006 for H1L2, H2L2, H3L2, and H4L2, respectively. This indicates that the occupancy level and ventilation system have no prominent effect over 24-hours on CO_2 concentration. H1L3 and H4L3 show significant difference with the p-values 0.012 and 0.004, respectively, while H2L3 and H3L3 show no significant difference ($p>0.05$) in the day- and night time with the p-values 0.583 and 0.060, respectively. Only H4L4 shows a significant difference with the p-value 0.034 ($p<0.05$) and all other medical wards have similar trends for the day- and night-time values with the p-values 0.695, 0.117 and 1.000 for H1L4, H2L4, and H3L4, respectively.

4.5. Box and whisker plots

4.5.1. Indoor temperature

Fig. 7 shows the box and whisker plot using the mean hourly values of indoor temperature at each location. The x-axis shows the location while the y-axis shows the range of indoor temperature. The red horizontal line in the plot indicates the upper limit of international standards as mentioned in Table 6 where exceedance from standards is discussed. This plot depicts the spread of data by showing the mean, maximum and minimum values of the temperature.

Table 5. Wilcoxon sign test statistics (Asymp. Sig. 2-tailed)

Parameter	***Location***			
	H1L1D - H1L1N	*H1L2D - H1L2N*	*H1L3D - H1L3N*	*H1L4D - H1L4N*
T	0.665	**0.003**	0.130	0.254
RH	0.209	0.050	**0.008**	0.158
CO_2	0.209	**0.002**	**.0012**	0.695
	H2L1D - H2L1N	*H2L2D - H2L2N*	*H2L3D - H2L3N*	*H2L4D - H2L4N*
T	**0.003**	**0.023**	0.432	**0.015**
RH	0.060	**0.041**	0.065	0.182
CO_2	0.695	**0.008**	0.583	0.117
	H3L1D - H3L1N	*H3L2D - H3L2N*	*H3L3D - H3L3N*	*H3L4D - H3L4N*
T	0.929	**0.005**	0.004	0.637
RH	0.753	**0.007**	0.695	0.610
CO_2	1.000	**0.008**	0.060	1.000
	H4L1D - H4L1N	*H4L2D - H4L2N*	*H4L3D - H4L3N*	*H4L4D - H4L4N*
T	**0.028**	0.099	**0.003**	**0.006**
RH	0.060	**0.028**	**0.005**	**0.028**
CO_2	0.136	**0.006**	**0.004**	**0.034**

Clearly, the means of each location in H1 are above the upper limits of the standards.

4.5.2. Relative humidity

Fig. 8 shows the box and whisker plot of indoor relative humidity in all the locations. Like the previous box plot, each location is given on the x-axis while the range of relative humidity is given on the y-axis. The red and blue horizontal lines indicate the upper and lower limits of the standards, respectively. It was observed that the lower limits were breached in most of the locations as compared to the upper limits.

4.5.3. Carbon dioxide

Like temperature and relative humidity, the box and whisker plot for indoor CO_2 values is shown in Fig. 9. The x- and y-axes show the location and range of CO_2, respectively. Similar to the previous graphs, the red and blue lines show the upper and lower standard limits, respectively. Two trends are evident in the plot. First, upper limits in all the locations in Hospital 1 are breached in the case of indoor CO_2, while lower limits in all the locations in Hospital 4 are crossed.

4.6. Percentage exceedance from standards

To ensure maximum accuracy in measuring the percentage exceedance from the standards, three standards for each selected parameter were studied: ASHRAE 2003 HVAC Design Manual for Hospitals and Clinics (Geshwiler et al., 2003), United States Department of Veterans Affairs 2001 HVAC requirements in Surgery Area (Khodakarami and Nasrollahi, 2012) and ASHRAE standards (ASHRAE Standard, 2007; Lee and Chang, 2000).

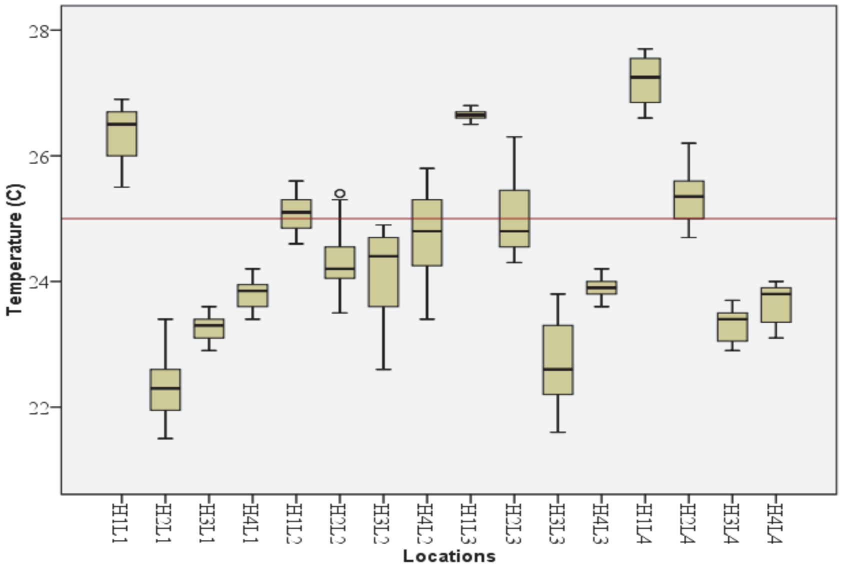


Fig. 7. Box and whisker plot (T)

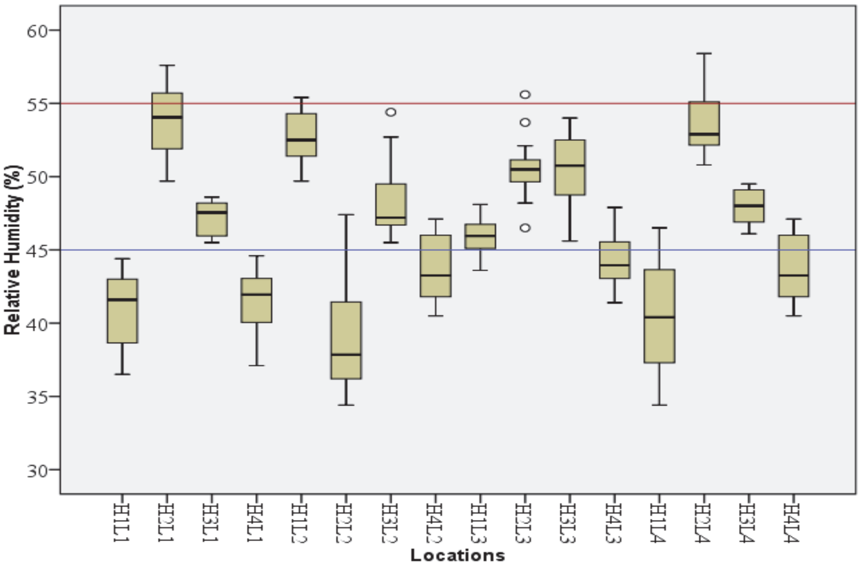


Fig. 8. Box and whisker plot (RH)

The closest value available in any of the selected standards was considered for comparison. This was done to observe the minimum level of exceedance. Also, larger values are preferred and reported in such building types where the sensitivity of IEQ is relatively lower such as academic facilities (Asif et al., 2018b).

4.6.1. Indoor temperature

It can be seen in Table 6 that none of the locations exceeds the lower limit of temperature during the day- and night-times as per the standards and the percentage exceedance is calculated as 0%. But in H1, all the locations exceed the upper limit of standards by 100%. Also, H2L3 and H2L4 cross the upper limits by 100%. But, H4L1, H4L2, H4L3, and H4L4 report the minimum exceedance from the upper limit of temperature standards; i.e. 16.7%, 75%, 41.7%, and 0%, respectively. Similarly, in the day-time, none of the locations has a lower value than the lower limit of standard indoor temperature values and the minimum percentage exceedance is calculated as 0%. The upper limits of standards show a similar trend in the day- and night-time. In H1, all upper limits are exceeded by 100% in each location. In H2L1 and H2L2, the percentage exceedance is 0% and 58.3%, respectively, while H2L3 and H2L4 exceed by 100%. In H3, upper limits of standards in the day-time at H3L2 exceeds by 25% while H3L1, H3L3, and H3L4 have 0% exceedance in the day-time. H4L1 and H4L2 show exceedance of 8.3% and 91.7%, respectively, while H4L3 and H4L4 show no exceedance.

4.6.2. Relative humidity

In Table 6, the percentage exceedance from standards of relative humidity is also shown. In H1L1, H1L2, and H1L4, no exceedance is observed but in H1L3, the lower limits are exceeded by 33.3% at the night-time. The upper limits in H1L1 and H1L4 exceed by 100%. In the day-time, no lower limits were crossed but upper limits of standards in H1L1, H1L2, H1L3, and H1L4 are 100%, 0%, 50%, and 75%, respectively. In H2, the lower limits at L2 exceed by 75% and the upper limits by 0% during the night-time. In H2L1, H2L3, and H2L4, the upper limits exceed by 8.3%, 8.3%, and 41.7%, respectively. In the day-time, the lower limits for H2L2 exceed by 100%, and upper limits for H2L1 and H2L4 exceed by 66.7% and 8.3%, respectively. H3 shows 0% exceedance in both limits during the day- and night-time. However, in the night-time, H4 has crossed the lower limits of relative humidity in L1, L2, L3, and L4 (100%, 41.7%, 41.7%, and 41.7%) but not the upper limits. Similarly, in the day-time, percentage exceedance crossed lower limits in L1, L2, L3, and L4 by 100%, 91.7%, 100%, and 91.7%, respectively with 0% exceedance in the upper limits.

4.6.3. Indoor CO_2 concentration

In H1, the standard upper limit of indoor CO_2 concentrations is crossed in almost all the locations in the day- and night-time by 100% expect for H1L4, i.e. 83.3% in the night-time and 91.7% in the day-time. Even after having a central air-conditioning system and controlled upper limit standards, the parameters do not observe the lower limits of standards. This indicates that balance in the occupancy and ventilation is also necessary. In H2, lower limits in L2 exceed by 100% in the day- and night-time while upper limits in L1 and L4 exceed by 50% and 25%, respectively, in the night-time and 75% and 66.7%, respectively, in the day-time. Remarkably, H3 has the most suitable values. In H3L1, the upper limits in the day- and night-time exceed by 33.3% and 41.7%, respectively. In H3L4, the lower limits in the day- and night-time exceed by 33.3% and 16.7%, respectively. In H4, 0% exceedance was calculated in the upper limits of the night- and day-time, while almost 100% exceedance was noticed in lower limits. This complies with the installed combination of exhaust fans and split air-conditioners, and also shows that the movement of occupants is controlled.

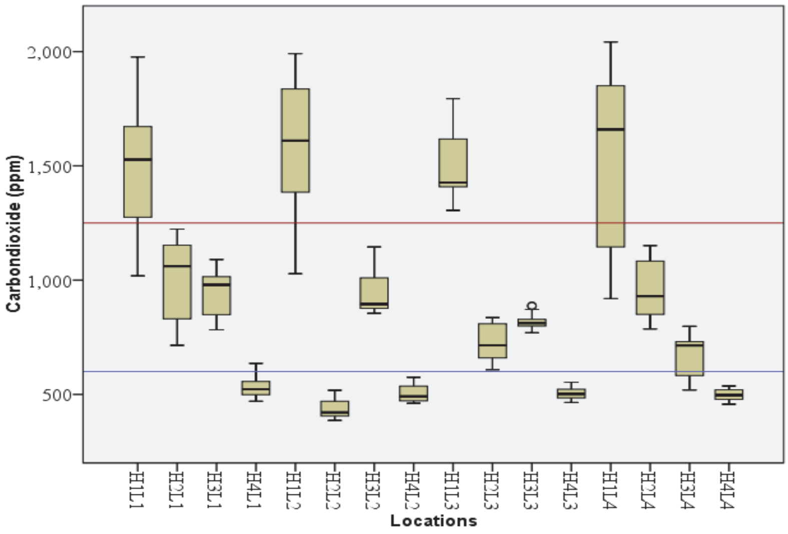


Fig. 9. Box and whisker plot (CO_2)

Table 6. Exceedance from the standards

Hospital Code	***Location Code***	***Temperature (%)***				***RH (%)***				***CO₂ (%)***			
		Night-time		***Day-time***		***Night-time***		***Day-time***		***Night-time***		***Day-time***	
		<20	*>24*	*<20*	*>24*	*<45*	*>55*	*<45*	*>55*	*<600*	*>1000*	*<600*	*>1000*
H1	**L1**	0	100	0	100	0	100	0	100	0	100	0	100
	L2	0	100	0	100	33.3	0	0	0	0	100	0	100
	L3	0	100	0	100	0	0	0	50	0	100	0	100
	L4	0	100	0	100	0	100	0	75	0	83.3	0	91.7
H2	**L1**	0	0	0	0	0	8.3	0	66.7	0	50	0	75
	L2	0	91.7	0	58.3	75	0	100	0	100	0	100	0
	L3	0	100	0	100	0	8.3	0	0	0	0	0	0
	L4	0	100	0	100	0	41.7	0	8.3	0	25	0	66.7
H3	**L1**	0	0	0	0	0	0	0	0	0	33.3	0	41.7
	L2	0	100	0	25	0	0	0	0	0	0	0	50
	L3	0	0	0	0	0	0	0	0	0	0	0	0
	L4	0	0	0	0	0	0	0	0	33.3	0	16.7	0
H4	**L1**	0	16.7	0	8.3	100	0	100	0	66.7	0	100	0
	L2	0	75	0	91.7	41.7	0	91.7	0	100	0	100	0
	L3	0	41.7	0	0	41.7	0	100	0	100	0	100	0
	L4	0	0	0	0	41.7	0	91.7	0	100	0	100	0

5. Discussions

As it has been mentioned in Table 3 that H1 has no central air-conditioning system, but it has ceiling and exhaust fans. So, it can be clearly seen in the graphs that H1 has the highest values of T, RH, and CO_2 concentrations. Contrary to that, H4 has a central air-conditioning system in L1, L3 and L4, and a laminar airflow system in OTs. That is why it has the lowest and controlled values of all three parameters. On the other hand, H2 and H3 have a mixed system of air-conditioning with ceiling fans, exhaust fan, and splits air-conditioners being operated manually. Therefore, the graphs of H2 and H3 have comparable trends. It can be observed that HVAC is a significant driver of IEQ. A comparative study conducted in a Hong Kong school investigated two classrooms one with natural ventilation and the other with the HVAC system. It was found that natural ventilation caused abrupt changes in the IEQ graphs, especially in the temperature readings, whereas there were comparatively lesser curves in the classroom with the HVAC system (Lee and Chang, 2000). Another study conducted in an educational institute of Pakistan was focused on the variation of T, RH, and CO_2 measurements on weekdays and weekends. Again, there was a noticeable increase in the parameters on weekdays as compared to weekends (Asif et al., 2018b). A similar study conducted in children nurseries in Portugal found that the control in occupancy levels and ventilation strategies can enhance the quality of the indoor environment (Branco et al., 2015). The result validates that the occupancy level is a major factor controlling the indoor temperature, humidity, and CO_2 concentrations (Asif et al., 2018b).

The randomization in occupancy affects the sudden changes as observed for CO_2 in the OTs (L2). A similar trend was noticed in a study of three hospitals in Lahore (Ishtiaq et al., 2017). Random peaks in OTs graphs were observed because most of the time, groups of medical students practice and study real-time cases there. But emergency rooms (L1) in all the hospitals typically show a single extensively rising graph which is mostly during the day-time. Similar peaks were noticed in the earlier studies when the occupancy was highest (Asif et al., 2018b; Branco et al., 2015). Such a phenomenon is observed either due to the flow of patients during the day-time or a higher ambient temperature which causes a rise in the values of thermal comfort parameters. It has been mentioned that indoor temperature has a strong relationship with the ambient temperature. This concept was endorsed by a study of a UK hospital building. The values of thermal comfort parameters decrease as the sun sets and were minimum during the night-time (Khodakarami and Nasrollahi, 2012). Likewise, almost in all the locations, the average temperature during the day-time was more than the average night-time temperature. And since H1 is located in a slightly warmer region of the country as compared to the other three hospitals, its overall graph shows higher values even after continuous natural ventilation.

6. Conclusions

A comparative analysis of indoor environmental conditions including basic thermal comfort (T and RH) and CO_2 of four hospitals shows that occupancy level and ventilation rates are responsible for the controlled IEQ. It is observed that ambient temperature and other parameters have a high effect on the indoor conditions especially when natural ventilation is the only source of air circulation. Due to better outside environmental conditions at night, IEQ is observed as closer to the standards. But random and undefined occupancy in hospitals accounts for the irregularity even in night-time environmental conditions. Centrally air-conditioned locations have linear and controlled trends in 24-hours indicating the best performance as compared to other ventilation strategies for this region. Splits air-conditioners and exhaust fans also show a better performance in standardizing CO_2 concentrations.

These findings can help improve the strategies for indoor environmental quality, especially in hospitals and healthcare buildings. These strategies not only include design consideration at the beginning of hospital projects but also various retrofitting techniques can be proposed for the existing buildings to avoid uncomfortable conditions. It is recommended that buildings must be designed on maximum occupancy rates and these numbers should strictly be controlled during building operations. Along with mechanical ventilation, HVAC systems are necessary for crowded public places like hospitals (Beggs et al., 2015). Also, further studies on the trends of ventilation rate changes for these factors are recommended which will help in defining the optimum retrofits strategies.

A limitation of this study is in the form of a few hospitals for data collection. But it is an established phenomenon that the process of acquiring permission from the authorities to place the equipment in hospitals is crucial due to privacy and reputation concerns, which is why there are limited environmental studies on hospitals. Therefore, it is recommended to perform the IEQ assessment in poorly governed local hospitals to reveal weaker data which will not only help improve the design and retrofitting strategies but also highlight the IEQ issues to be resolved through better management. Another limitation is the duration of data collection. The current study collected data for 3 months but a 12-month full-year data collection cycle will reveal much broader aspects of IEQ. Therefore, a full-year data collection is recommended for future studies.

As a next step to the current study, simulations are performed and retrofitting design is suggested as a solution to the IEQ problem using the findings of this study. Those details are given in continuation of this article in “Thermal comfort and ventilation conditions in healthcare facilities - Part 2: Improving indoor environmental quality through ventilation retrofitting”. Only by following both parts, the reader will be able to grasp the whole picture.

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