ORIGINAL PAPER

Comparison of classical and sensor-based methods for determination of indoor air quality

S. Lakestani[1] · M. Milli[2]

Abstract
People spend approximately 80% of their time indoors, which is why indoor air quality is important for human health in recent years. Instant determination of the changing indoor air quality, especially in public buildings, and implementing appropriate prevention measures is therefore necessary. One of the most important air pollutants is total volatile organic compounds. The purpose of this study was to measure simultaneously the concentration of total volatile organic compounds by two different methods; wireless sensor and passive sampling. The passive sampling period was chosen as one week, so samples were collected 4 times in one month. Passive samples were collected using Radiello stainless steel tubes in two different laboratories and were analyzed by thermal desorber and gas chromatography-mass spectrometer instrumentals. In the wireless sensor networks, data were collected every minute for a month at the same points in the same laboratories. The two methods were compared and the observed accuracy of the methods was about 5.89%. The classical method (passive sampling) is expensive and the result isn't prepared on time. In this paper, we offer a low-cost indoor air quality monitoring wireless sensor network system. Hence, the sensors record the results in real time, allowing us to observe changes immediately and intervene as needed. Therefore, in public places, the use of wireless sensor network systems will have a major positive impact in terms of saving time and money, as well as protecting the health of personnel.

Keywords Monitoring · Health · Wireless sensor network · Passive sampling · Total volatile organic compounds

Introduction

People spend approximately 80% of their time indoors. This has exacerbated concerns about the health effects of indoor exposure to air pollutants. Some indoor air pollutants can be recognized by their immediate impacts on our bodies, such as throat irritation or watery eyes (Joshi 2008). Studies have found that people living in the USA spend 89% of their time in indoor environments, and people living in developing countries spend 79% of their time indoors (WHO 1984; Jacobson 2002). A study conducted in Turkey revealed that individuals spend approximately 79% of their daily time indoors (Sofuoglu and Sofuoglu 2011). Hence, the improvement of indoor air quality will ensure the protection of human health, the reduction of labor losses caused by diseases, and the prevention of economic losses due to medical treatments.

Volatile organic compounds (VOCs) comprise a large group of chemicals ranging from harmless cooking odors to hazardous compounds such as aromatics (e.g., benzene, toluene, and xylene) and aldehydes (e.g., formaldehyde and acetaldehyde), which make the detection and monitoring of VOCs a challenge, along with exposure quantification (Demanega et al. 2021). The health effects of exposure to VOCs are widely studied in the literature (Adgate et al. 2004; Dodson et al. 2007). The most common VOCs were benzene, toluene, ethylbenzene, and xylene called BTEX (Srivastava and Devotta 2007; Kamani et al. 2023). These compounds can be grouped as the most harmful VOCs with

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their high toxicity. Sometimes indoor VOCs are 2–5 times higher than outside (Walgraeve et al. 2011; Çankaya et al. 2020). These toxic compounds not only cause respiratory diseases but also in high concentrations cause damage to the nervous system (Hazrati et al. 2016; Çankaya et al. 2020; Kamani et al. 2023).

Globally, levels of VOCs in indoor environments have been determined and discussed adequately. However, there is no comparison between classical methods and wireless sensor networks (WSNs) systems. Although the concept of semantic web and ontologies came into our lives in the mid-90s, the use of these concepts for sensor data was first put forward by Avancha in 2004. After this study, the concept of sensor ontology has been expanding day by day, with a focus on enrichment, interoperability, and a better understanding of sensor data (Milli et al. 2023). In addition, the community created by the World Wide Web (W3C) has defined the SOSA/SSN Sensor Ontology Framework to establish a common vocabulary for sensor-based systems and ensure the interoperability of sensor data from different platforms (Haller et al. 2017). In the past, many studies on breath analysis involving combined gas chromatography/mass spectroscopy (GC/MS) have been published (Phillips et al. 1999); the presence of several hundreds of different compounds in human breath was reported in a 2003 study on lung cancer (Di Natale et al. 2003).

In a laboratory study concerning neglected safety precautions, the probability of small- and large-scale accidents was high. Depending on the size of the accident, very heavy financial and moral costs may be incurred. Safety precautions come first through periodic monitoring of environmental parameters and timely detection of potentially hazardous situations such as gas, chemical, and biological waste leaks. The first step to prevent or minimize accidents in laboratory work areas is to identify the risks in the work environment (Aktar T. 2016; Aktas et al. 2020; Milli et al. 2023).

In the indoor environment, the WSNs are set up to collect the parameters that will affect human health (Jin and Kim 2018). Especially since the COVID-19 pandemic, the use of sensor-based systems in areas where social health is important, such as hospitals, schools, and public transport, has become of great importance for the timely operation of action plans (Kapoor et al. 2021). In most of the studies reported on indoor air, VOCs were analyzed using thermal desorption, gas chromatography, and mass spectrometry (TD-GC–MS). In air sampling, TD-GC–MS is a powerful system for qualitative and quantitative analysis of VOCs but is costly and time-consuming (Heavner et al. 1992; Massold et al. 2005; Markert 2016; Lee et al. 2021; Kaikiti et al. 2022; Isinkaralar et al. 2023; Soysal et al. 2023).

In the present study, a sensor-based system was established to eliminate the disadvantages of classical and conventional methods in detecting possible unexpected situations in laboratory environments and to activate the internal dynamics of businesses or institutions in emergencies as soon as possible (Markert 2016). To overcome the limitations of GC–MS analysis we used WSNs. The study was conducted in two laboratories for one month October 01 to November 01 2020 using real-time monitoring of indoor air quality using two different methods for determining Total volatile organic compounds (TVOC): passive sampling and WSN. By comparing these two methods, their accuracy was determined and their advantages and disadvantages were evaluated.

Materials and methods

Selection of experimental areas

The error margins of the sensors, which are used extensively in all areas of life in today's technologies, were determined. With these margins of error, we examined how companies or institutions using sensor-based systems can rely on sensor data when implementing their critical action plans. While making this comparison, passive sampling, which has been proven correct before, was compared with the sensor data, and the error margins of the sensor data were determined according to the passive sampling data.

The Electromagnetic Laboratory and Electronic Design Laboratory were chosen from more than 10 laboratories in the research center as the sensor measurement area to compare the two methods (Fig. 1). These laboratories will be referred to as Lab-1 and Lab-2, respectively, hereafter. The main reason for choosing these laboratories as measurement areas is that fewer manipulative activities take place there compared to the other laboratories. Thus, the error rates of the sensor data can be compared with those of passive sampling and more reliable results can be obtained.

To carry out this comparison, two sensor nodes were placed in different parts of both laboratories selected as the measurement area. A passive sampling tube was placed at almost the same point as the sensor nodes. The measurement parameters in these two laboratories were continuously recorded by the sensor nodes and saved in the database every day on the sampling dates.

Sampling

The sensor nodes and passive sampling tubes were positioned at a distance of 1.5 m, which is considered average human respiratory protection. They were placed parallel to the ground so that they could make healthier measurements and collect healthier samples, respectively. The samples collected by the passive measurement system, while appearing
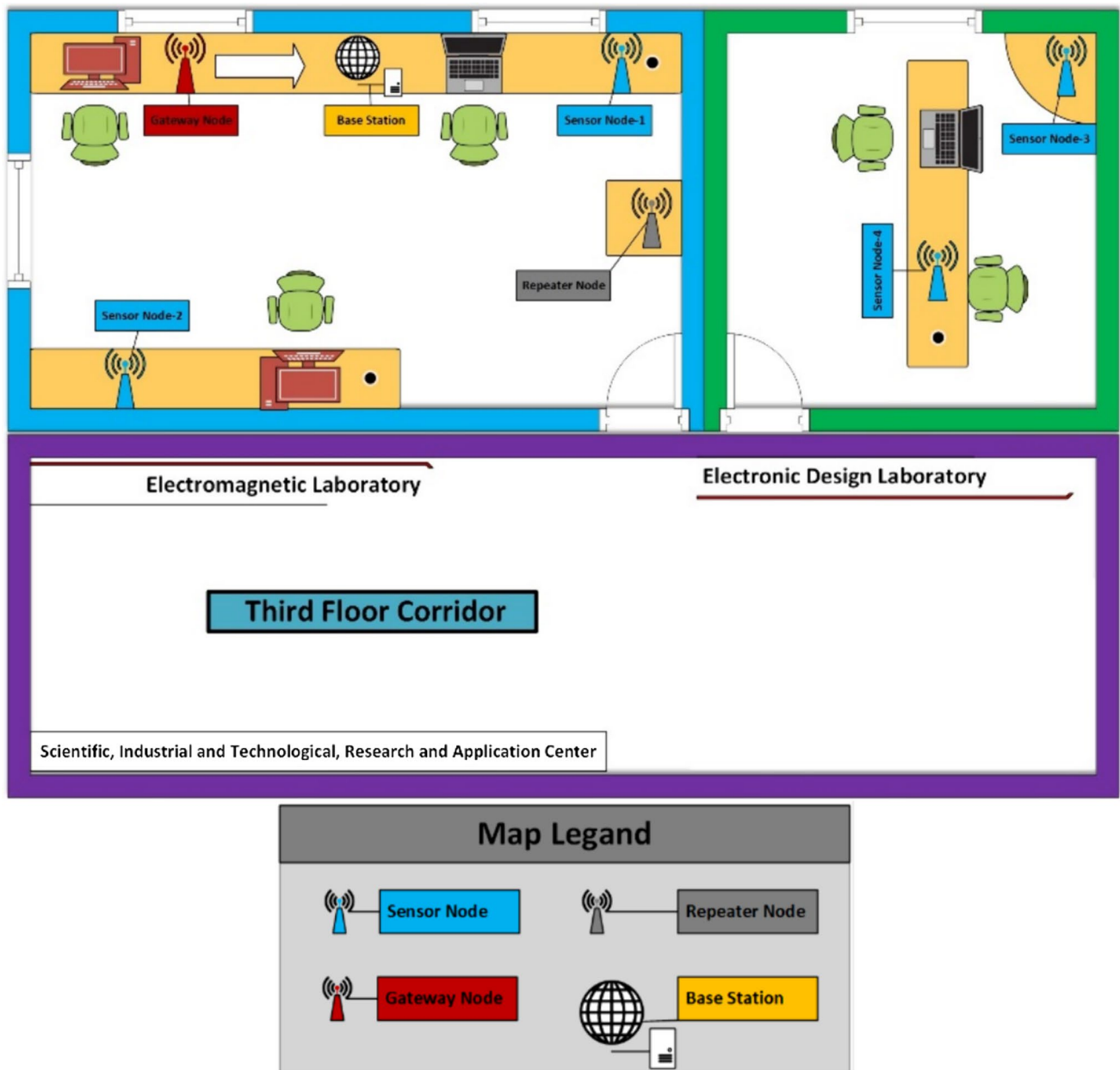
Fig. 1 Schematic layout of laboratories (Not drawn to scale)

in the user interface as an extension of the wireless sensor network, were analyzed once a week.

Study design

Creating sensor nodes

In the proposed study, a wireless sensor network was established for the measurement of the previously determined parameters. The nodes forming the wireless sensor network contain 2 sensors in total. One of these sensors is the

CCS811 sensor module that measures TVOC. The CCS811 is an ultra-low power digital gas sensor solution that integrates a metal oxide (MOX) gas sensor to detect a wide range of Volatile Organic Compounds (VOCs) for indoor air quality monitoring (Ams 2017). Another sensor forming the sensor network is the Digital Output Relative Humidity and Temperature (DHT22) sensor module that measures temperature and humidity parameters. The reasons for using the sensors given in Table 1 for parameter measurement in the proposed study; can be listed as (1) sensitive measurement, (2) low energy consumption, (3) low cost, (4) long-term stable operation, (5) resistance to environmental factors. Also,

Table 1 Sensors used to measure TVOC, temperature, and RH% parameters

| Sensor	Parameters	Resolution
*CCS811	TVOC	4.5 µg/m^3
**DHT22	Temperature	0.1 °C
**DHT22	Relative humidity (RH)	0.1% RH

*CCS811: A sensor with a wide range for detection of VOCs

*DHT22: Digital output relative humidity and temperature

the accuracy, sensitivity, calibration, and operating voltage of the sensors used are shown in the studies for some models and sensors with the specified specifications (Milli et al. 2023). These sensor nodes, which were created to collect instant data in this study, are widely used in many air testing applications such as indoor air quality applications or real-time air quality monitoring stations.

In addition to the created sensor nodes, a Gateway node without any sensors was designed. The task of this created Gateway node in WSN is to pass the data collected by other sensor nodes to the base station (Computer) via the serial port. The gateway node is the most important node that manages the entire sensor network and acts as a bridge between the computing environment and other nodes. The data received from the sensor nodes were transferred to the computer environments (Fig. 2). Finally, repeater nodes are designed for sensor nodes that have difficulty reaching the gateway node due to the distance and obstacles (Fig. 3). Repeater nodes strengthen the signal when the sensor nodes cannot reach the gateway node due to distance, physical obstacles, and indoor density, thus ensuring healthier communication between the nodes. Detailed information on the installation of sensor nodes is available in the previously published article by the project team (Aktaş et al. 2020).

The nrf 24L01 (Nordic Semiconductor, "nRF24L01 + Single Chip 2.4GHz Transceiver Product Specification v1.0,"
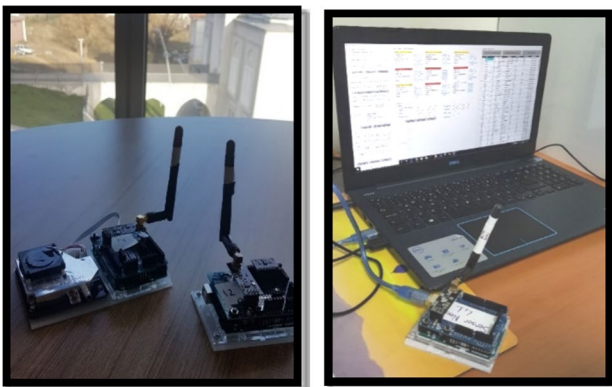
Fig. 2 Sensors and gateway node
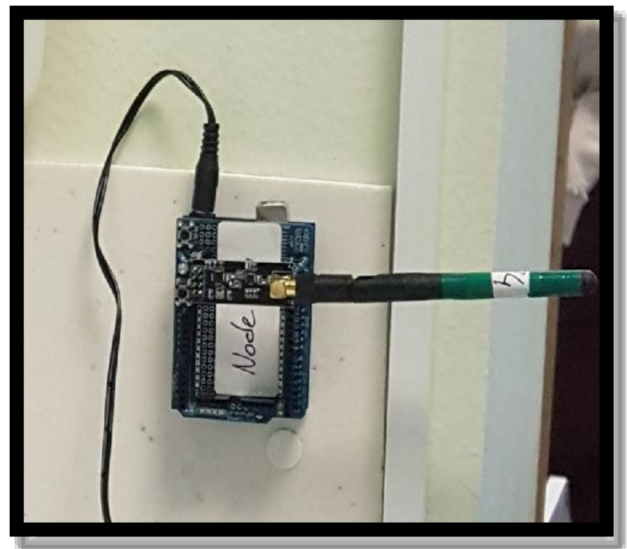
Fig. 3 Repeater

2008) sensor module, which is frequently employed by researchers, was used to ensure communication between the sensor nodes to be used for measurement. The node was developed for wireless applications and is aggregated with a single-chip transceiver communication module capable of operating at 2.4 GHz frequency. The data received from the sensor nodes were transferred to the computer (Fig. 2).

Monitoring

Wireless network sensors

The parameters in the measurement environment were instantly monitored by the WSN, which was established within the scope of the study, 24 h a day for one month. Each sensor in the installed system was programmed to take an average measurement per minute and send it to the gateway. During the measurement dates, a sensor collected approximately 43,000 items of data for each parameter it measured. Since there were air conditioning systems in Lab-1 and Lab-2, which were chosen as the measurement areas, the temperature was always kept constant at around 20 °C. Data from the sensor nodes confirmed that the temperature was consistently 20 °C in the two laboratories. In the laboratories, the relative humidity measured was approximately 37% on average.

TVOC passive sampling

For passive sampling of TVOCs, tubes with the following characteristics were used (Fig. 4):

Fig. 4 TD-GC/MS and radiello sampler tube

- Made of stainless steel,
- Packed with 350 ± 10 mg of graphitized charcoal,

Samples collected were brought to the laboratory by cold chain immediately after sampling, and efforts were made to analyze them the same day or the next day. All analyses were performed at Bolu Abant Izzet Baysal University's Scientific Industrial and Technological Application and Research Center.

In the present study, the EPA method TO-17 (EPA 1999) was used for sampling and analyses of samples (Lakestani et al. 2013). Samples collected were analyzed by thermal desorption (Markez TD-100)-gas chromatography (Thermo Scientific 1300)/mass spectroscopy (Thermo Scientific ISQ-QC) detector (TD-GC–MS) (Fig. 4) with a fused-silica capillary column (TG-624, ID: 0.25 mm, length: 30 m, film: 1.4 µm). Temperature programming was maintained from 65 to 170 °C with a constant rise of 5 °C/min and the temperature was increased further by 10 °C/min up to 220 °C and held isothermal at 220 °C for 5 min. Mass spectra were recorded at 70 eV, interface temperature 250 °C, ion source temperature 220 °C. For TVOC determination, data from the Wiley and NIST libraries were used.

Results and discussion

The concentration of TVOCs in the indoor environment

After analysis of the samples, the concentration of VOCs was calculated with the help of Eqs. 1 and 2 (Radiello 2019).

$$Q_k = Q_{298}(K/298)^{1.5} \tag{1}$$

where Q_K is the sampling rate at the temperature K and Q_{298} is the reference value at 298 K.

$$C = \left(M/Q_k^* t\right) \times 1,000,000 \tag{2}$$

where:

C: Average concentration µg/m.^{3}

M: Mass of analyte in µg.

Q_K: The sampling rate.

T: Exposure time in minutes.

In the proposed real-time system, sensor nodes were programmed to measure data once a minute. However, their hourly averages were taken into account when recording in the database. The concentration of TVOCs was recorded by the WSN and passive tubes. The mean, maximum, and minimum concentrations of samples of TVOCs (µg/m^3) are shown in Table 2.

Table 2 Mean, maximum, and minimum, concentrations of TVOCs (µg/m^3) collected by WNS and passive sampling tubes in the lab

| Place	TVOC (µg/m^3)			
	*N	Mean	Maximum	Minimum
Collected data from 2 WSN Lab 1 (per min)	1238	79.65	392.86	11.23
Collected data from 2 WSN Lab 2 (per min)	1238	78.04	298.19	4.86
Collected data from 2 Passive sampling Lab 1 (per week)	16	85.76	152.12	37.73
Collected data from 2 Passive sampling Lab 2 (per week)	16	81.87	127.18	34.52

*N: Numbers of samples were monitored in one month by WSN and passive sampling

The maximum concentration of TVOCs was measured by the WSN at 392.86 μg/m^3 in Lab-1 on 13 October 2020 at about 10:00. The minimum concentration of TVOCs was measured by WSN at 4.86 μg/m^3 in Lab-2 on 1 October to 2 November 2020 at about 11:00 (Table 2).

## Comparison of TVOCs collected from passive sampling and values with sensors:

The mean concentrations of TVOCs measured by WSN and passive sampling are shown (Fig. 5). As seen in the graph, the concentrations of TVOCs collected by the passive sampling method were close to the values collected with sensors. During the period specified in the study, the WNSs data were measured every minute and recorded in the central database. In the passive conventional method, sampling tubes were placed in the measurement area and weekly samples were collected. These collected samples were analyzed in the laboratory. Methods were compared and the observed accuracy of the methods was about 5.89%. This result proved that the data recorded by sensors, which was the main purpose of the study, would produce data as high quality as passive sampling.

We compared the two methods of sampling and, as a result, identified the advantages and disadvantages of these
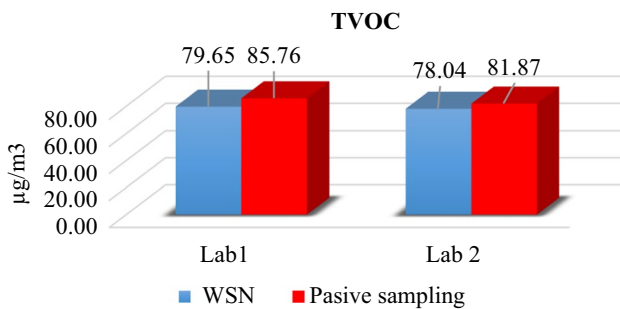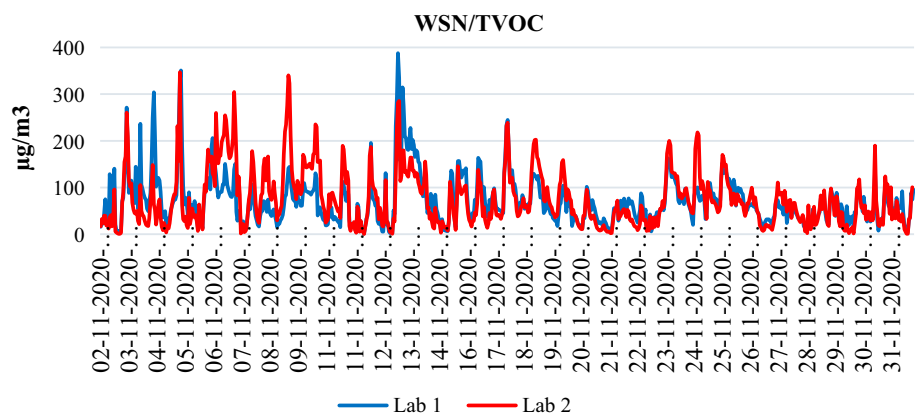
two systems. WSNs are low-cost and require less workforce than passive sampling. In addition, in terms of time, it has more advantages than passive sampling. In passive sampling, the collected samples need to be analyzed, and the cost of the analysis is high, but in WSNs, there is no need for any analyses, and the data is recorded directly. In general, when the two methods are compared in terms of workforce need and cost, WSNs are thought to be much more advantageous. In addition, WSNs can be used as proactive systems in hazardous measurement areas or processes to take precautions against subsequent damage before it reaches larger dimensions. In passive sampling, the samples collected from the area must be analyzed in a laboratory, so possible risks cannot be predicted quickly.

Based on the advantages and disadvantages of these two methods, unlike the passive sampling method, with WSN it is possible to pinpoint deterioration in indoor air quality at any specific time. In the case of the latter method, data are continuously monitored every minute by sensors (Fig. 6). The TVOC concentration was compared between two laboratories. Entries and exits, as well as the cleaning of these laboratories, were recorded daily. Generally, cleaning was done in the labs 1 or 2 days a week between 10 and 11 AM. As a result, the sensors recorded high values in both labs during that time. At 10 o'clock on November 13, TVOC levels were observed to be higher in Lab 1, at about 396.86 μg/m^3. According to the records, a meeting was taking place at that time, and the number of people in the room was high. According to the general findings, the TVOCs rate in Laboratory 2 were higher than in Laboratory 1. This was because Lab 2 has a smaller area and fewer people entering and exiting compared to Lab 1. When analyzing the results, it was impossible to observe hourly changes in VOCs concentrations using the classical method (passive sampling). However, with the WSN systems, staff could promptly detect the changes. Consequently, an intervention to deal with poor indoor air quality could be implemented to avoid exposure to excessive VOCs.

Fig. 5 The mean concentrations of TVOCs measured by WSN and passive sampling

Fig. 6 Continuous monitoring of TVOCs by WSN

Conclusion

Indoor air quality levels in public areas such as hospitals, schools, and research laboratories are an important issue for local administrators. Unfavorable environmental conditions due to poor quality of the indoor air not only pose a threat to the health of the laboratory staff but also can greatly affect the results of some analyses. In these places, continuous monitoring of air quality is vital in terms of the health of personnel. However, continuous monitoring of these places with passive methods is impossible for many institutions in terms of cost, workforce, and time. Continuous monitoring of these areas and on-time prevention of potential risks require different perspectives and approaches. Recently, it seems that Wireless sensor networks (WSNs) have been used in similar studies. Although the accuracy of classical methods has been proven, setting them in measurement areas and analyzing the collected data regularly is a time-consuming and costly process. In addition, there is a constant need for a workforce. WSNs offer many advantages over passive sampling, but errors may arise from sensor measurement methods. Within the scope of this study, the accuracy of the sensor data has been proven. By comparison with the passive method, it has been proven that the WSN systems produce accurate data that will enable action plans to be implemented promptly. Result of this study the weekly averages of the data from the classical method and WSNs were comparable in terms of correctness. The WSN nodes used in the study can be used to detect potential risks on time in the laboratories and similar hazardous areas. In the WSN systems, results are obtained in a short time and the cost required for the established infrastructure is lower. After WSN systems are installed, online monitoring of the results will allow immediate recognition of changes in indoor air quality parameters. An ideal WSN system for healthcare in public buildings (laboratories, hospitals, schools…) can predict changes in time and alert the user. This system is immensely beneficial in monitoring indoor air quality conditions in public buildings to comprehend the current situation of air quality. This study also provides the opportunity to control the impact of poor air quality on public health in the short and long term.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Not applicable (There is no human or animal subject in this study so no need for ethical approval).

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