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Testbed Development of IoT-Based Volumetric 3D Air Monitoring for Indoor Artificial Photosynthesis Applications

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Abstract

Indoor air quality (IAQ) monitoring is critical in offering healthy indoor environments especially to applications that demand accurate control of the environment like artificial photosynthesis, which is used indoors. Traditional methods of IAQ monitoring, which are single-point, or two-dimension (2D) sensors, cannot be relied on to detect spatial and vertical variations on pollutants indoors. It introduces the Internet of Things (IoT)-based volumetric three-dimensional (3D) IAQ monitoring architecture in this project with numerous M5Stack sensor nodes to measure the Total Volatile Organic Compounds (TVOC), equivalent carbon dioxide (eCO2), hydrogen, and ethanol concentrations and transmit them wirelessly to a cloud-based visualisation platform. The experimental analysis, which is carried out in a lecture hall setting where perfume spray is used as a source of volatile organic compounds under a controlled environment, proves that the proposed 3D monitoring system is capable of detecting the spikes in the concentration of the local pollutants and the pattern of the vertical dispersion. The findings indicate that the 3D system is effective in determining the spatial source and concentration of the pollutants that cannot be easily detected through the 2D techniques of monitoring. Such results demonstrate that the suggested 3D IAQ monitoring testbed offers improved spatial resolution and a more steady insight into the environment to approve its applicability to scalable indoor air monitoring and future uses in smart environmental control systems.

1. Introduction

Indoor air quality (IAQ) is now a critical issue in industry, education, and the home since it directly affects human health, comfort and productivity. The indoor air quality regulatory agencies have also established the indoor air quality regulations to regulate the exposure level to chemical and biological pollutants, but the traditional methods of measuring IAQ uses only the fixed point sensors and the laboratory analysis and testing, which is too expensive and cannot be applied to real-time measurement of the indoor environment, which is dynamically changing [1]. Air pollutants like carbon dioxide (CO2), volatile organic compounds (VOCs), hydrogen (H2), and ethanol are not uniformly distributed spatially at an occupancy level or equipment layout but instead depend on the airflow patterns and this is why they are incompletely represented when measured either by the traditional two-dimensional (2D) or single-point methods [2].

The eCO2 is a universal IAQ indicator commonly applied to ventilation efficiency and occupancy rates. High levels of eCO2 are also indicators of poor ventilation and relate to poor mental performance and occupant distress [3]. TVOC is a total measure of chemical pollution that can be attributed to cleaning agents, furnishings, industrial operations and human actions. Long-term exposure to high levels of TVOC may have neurological, respiratory, and immune system effects [4]. Though hydrogen and ethanol are less popular in the field of IAQ research, they are applicable to artificial photosynthesis set-ups since they take part in chemical reactions and may be concentrated in small, enclosed areas of houses [5].

The majority of available IAQ monitoring systems are 2D volumetric mappings, in which the sensors are located at a constant height, usually in the human breathing zone, to form horizontal maps of pollutants distribution [6]. Although it offers more spatial information as compared to single-point sensing, this approach does not measure air movement in a vertical direction or layers of gas. This limitation can be resolved with the use of three-dimensional (3D) IAQ monitoring systems which deploy sensors at various heights and spatial positions to provide a complete volumetric study of the dynamics of indoor air [7]. These systems give more precise portrayal of the pollutant behavior that is dependent on ventilation systems, thermal gradient, and human activities.

The recent advancements proved the usefulness of IoT-based IAQ systems that utilize a microcontroller platform with gas sensors and cloud services. Such systems are scalable, low power usage and provide real time visualization using dashboards and cloud repositories [8]. Indeed, comparative research validates IoT-based monitoring architectures to contribute to higher reliability, adaptability, and environmental consciousness of building and industrial-based smart designs [9].

According to the formulated research gaps, the study plans to design and test an IoT-based three-dimensional indoor air quality monitor testbed to suit artificial photosynthesis use. This study aims at examining currently available IAQ monitoring methods and IoT technologies as applied to indoor environmental control, developing and implementing an operational 3D IAQ monitoring system that can provide volumetric gas distributions, and evaluating the performance and effectiveness of the proposed system in aiding artificial photosynthesis research by providing accurate, reliable, and continuous environmental data.

2. Methodology

The proposed system is an indoor air quality testbed with IoT technology and comprised of a series of sensor nodes in Volumetric 3D arrangement. The nodes will measure the air quality parameters and send information wirelessly to a cloud platform to monitor the air quality in real time.

2.1 Materials and Methods

The hardware platform of the system is comprised of a series of identical sensing nodes which are constructed around the M5Stack Basic microcontroller, which is based on the ESP32 chipset, and provides an integrated Wi-Fi connection, enough computational ability as well as low power consumption appropriate to IoT implementation [10]. Each of the nodes has a TVOC/eCO2 gas sensor, which can measure total volatile organic compounds (TVOC), equivalent carbon dioxide (eCO2), hydrogen (H2) and ethanol. The sensor interacts with the microcontroller through the I2C interface enabling the sensor to acquire environmental data reliably and continuously. The battery supply was also regulated so that the nodes could be powered, allowing effective location and independent working within the indoor environment.

Each sensing node was programmed with the embedded software created with the help of UIFlow programming environment which facilitates rapid development of firmware and integration with the cloud services easily [11]. In use Fig.1(a), IAQ parameters are sampled by each node periodically, sensor data are processed locally at the node, and the formatted results are sent wirelessly by Wi-Fi back to a central access point. The implementation of a cloud-based data logging platform was done in Google Sheets that acts as a lightweight database and a real-time visualization dashboard. The incoming data are also stamped automatically and systematically arranged based on the location of the sensors, which allow real-time monitoring, analyzing of historical data and observing the trends without using sophisticated server systems [12]. The circuit schematic, show in Fig. 1 (b) presents the detailed with wiring of the M5Stack Basic to the TVOC/eCO2 sensor for the IoT-based monitoring system.

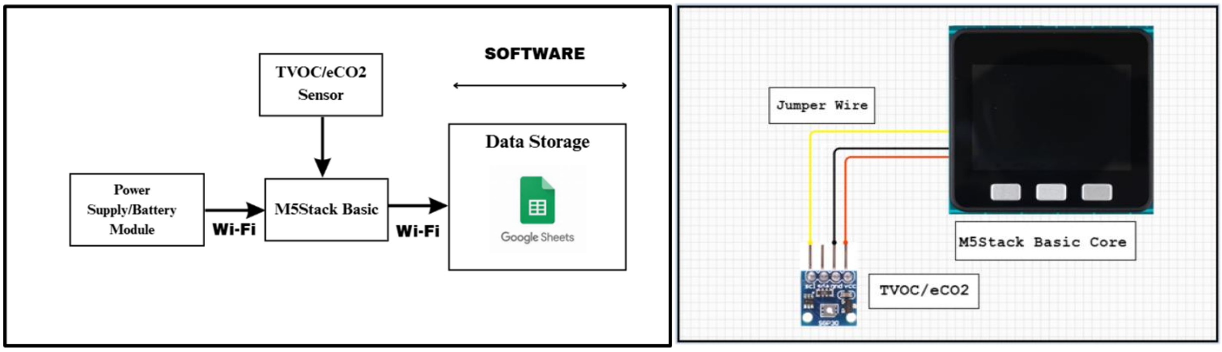


Fig. 1 *Project (a) Block Diagram (b) Circuit Diagram*

The sensing nodes embedded software was created in the UIFlow programming environment which can be used to develop firmware quickly and easily integrate it with cloud services [13]. In the working process in Fig. 2, every node is sampling IAQ parameters periodically, processing sensor data on the node and transmitting the formatting measures wirelessly over Wi-Fi to a central access point. An online data logging platform was developed with the help of Google Sheets database and visualization dashboard that works as a lightweight database and real-time visualization. The incoming information is automatically time-stamped and sorted by sensor position, thus allowing real-time data tracking, historical data analysis, and trend visualization without the need to have sophisticated server infrastructure [14].

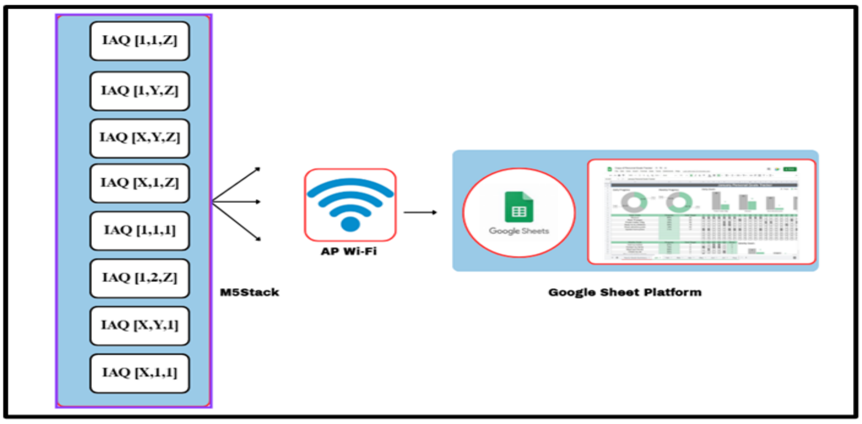


Fig. 2 *Data Flow Diagram of IoT-Based Indoor Air Quality Monitoring System*

In Fig. 3 the designed testbed was installed in a closed indoor system that was an imitation of a possible artificial photosynthesis deployment area. This system runs continuously to find the IAQ data at various spatial positions and at various heights. The aspects of system performance that were assessed included the data consistency, the reliability of wireless communication, real-time responsiveness and the ability to detect spatial variations in the gas concentration. The results collected were used to determine how effective the proposed IoT-based 3D IAQ monitoring system was in the capture of volumetric indoor air quality data in relation to the use of traditional monitoring systems.

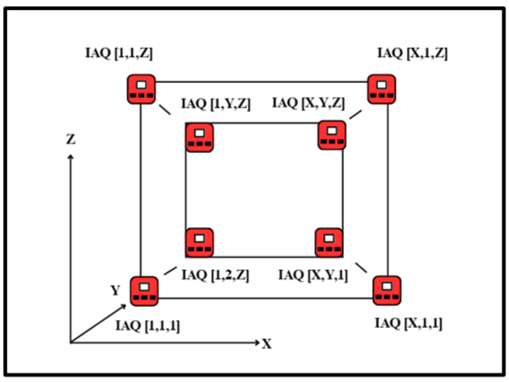


Fig. 3 *Volumetric IAQ device configuration model in 3D space*

The workflow of the proposed gas monitoring system based on the IoT is presented in Fig. 4. After the microcontroller boils, the sensors connected to it are set up and turned on to measure the most important indicator of indoor air quality, such as Total Volatile Organic Compounds (TVOC), equivalent carbon dioxide (eCO2), hydrogen (H2), and ethanol. These parameters are on-gangly obtained in the real-time mode of detecting changes in gas concentrations in the monitored environment. The sensor information is received by the microcontroller where sensory information is assessed to maintain signal stability and data integrity prior to data transmission. Processed data are then transmitted wirelessly to a cloud-based platform and are logged and visualized with Google Sheets to monitor them in real time and to analyze them historically. The closed loop process enables the continuous monitoring of the presence of gases and helps detect the abnormal state in time to enhance the control of environmental safety.

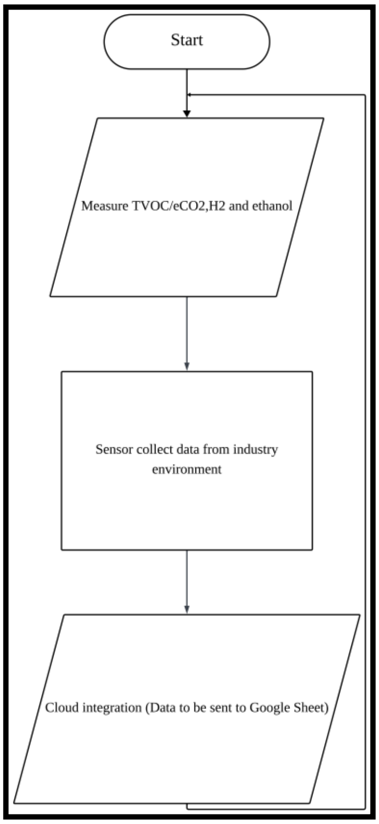
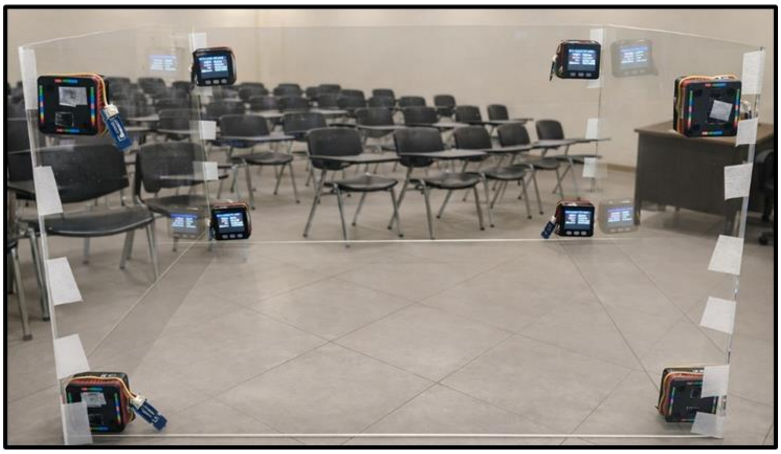


Fig. 4 *System Flowchart*

2.2 Design Visualization of Prototypes

The 2D prototype is a spatial layout of small sensor nodes, which is supported by the M5Stack Basic microcontroller with each sensor node, having SGP30, and other sensors to measure TVOC, eCO2, H2, and Ethanol. The arrangement in Fig. 5 (a) shows the operational arrangement of the nodes and their local presentation abilities, which show how the concept of multi-point monitoring can be utilized to detect changes in air quality over a specified plane. The final prototype, as shown in Fig 5 (b) was built on a compact and properly aligned. The monitoring system uses an 8-M5Stack-based sensor grid with eight strategically placed 3D grid over Bilik Kuliah 6 to reduce blind spots and increase the quality of gas concentration mapping. TVOC, eCO2, H2, and Ethanol are all measured in each node using an SGP30 sensor, thus allowing the volumetric air quality to be measured. The empirical results prove the efficiency of the system to record spatial variations and high-risk events to facilitate chemical safety management and accurate control of the experimental conditions.

(a)



(b)

Fig. 5 *Overview of the (a) 2D Prototype Air quality (b) 3D Prototype Air Quality*

3. Result

The experimental findings approve that all eight sensing devices of indoor air quality were able to transmit real-time air quality data to the Google sheets cloud-based system without loss and discontinuity of data. Demonstrates the interface of Google Sheets that indicate synchronized streams of data on devices 1-8, including TVOC, and eCO2 measurements. The fact that the data is updated constantly and consistently on all devices means that wireless communication is stable and the data logging onto the cloud is credible. The possibility of reading the air quality simultaneously on several devices allowed a direct comparison of the spatial differences in air quality, as well as the in-depth analysis of volumetric data. This data transfer has been successful to confirm the usefulness of Google Sheets as a central data repository to monitor, visualize and post-analyze data on the indoor air quality of multiple devices in real-time.

The concentrations of TVOCs recorded by eight sensor nodes, as shown in Fig. 6, can be characterised by the start of a slow increase and a subsequent decreasing pattern, with the strongest peak during the period of 11: 20 AM- 11: 30 AM between a majority of devices. This concomitant increase indicates a short-term event of VOC emissions that is characterised by spatially heterogeneous dispersion. The highest readings reported in device 3 were 191 ppb at 11:28:05 AM, which is repeatedly followed by the high readings of 138 ppb and 98 ppb as well, which showed that there was a localised or persistent source of emission. Devices 1 and 2 showed intermediate peaks of 77 ppb and 84 ppb which is indicative of intermittent exposure to the device whereas Devices 4, 5 and 6 showed low levels of concentrations of below 25 ppb otherwise being the relatively clean areas. Devices 7 and 8 had the short-duration peaks of 50 ppb and 25 ppb respectively. These spatial and temporal differences in Fig. 6 indicate how the proposed 3D IAQ monitoring system can localise areas of

Progress in Engineering Application and Technology Vol. 7 No. 1 (2026) p. 404-412

emission prone and concentration gradients. This ability comes in handy especially in artificial photosynthesis processes where local gas composition and flow dynamics play a crucial role in determining the performance, safety and optimization of the reactor.

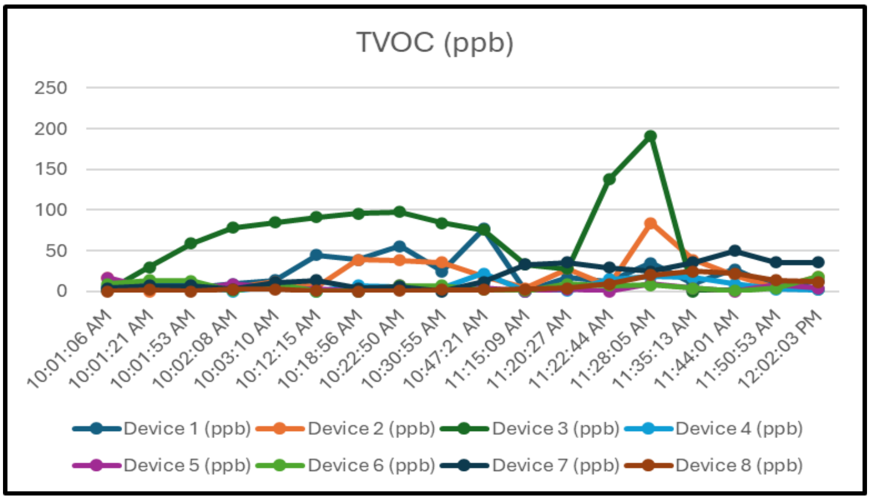


Fig. 6 *Graph Plot of TVOC comparison*

Fig. 7 demonstrates that the concentrations of eCO2 of the eight sensor nodes have specific spatial and temporal differences over the course of monitoring. Most devices kept the baseline eCO2 values at 400-450 ppm, which is in line with the ambient air and signifies relatively stable ventilation. Conversely, the readings of Device 3 had a high concentration of eCO2, with a peak value of 2200 ppm at 11:28:05 AM, and high values of 1589 at 11:22:44 AM, indicating that there was a local and active source of CO 2 or a lack of air movement. Devices 7 and 8 increased moderately with the maximum values of 528 ppm and 573 ppm, respectively, whereas the rest of Devices 1, 2, 4, 5 and 6 were near the background of the area (570-580 ppm). The spatial heterogeneity of Fig. 7 indicates the relevance of distributed multi-point sensing and shows that gradients of CO 2 accumulation and concentration can be localized by the proposed 3D IAQ monitor system. This ability is important in artificial photosynthesis systems, in which the efficiency of reactions catalytic activities, and operation safety are strongly dependent on the CO 2 concentration and distribution.

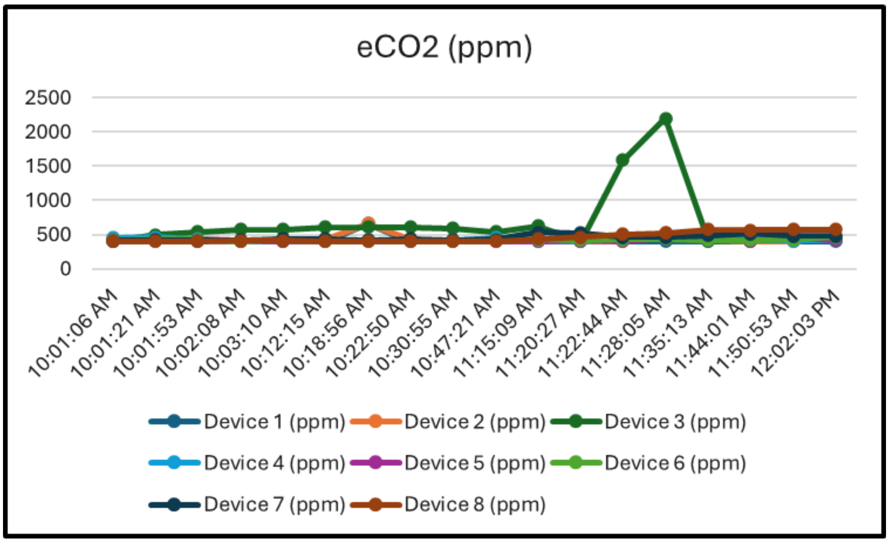


Fig. 7 *Graph Plot of eCO2 comparison*

To test the responsiveness and spatial sensitivity of the proposed 3D air quality monitoring system with respect to a commercial perfume as a surrogate of volatile organic compounds (VOCs), a controlled gas release experiment was carried out as illustrated on Fig. 9. Perfume was chosen because it is highly volatile and contains ethanol which can be reliably detected by the TVOC, eCO2 and ethanol embedded sensor, which can be performed safely and reproducibly. The perfume was released in place of Device 3 that had already contained high levels of pollutants. Immediately, the sensor node replied to the sensor node with a sharp rise in the TVOC and ethanol concentrations, with a resultant corresponding rise in the eCO2 values.

Fig.9 *Simulated Gas Leakage Test Using Perfume Near Device 3*

Fig. 10 represents spatial distributions of TVOC and eCO2 observed on the indoor site using eight monitoring equipment. The concentrations of TVOC (191 ppb) and eCO2 (2200 ppm) were much higher in device 3 than in other devices, which had lower and stable results. This localized rise shows that the concentration of the gas is not distributed all over as it is concentrated on the area around Device 3. The low concentrations read by the neighboring instruments also support a minimal dispersion of the source, proving the system to be able to focus on possible gas leakage and find dangerous areas.

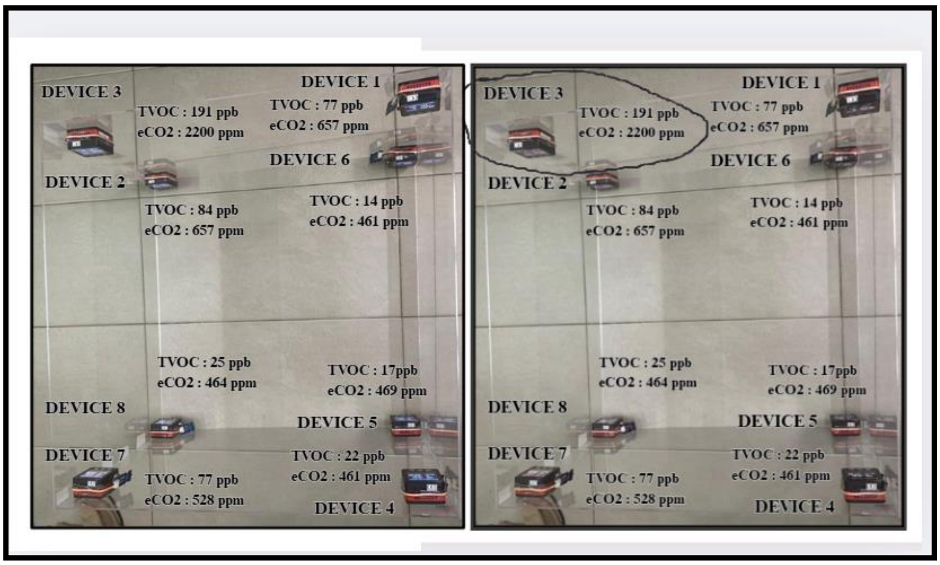


Fig. 10 Localized Gas Accumulation Detection based on TVOC and eCO2 Measurement

4. Conclusion

This project was able to design and deploy a 3D indoor air quality (IAQ) volumetric monitoring system based on IoT in real-time and applied in artificial photosynthesis. The system was successful in measuring the essential IAQ parameters (TVOC (eCO2 equivalent), hydrogen (H2), and ethanol) in a model indoor environment using a distributed multi-point sensing architecture utilizing the M5Stack Basic microcontroller. The experimental findings revealed credible real-time data transmission, visualization, and storage with Wi-Fi and cloud infrastructure without loss of data. The multi-point approach allowed detecting the spatial and temporal differences in the air quality and identifying localized sources of the emission and possible risk areas, which cannot be identified with the help of the single-point measurements. Altogether, the suggested system provides a stable, scalable, and robust solution to real-time volumetric IAQ mapping and would be suitable for indoor artificial photosynthesis testbeds and other complicated indoor settings, with a high potential of future improvement by advanced sensor-based solution through advanced analytics and intelligent control methods

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: study conception and design: Nik Syazwa Najihah Nik Zin, Faiz Asraf Saparudin; data collection: Nik Syazwa Najihah Nik Zin; analysis and interpretation of results: Nik Syazwa Najihah Nik Zin; draft manuscript preparation: Nik Syazwa Najihah Nik Zin, Faiz Asraf Saparudin. All authors reviewed the results and approved the final version of the manuscript.

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