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Plant-Based Air Purification with Real-Time Monitoring: A Hybrid Hydroponic Sensor System for IAQ Enhancement

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Abstract

This study addresses the growing concern of poor indoor air quality (IAQ) in urban environments, which has been associated with various health problems. Many conventional air purification systems are energy-intensive and less effective against certain gaseous pollutants. To overcome these challenges, a hybrid hydroponic-sensor system is developed, combining air purification by plants with IoT-enabled real-time environmental monitoring. Spider plants, golden pothos, and philodendron gold, known for their natural air-cleaning capabilities, were cultivated using a nutrient film technique (NFT) setup. Environmental parameters including temperature, humidity, CO_2, total volatile organic compounds (TVOCs), and pH were monitored using an ESP32 microcontroller integrated with SHT31, CJMCU-811, and analog pH sensors. Data was displayed on an LCD and accessible via the Blynk mobile application. A three-week experimental evaluation demonstrated a reduction of 20–30% in CO_2 and 35–50% in TVOC concentrations, while maintaining optimal plant growth conditions. This affordable and low-power consumption solution enhances IAQ and contributes to healthier indoor environments in homes, offices, and classrooms. The findings highlight the potential of integrating plant-based phytoremediation with off-the-shelf IoT technology for sustainable and scalable indoor air management.

1. Introduction

Indoor air quality (IAQ) is a growing concern in urban environments where individuals spend the majority of their time indoors. Exposure to elevated levels of carbon dioxide (CO_2), volatile organic compounds (VOCs), and particulate matter can lead to respiratory illnesses and cognitive impairment. Conventional air purification systems, such as HEPA filters and mechanical ventilation, are often energy-intensive and limited in addressing both chemical and biological contaminants.

Recent studies have highlighted the potential of phytoremediation using indoor plants to improve IAQ. However, most hydroponic systems focus primarily on plant cultivation without incorporating real-time environmental monitoring. This paper presents a hybrid hydroponic-sensor system that integrates air-purifying plants with Internet of Things (IoT)-based monitoring using ESP32, SHT31, CJMCU-811, and pH sensors. Data is visualized via LCD and the Blynk mobile platform. The system offers a low-cost, energy-efficient solution for enhancing IAQ in confined spaces, contributing to sustainable indoor environmental management.

Indoor air pollution poses a significant threat to human health, particularly in enclosed environments with limited ventilation. Prolonged exposure to pollutants such as CO_2, VOCs, and fine particulate matter has been associated with respiratory disorders, cognitive decline, and other chronic conditions. Existing air purification technologies though effective in particulate removal often involve high energy consumption, recurring maintenance costs, and limited efficiency in removing gaseous contaminants.

Moreover, current hydroponic systems are primarily designed for plant growth and do not address air purification as a primary objective. They also lack integrated real-time monitoring mechanisms, which are essential for optimizing both plant health and indoor environmental quality. There remains a gap in the development of a cost-effective, energy-efficient system that simultaneously supports plant cultivation and enhances IAQ through intelligent sensing and data-driven feedback.

The primary objective of this study is to develop a hybrid hydroponic-sensor system that enhances indoor air quality through a combination of plant-based purification and real-time environmental monitoring. The specific goals are as follows:

- To design an integrated air purification mechanism utilizing hydroponic plants known for their phytoremediation capabilities.
- To develop a compact, automated hydroponic system equipped with sensors for monitoring air and water quality parameters.
- To evaluate the effectiveness of the system in reducing indoor CO_2 and VOC concentrations, and maintaining optimal temperature, humidity, and pH levels using data collected via the Blynk IoT platform.

This work focuses on the design, development, and evaluation of a hybrid hydroponic -sensor system aimed at improving indoor air quality (IAQ) in confined environments. The scope is defined as follows:

- Environmental Scope:
  The system is designed exclusively for indoor use, targeting environments such as homes, offices, and classrooms with limited natural ventilation.
- System Integration:
  The work integrates air-purifying hydroponic plants with real-time sensing of key environmental parameters, including CO_2, VOCs, temperature, humidity, and water pH.
- Sensor and IoT Implementation:
  Environmental data is collected using the ESP32 microcontroller interfaced with SHT31, CJMCU-811, and pH sensors. Data is visualized through an LCD and transmitted to the Blynk IoT platform for remote monitoring.
- Testing Conditions:
  System performance is evaluated under controlled indoor conditions (temperature: 25 ± 2°C, relative humidity: 50 ± 10%), over a three-week monitoring period.
- Limitations:
  The work excludes outdoor environments, large-scale commercial deployment, and long-term multi-seasonal analysis.

2. Literature Review

Indoor air quality (IAQ) significantly impacts human health, with pollutants such as CO_2 and VOCs linked to respiratory issues and cognitive decline [1], [2]. Conventional purification technologies like HEPA filters and mechanical ventilation systems are effective for particulate removal but consume high energy and lack efficiency against gaseous pollutants [3]. Phytoremediation using indoor plants (e.g., spider plant, golden pothos) offers a natural method to reduce indoor CO_2 and VOCs [4], [5]. Hydroponic systems, particularly those using the Nutrient Film Technique (NFT), enhance plant growth in controlled, soilless environments while conserving space and resources [6].

However, most hydroponic setups focus solely on cultivation and lack integration with IAQ monitoring. Recent developments in IoT and embedded systems enable real-time tracking of environmental conditions using sensors such as SHT31, CJMCU-811, and pH probes, managed via microcontrollers like the ESP32 [7]. Despite these advancements, limited research combines hydroponics with sensor-based air quality monitoring. This study addresses that gap by developing a compact hybrid system that integrates phytoremediation with IoT-based monitoring to enhance indoor air quality.

2.1 Current Air Purification Technologies

Several air purification technologies have been developed to address poor indoor air quality (IAQ), including mechanical ventilation systems, air purifiers, and indoor greenery. While HEPA filters effectively remove particulate matter, they are limited in addressing gaseous pollutants like VOCs. Activated carbon filters absorb VOCs and odors but require frequent replacement. Mechanical ventilation systems improve air circulation but may also introduce outdoor pollutants and increase energy consumption [8][9]. Recent IoT-based monitoring systems offer real-time data for early detection of pollutants; however, effective IAQ management also requires better building materials, occupant awareness, and integrated environmental control strategies [10], [11].

Table 1 *Pros and cons air purification technologies*

Technology	Pros	Cons
HEPA Filters	Highly Effective at removing particles (99.97% efficiency).	Ineffective against VOCs or gases.
Activated Carbon Filters	Absorb VOCs, Odors, and harmful gases.	Limited lifespan requires frequent replacement.
Hybrid	Combines multiple technologies for comprehensive purification.	Higher upfront cost.

2.2 Plant-based Air Purification

Plants naturally purify air through the process of phytoremediation, where they absorb CO_2 and harmful VOCs and release oxygen. Common indoor plants like spider plants, peace lily, and golden pothos have been proven to reduce levels of formaldehyde, benzene, and other pollutants [8]. Hydroponic systems, which grow plants in nutrient-rich water without soil, offer an ideal platform for controlled indoor environments. These systems allow for precise control of plant conditions and eliminate pests or mold often found in soil. Studies confirm that hydroponic plants, especially when combined with microbial action in the root zone, can significantly improve air quality in enclosed spaces [3], [4].

2.3 Research Gap

While prior studies highlight the effectiveness of indoor plants for phytoremediation and the use of sensors for air quality monitoring, most systems are designed in isolation either focusing on plant cultivation or environmental sensing. Existing hydroponic setups primarily aim to optimize plant growth without addressing indoor air purification. Similarly, IoT-based monitoring platforms are often applied for data collection but lack integration with biological purification mechanisms. Furthermore, many studies are conducted in controlled laboratory settings, with limited evaluation in realistic indoor environments. There remains a significant gap in developing a compact, real-time, low-cost hybrid system that combines hydroponic-based phytoremediation with intelligent environmental monitoring to actively enhance indoor air quality in everyday settings.

3. Methodology

A functional flowchart and block diagram were developed to illustrate the process logic (see Figs. 1 and 2). The study begins by gathering relevant information about hybrid hydroponic and air purification systems through a review of previous research, journals, books, and online resources. To ensure the project runs smoothly, a detailed flowchart has been developed.

Fig. 3 illustrates the main electronic components involved in the system. The schematic diagram of this work is shown in Fig. 4. Fig. 5 presents a 3D model of the hydroponic structure designed to support optimal plant growth and water circulation. For this work, Thinker Cad software has been used to design the 3D sketch. To ensure reliable data acquisition, the system utilizes the sensors listed in Table 2.

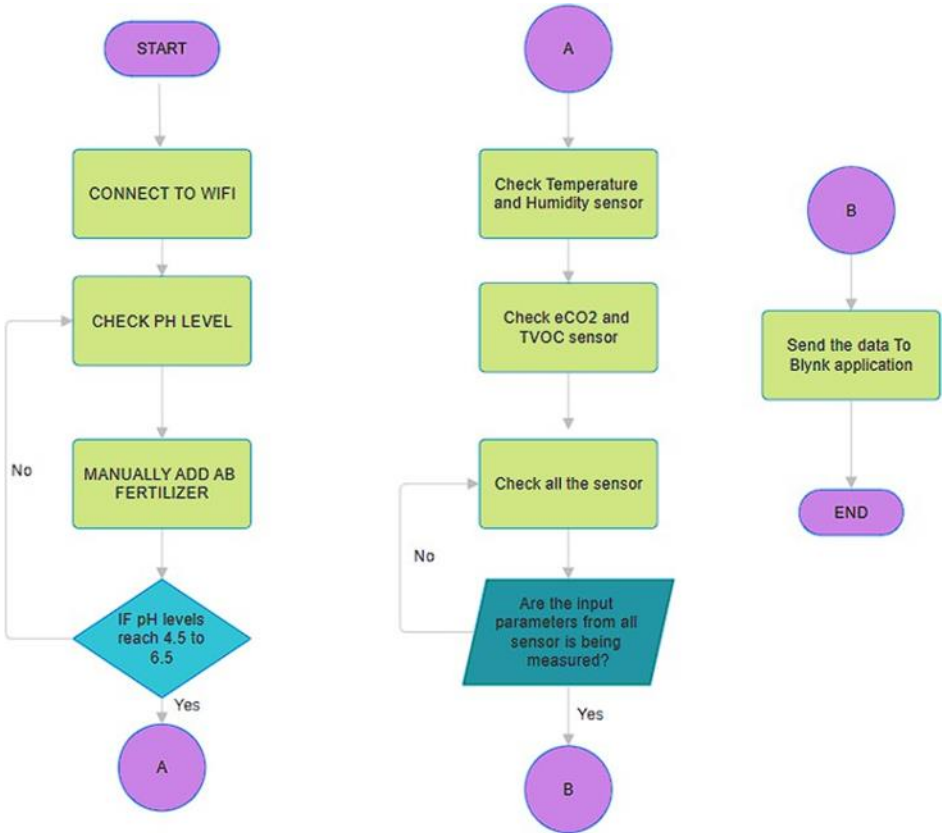

Fig. 1 *Project flowchart*

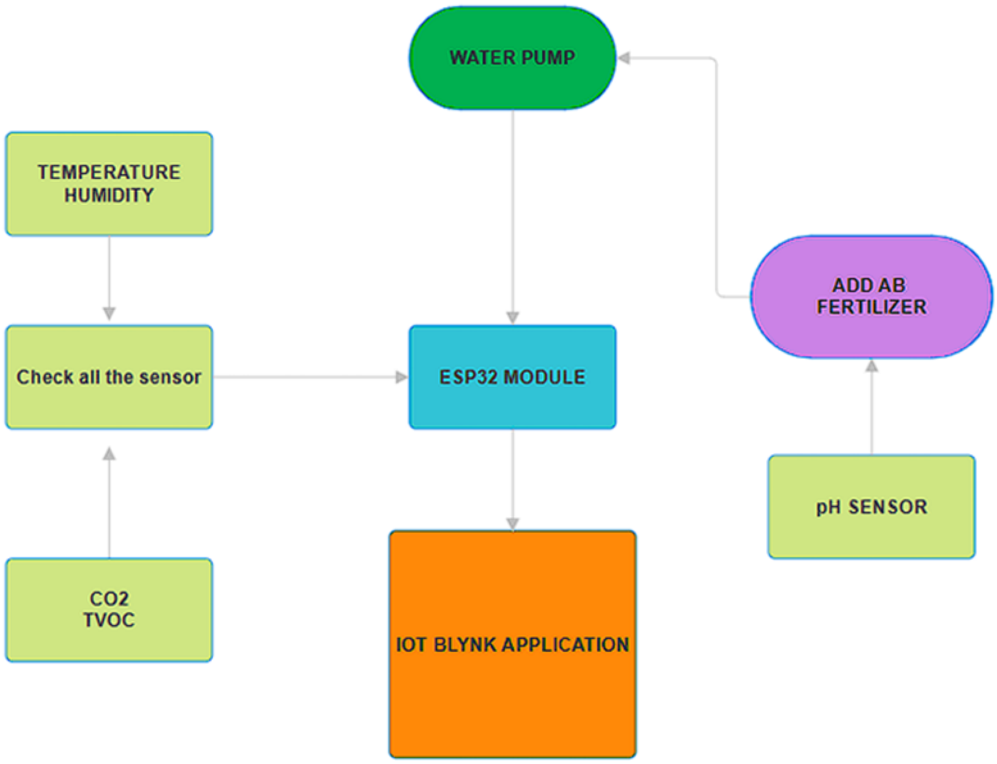

Fig. 2 *Block diagram of this project*

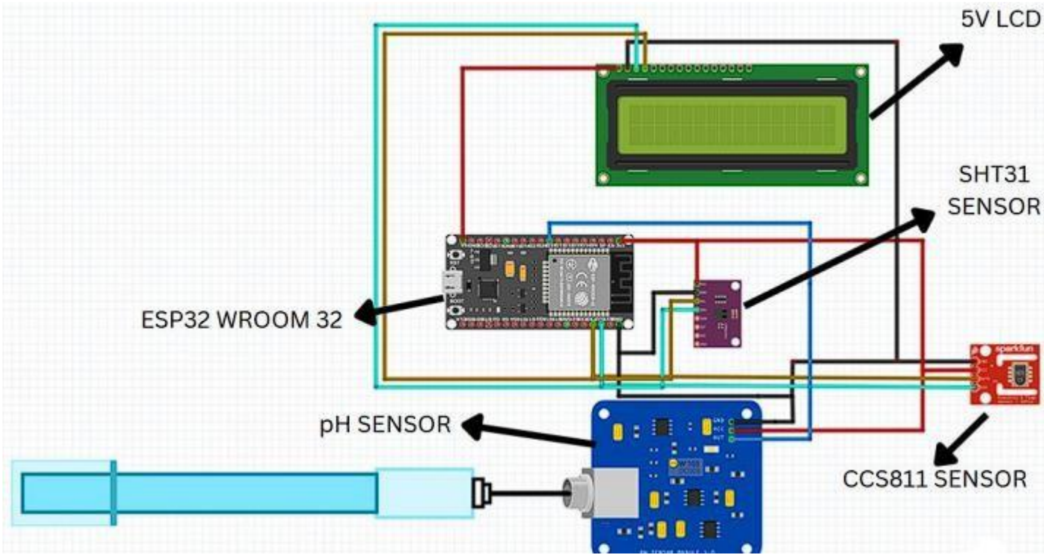

Fig. 3 *Main component of this project highlights the hardware including the ESP32 microcontroller, sensors, and wiring connections*

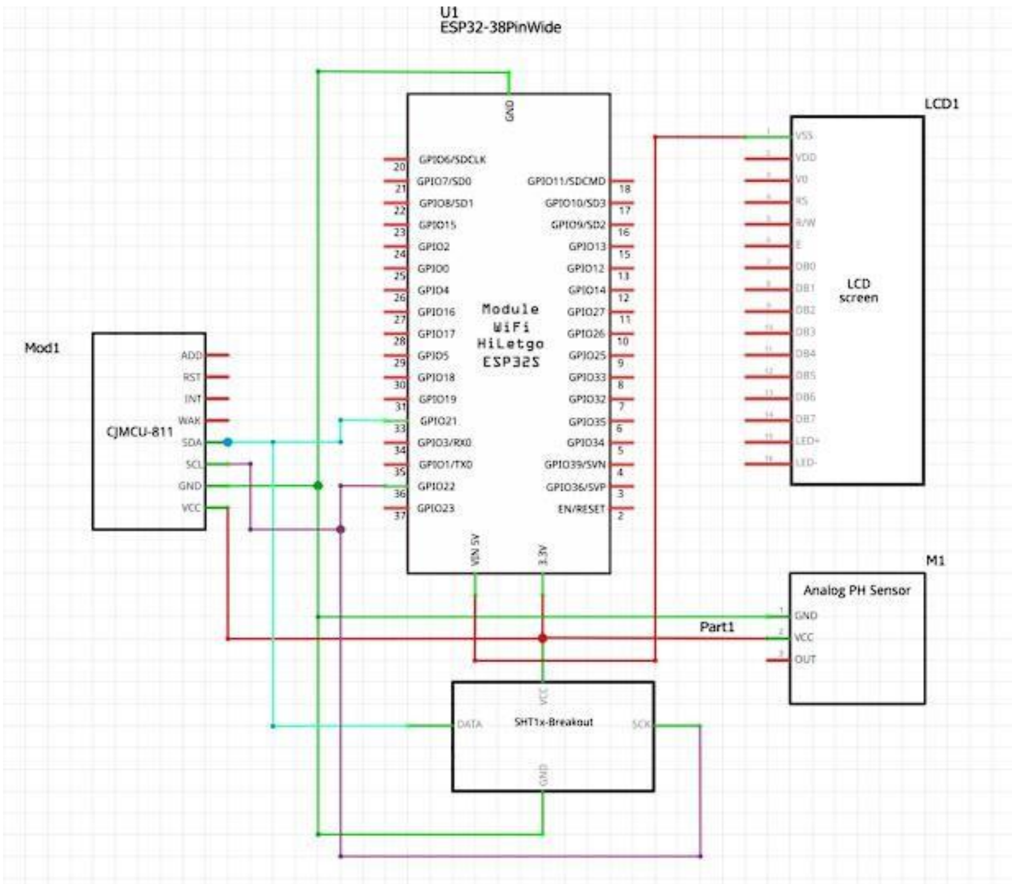

Fig. 4 *Schematic diagram of the project*

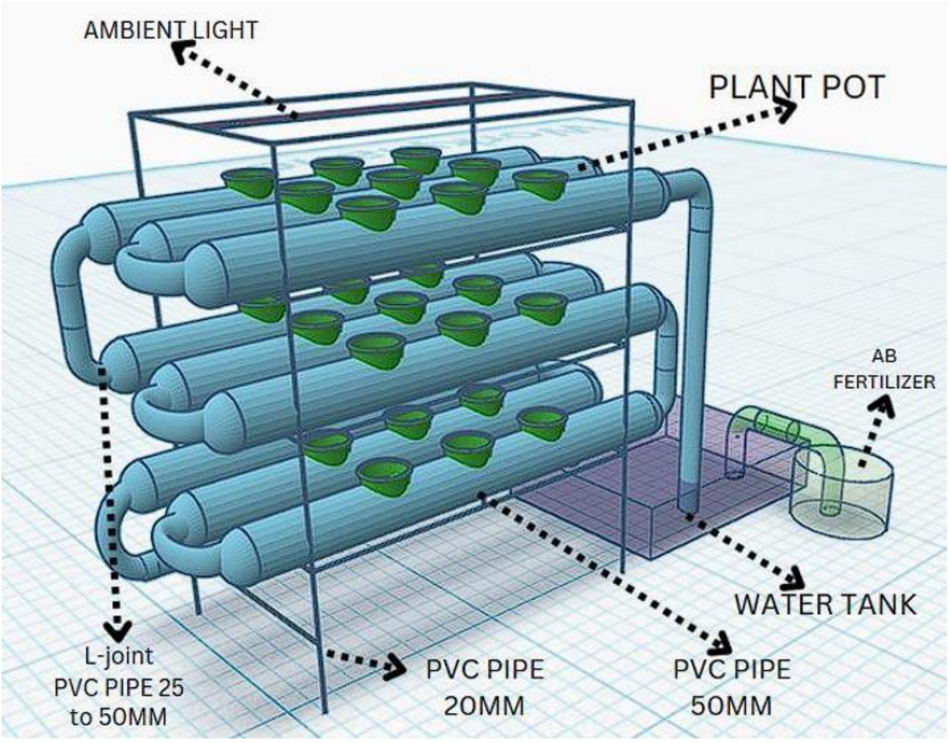

Fig. 5 *Hydroponic structure using 25mm and 50mm PVC pipes, a water tank, and plant holders*

Table 2 *Sensors and its specifications*

Sensors	Specifications
SHT31 (Temperature and Humidity Sensor)	• Temperature range: -40°C to 125°C • Humidity range: 0–100% RH • Accuracy: ±0.3°C (temperature), ±2% RH (humidity) • Response time: <8 seconds
CJMCU-811 (VOC and CO_2 Sensor - CCS811)	• CO_2 detection range: 400 to 8192 ppm • TVOC detection range: 0 to 1187 ppb • Accuracy: ±3% (CO_2); ±10% (TVOC under standard conditions) • Resolution: 1 ppm for CO_2; 1 ppb for TVOC
Analog pH Sensor	• Detection range: pH 0 to 14 • Accuracy: ±0.1 pH at 25°C • Resolution: 0.01 pH • Response time: <1 minut

4. Results

In this section, it will show and describe the result of the experimental hybrid hydroponic sensor system and report on how well the system has worked for indoor air purification. The performance of the system was tested with data from CO_2, TVOC, temperature, and humidity sensors. The response from the collected data was used to understand if the system's effectiveness in enhancing IAQ.

4.1 Hydroponic System Design

Fig. 6 shows the hydroponic design for the front view and sideview.

4.2 Sensor Data Analysis

The experimental findings CO_2 levels exceeded 700 ppm before the system was activated, indicating poor IAQ. After hydroponic plants were added, the CO_2 levels dropped and stabilized between 450–600 ppm. This demonstrates effective CO_2 absorption by the plants through photosynthesis. TVOC readings dropped from an initial 150 ppb to 50 ppb after plant introduction, confirming the plants' ability to reduce airborne chemical compounds. Temperature remained between 28–32°C, while humidity increased slightly from 65% to 75%, consistent with plant transpiration.

(a) **(b)**

Fig. 6 *Hydroponic design at (a) front view and (v) sideview*

Fig. 7 shows that over the three-week period, environmental data such as temperature, humidity, equivalent CO_2 (eCO_2), and total volatile organic compounds (TVOC) reflected variations influenced by weather conditions. The temperature ranged between 29°C and 33°C with daily fluctuations and showed a slight drop of about 2°C during rainy days. Humidity stayed mostly between 60–70%, rising by approximately 5% during the rain. eCO_2 levels began around 430 ppm and decreased by 20–30 ppm during rainy periods, indicating improved air quality. Similarly, TVOC levels remained low but dropped by around 4 ppb on rainy days, likely due to rain reducing airborne pollutants.

Fig. 7 *Air quality monitoring data over 3 weeks*

4.3 Descriptive Statistics

To support these findings, the mean, standard deviation (SD), and percentage change were calculated as shown in Table 3.

Table 3 *Descriptive statistics of environmental sensor data*

Parameter	Unit	Initial Mean	Final Mean	SD (Before)	SD (After)	% Change
CO2	ppm	700	525	±45	±38	-28%
TVOC	ppb	150	60	±15	±10	-60%

5. Conclusion

This study presents the design and validation of a hybrid hydroponic-sensor (HHS) system aimed at improving indoor air quality (IAQ). The system integrates hydroponic plants with IoT-based real-time monitoring, using sensors (SHT31, CCS811, and analog pH) connected to an ESP32. Data is displayed on an LCD and via the Blynk mobile app, enhancing user accessibility. The results showed a significant reduction in CO_2 levels (from >700 ppm to 450–600 ppm) and TVOC concentrations, indicating improved IAQ. The system maintained stable temperature and humidity, supporting both plant health and occupant comfort. Overall, the HHS system is a sustainable, low-cost, energy-efficient, and user-friendly solution for smart indoor air purification.

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Conflict of Interest

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

Author Contribution

The authors confirm contribution to the paper as follows: study conception and design: Scanly Wong Tze Hau, Nan Mad Sahar; data collection: Scanly Wong Tze Hau, Nan Mad Sahar; analysis and interpretation of results: Scanly Wong Tze Hau, Nan Mad Sahar; draft manuscript preparation: Scanly Wong Tze Hau, Nan Mad Sahar. All authors reviewed the results and approved the final version of the manuscript.

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