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The Investigation of QCM-Based VOCS Gas Sensor Sensitivity Using Impedance Analysis

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Abstract

Gas sensors play a crucial role in contemporary environmental surveillance and industrial safety, acting as an important defense against the detrimental impacts of toxic materials, especially Volatile Organic Compounds (VOCs). This study investigates cutting-edge developments in gas sensor technology using the Quartz Crystal Microbalance (QCM) dipping technique. The study improves sensor performance by applying calix[6]arene and 4-tert-Butylcalix[4]arene onto the QCM surface, showcasing its capability for accurate and effective gas detection. Experimental findings show that raising the quantity of chemical deposition layers on the QCM surface greatly enhances its sensitivity, as reflected by variations in impedance peaks. In particular, the impedance peaks diminish with more layers, emphasizing the QCM's capacity to identify even slight mass variations. Of the VOCs tested, Toluene showed the greatest impedance values, signifying stronger molecular interactions with the QCM surface in comparison to Ethanol and Acetone. This behaviour can be explained by Toluene's greater molecular size and distinctive chemical characteristics. Additional examination of vapor levels indicated that reduced concentrations lead to increased impedance peaks, highlighting the sensor's improved sensitivity at low vapor amounts. This trait is especially beneficial for identifying small quantities of dangerous gases in practical situations. To conclude, this study marks an important advancement in gas sensing technology, providing valuable information on the capabilities of QCM-based sensors for various applications. This research establishes a foundation for future advancements in gas detection systems by tackling issues like sensitivity, selectivity, and portability. The results not only advance sensor technology but also emphasize the essential function of QCM-based sensors in protecting public health and the environment.

1. Introduction

Gas sensors are essential in tracking different gases across sectors such as environmental conservation, healthcare, and workplace safety. Among these sensors, Quartz Crystal Microbalance (QCM) instruments have garnered interest due to their excellent sensitivity, rapid response time, and possibility for miniaturization. The QCM sensor functions based on the idea that adding mass to a quartz crystal changes its resonance frequency, allowing for the identification of gas molecules. Recent developments in QCM sensor technology have aimed at improving sensitivity and selectivity, with one notable method involving the application of thin film coatings.

Thin films applied to the QCM surface can selectively engage with particular gas molecules, enhancing sensor efficiency [1]. Methods such as the Layer-by-Layer (LbL) deposition approach, especially the immersion technique, provide reliable, reproducible outcomes and are particularly appropriate for sensors made from metal. Although advancements have been made, difficulties persist in enhancing the performance of QCM sensors, particularly regarding deposition techniques and their effects on thin film characteristics.

A major concern in gas detection pertains to the tracking of volatile organic compounds (VOCs), which are dangerous elements present in multiple settings, including air, water, and industrial locations. VOCs, such as benzene, formaldehyde, and toluene, are harmful not only to human health leading to respiratory problems, cancer, and various illnesses but also play a role in environmental deterioration, including air pollution and climate change [2],[3]. Employees in sectors like chemical production are especially vulnerable to these substances. Due to the prevalence of VOCs and their possible dangers, effective and precise monitoring techniques are essential. QCM sensors serve as an efficient method for VOC detection by monitoring frequency alterations as VOCs attach to their surfaces. Nonetheless, completely optimizing QCM sensors for high sensitivity, rapid response, and cost-effectiveness continues to be a major challenge.

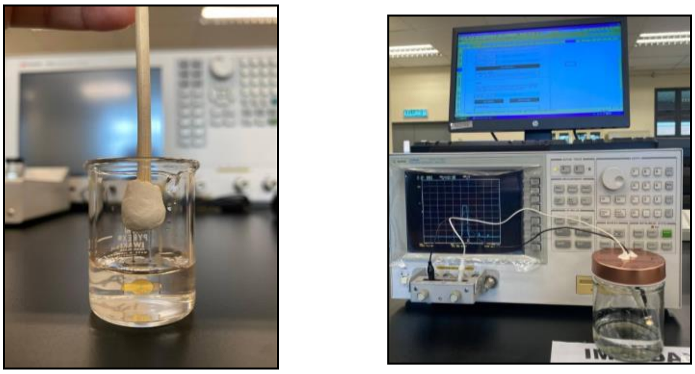
This research seeks to improve the efficiency of QCM gas sensors by examining the effects of thin film coatings, particularly via the dipping deposition technique. The study will methodically investigate how factors like immersion duration, concentration of the solution, composition, and sensing performance of the thin films. This research aims to enhance the selectivity and sensitivity of QCM sensors by comprehending the interactions between gas molecules and thin films, thereby making them better suited for diverse gas detection uses. The main objective is to create QCM sensors capable of effectively identifying VOCs and other gases at minimal concentrations, thereby enhancing safety in environmental and industrial applications.

The importance of this study resides in its ability to enhance gas sensor technology, especially for environmental monitoring, industrial safety, and healthcare applications. Enhancing the sensitivity and selectivity of QCM sensors may result in more efficient and dependable instruments for identifying harmful gases. The study also offers important insights into the basic mechanisms of thin film deposition and its impact on sensor performance, paving the path for future advancements in gas detection technology. In conclusion, this research may aid in formulating solutions that tackle the issues caused by VOCs and other environmental contaminants, providing practical uses in assessing air quality and industrial risks.

2. Materials and Methods

The approach for this research aimed at improving the sensitivity of Quartz Crystal Microbalance (QCM) gas sensors includes a sequence of specific steps, beginning with the preparation of solutions for thin films. Calix[6]arene and 4-tert-butylcalix[4]arene substances were precisely measured and dissolved in chloroform to prepare stock solutions at a concentration of 10 mg/ml. The solutions were created in a tightly regulated setting to prevent oxidation and guarantee accurate dilution. The thin films were applied to QCM sensors via the immersion technique, with layers deposited one after another. For every deposition, the QCM sensors were immersed in a solution of either calix[6]arene or 4-tert-butylcalix[4]arene for 90 seconds, then dried. This procedure was reiterated to form as many as five layers, with the quantity of layers adjusted to examine their impact on sensor efficacy. Every step was recorded to guarantee consistency and precision. An Agilent 4294A Precision Impedance Analyzer was utilized to assess the impedance characteristics of the QCM, monitoring the variations in the resonance frequency of the QCM crystal due to gas adsorption, offering valuable information about sensor performance [4],[5].

In the VOC detection segment of the research, three VOCs ethanol, acetone, and toluene were chosen because of their significance in industry and the environment. VOCs were produced by mixing each substance with deionized water at various ratios (1:100, 1:200, 1:300, 1:400, 1:500) to establish uniform exposure conditions for the QCM sensor. The QCM sensor was placed in a chamber regulated for temperature and humidity, where the resonance frequency was tracked with a frequency counter to assess the sensor's reaction to the adsorption and desorption of gases. The baseline frequency was adjusted prior to exposure, and changes in frequency were monitored to assess the sensor's responsiveness to different levels of VOCs. The QCM sensor's performance was subsequently evaluated against conventional gas detection techniques to determine its efficiency in identifying VOCs at minimal concentrations [5],[6]. This approach seeks to enhance the sensitivity and selectivity of QCM sensors, progressing their use in VOC detection for environmental and industrial surveillance.



(a) (b)

Fig. 1 Methods and equipment used for QCM analysis (a) Dipping method on QCM sensor; (b) The Agilent 4294A Precision Impedance Analyzer setup

3. Results and Discussion

3.1 Impedance Analysis of Fabricated QCM

The study examined how layer deposition affects the impedance properties of the QCM sensor, particularly with calix[6]arene and 4-tert-butylcalix[4]arene in different layer arrangements (one pair, two pairs, three pairs, four pairs, and five pairs). The results showed that a reduced number of layers resulted in a greater impedance response, as a denser mass loading on the QCM surface had a more pronounced impact on the resonance frequency. A single set of layers, containing a greater mass concentration, generated the most significant impedance peak. With the addition of more layers, the total mass loading was distributed over a wider area, leading to lower impedance values. This research underscores the intricate connection among mass loading, viscoelastic characteristics, and layer deposition, all of which affect the QCM sensor's impedance response and its general effectiveness in sensing tasks.

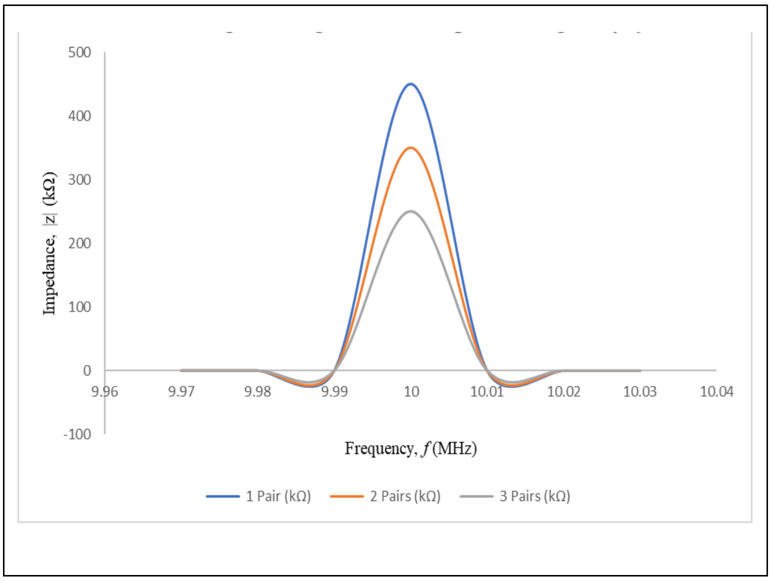
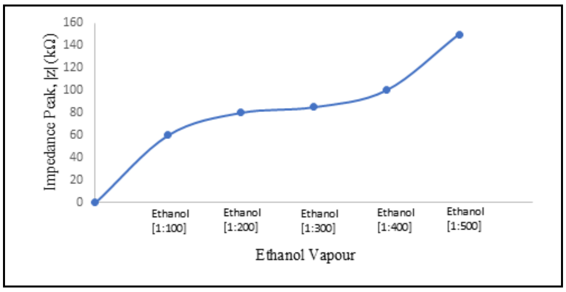


Fig. 2 Graph of impedance peak versus frequency for deposition layer by layer in pairing

3.2 Sensitivity QCM Sensor Based on Their Layer of Pair

The experiment examined the connection between impedance (Z) and frequency (ƒ) on a synthetic QCM sensor surface subjected to VOC vapours Ethanol, Acetone, and Toluene. The findings indicated a distinct relationship between impedance and frequency, where impedance rise alongside increasing VOCs concentrations, attributed to the additional mass loading on the QCM surface. The impedance peaks increased with the addition of more layer pairs on the surface, as the extra layers resulted in greater shifts in resonance frequency. Among the various configurations, the sensor featuring three pairs of layers showed the greatest impedance, indicating its enhanced sensitivity to mass concentration. Toluene, due to its increased molecular weight and distinctive chemical characteristics, exhibited the highest impedance, surpassing both Ethanol and Acetone. These results emphasize the significance of grasping the connection between impedance, layer deposition, and VOCs detection to enhance sensor efficacy in applications like environmental monitoring and industrial safety.



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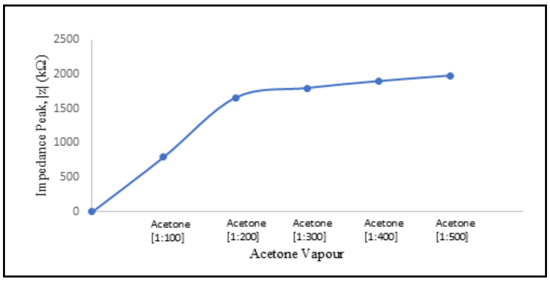

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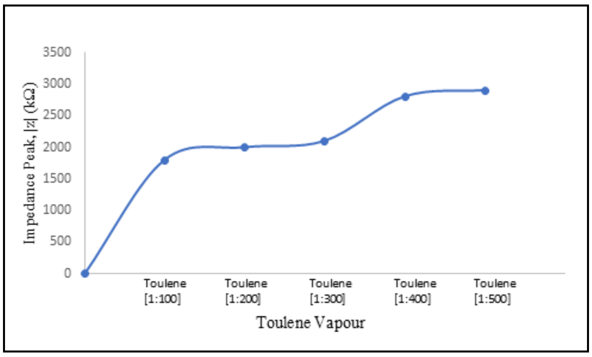
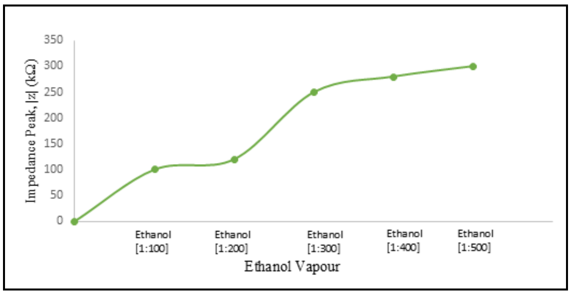


(c)

Fig. 3 Graph of impedance peak versus different concentration VOCs vapour for (a) Ethanol; (b) Acetone; (c) Toulene



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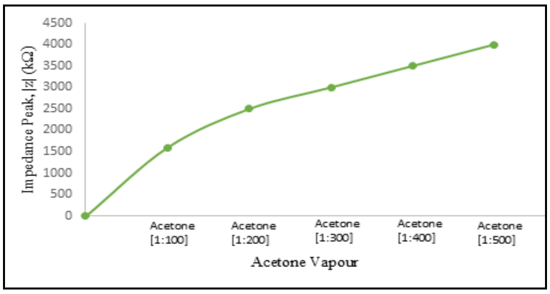

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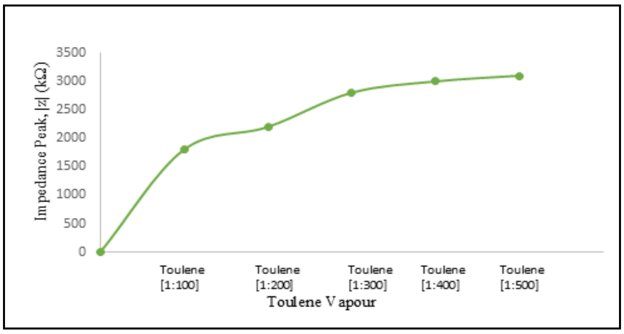

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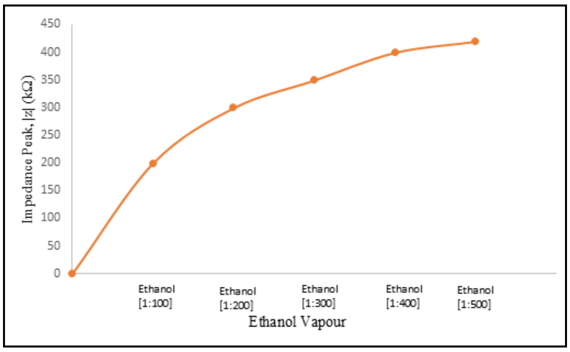
Fig. 4 Graph of impedance peak versus different concentration VOCs vapour for (a) Ethanol; (b) Acetone; (c) Toulene



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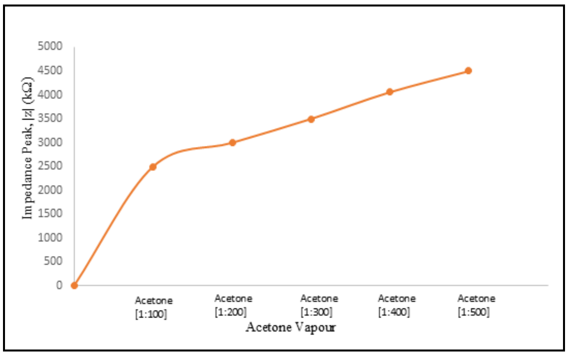

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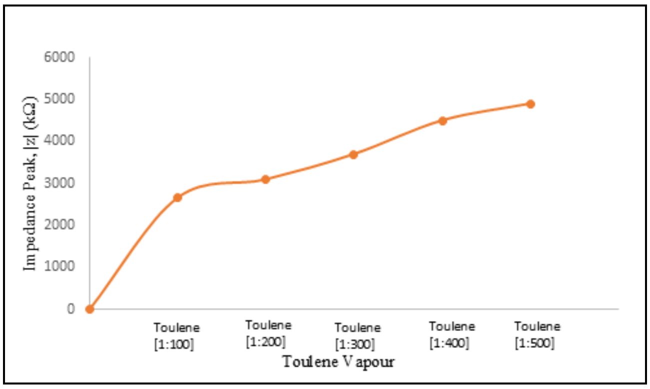

(c)

Fig. 5 Graph of impedance peak versus different concentration VOCs vapour for (a) Ethanol; (b) Acetone; (c) Toulene

3.3 Sensitivity of QCM Sensor Towards Different Concentration of VOCs

The sensitivity of the QCM sensor was evaluated to varied the amount of VOCs, ethanol, acetone, and toluene via different concentration ratios (1:100, 1:200, 1:300, 1:400, 1:500) for one pair, two pairs, and three pairs of QCM layers. First, the cumulative effect of mass loading can be used to explain the observed increase in impedance (Z) with increasing number of QCM layer pairs. As the number of layers rises, the sensor becomes more sensitive to variations in mass concentration since each additional layer increases the overall mass on the QCM surface. This also leads to greater impedance values. QCM's sensitivity to different VOCs bulk loading is closely related to concentration ratios and dilution effect. Understanding these dynamics improves the use of the sensor in a variety of applications, especially those requiring accurate and simple detection of VOCs. The concentration of varies.

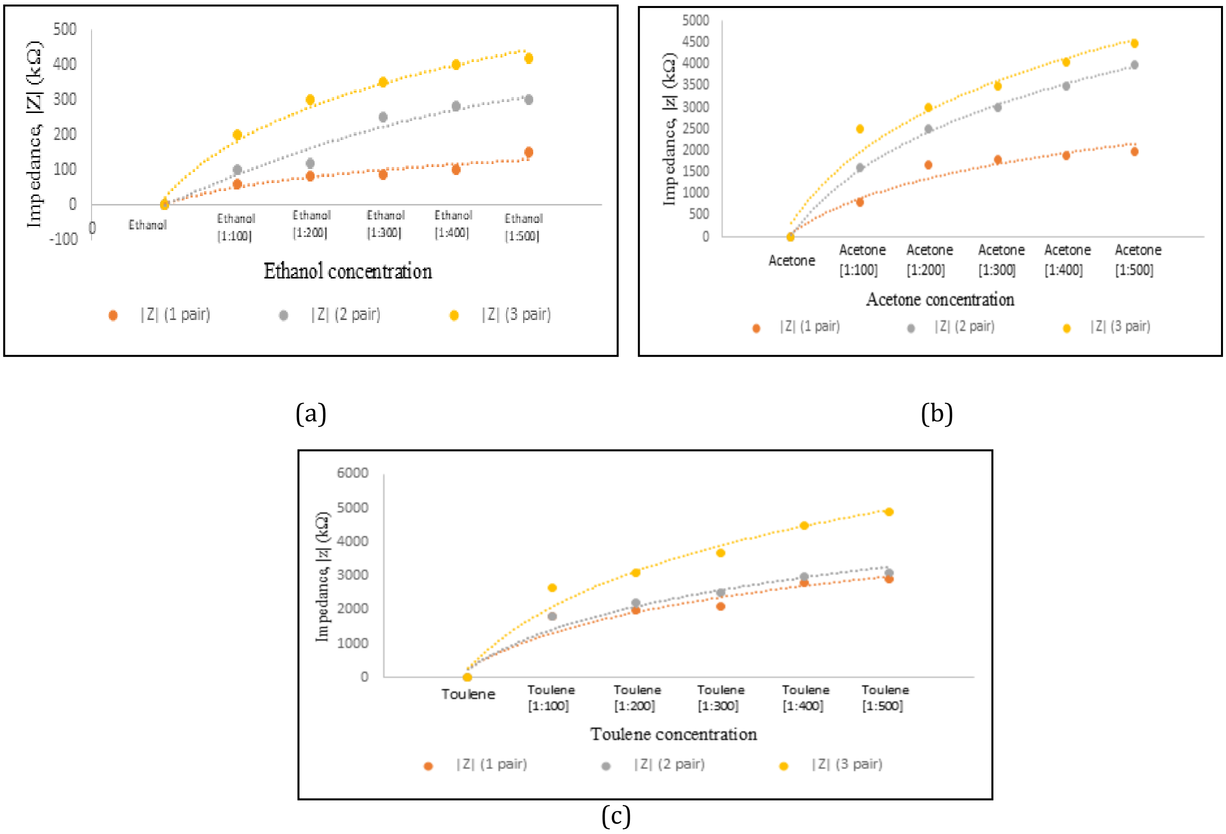

Fig. 6 Graph of impedance peak versus ratio concentration of different VOCs vapour

3.4 Sensitivity of QCM Sensor Towards Different Types of VOCs at 1:500 Vapour Concentration

This research examined the effectiveness of Quartz Crystal Microbalance (QCM) sensors in identifying various Volatile Organic Compounds (VOCs) such as ethanol, acetone, and toluene, uncovering important trends in sensor sensitivity and reaction. It was discovered that the impedance values changed according to the molecular properties and concentration of the VOCs. Ethanol, as a smaller molecule, exhibited reduced impedance, whereas toluene, with its larger molecular framework, resulted in increased impedance due to more intense interactions with the sensor surface.

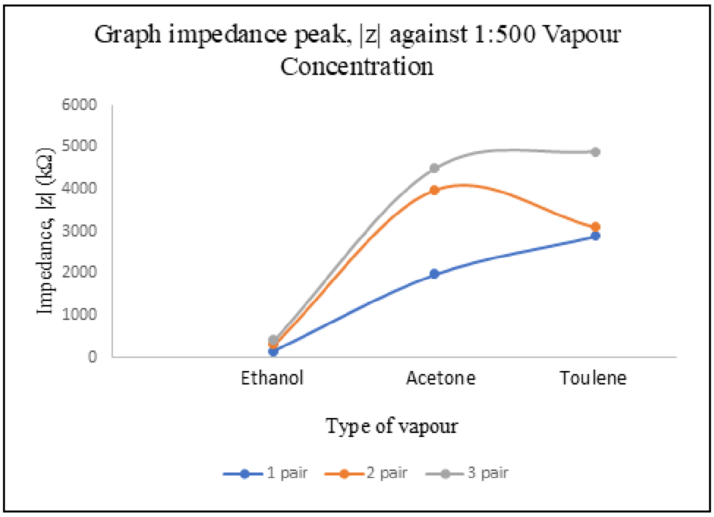

Fig. 7 Graph of impedance peak versus type of VOC vapour at 1:500 concentration

Moreover, as the concentrations of VOC vapours were reduced, the impedance levels rise, indicating the sensor's responsiveness to variations in mass loading. This underscores the QCM sensor's capability to identify minor variations in vapor characteristics and differentiate among VOCs, positioning it as an important instrument for multiple uses, such as environmental surveillance and industrial safety [7]. Recent developments in QCM technology, including the application of molecularly imprinted sol-gel coatings and metal-organic frameworks, are enhancing the sensor's sensitivity and selectivity, thereby increasing their reliability for detecting dangerous VOCs [8].

4. Conclusion

This research aimed at creating a very sensitive gas sensor utilizing the Quartz Crystal Microbalance (QCM) and chemical deposition methods, specifically employing calix[6]arene and 4-tert-Butylcalix[4]arene. The study validated that QCM serves as a powerful and adaptable instrument for gas detection, with impedance analysis demonstrating its notable sensitivity to different vapours, particularly toluene, which showed the greatest impedance because of its larger molecular size. The research indicated that when the concentration of VOCs dropped, the impedance response rose, emphasizing the sensor's improved sensitivity at reduced concentrations. Furthermore, the application of calix[6]arene and 4-tert-Butylcalix[4]arene was observed to notably boost the sensor's efficiency, illustrating that tailored chemical coatings can increase sensitivity and selectivity. These results aid in the progression of gas sensing technology, providing perspectives for developing more effective sensors for use in environmental monitoring and industrial safety.

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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, data collection, methodology, analysis and interpretation of results:*** *Nur Raudatusyahirah Mokhtar and Kamarulzaki Mustafa. All authors reviewed the results and approved the final version of the manuscript.*

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