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Smart sensor integration for real-time quality monitoring in processed frozen foods

Aina Hayani Amran[1], Nur Hazahsha Shamsudin[1,2], Siti Asma Che Aziz[3], Siti Amaniah Mohd Chachuli[2,3], Nur Fazira Haris[4]
[1]Department of Engineering Technology, Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Durian Tunggal, Malaysia
[2]Advanced Sensors and Embedded Controls System, Faculty of Electronics and Computer Technology and Engineering, Universiti Teknikal Malaysia Melaka, Durian Tunggal, Malaysia
[3]Department of Engineering Technology, Faculty of Electronics and Computer Technology and Engineering, Universiti Teknikal Malaysia Melaka, Durian Tunggal, Malaysia
[4]Instrumentation and Control Engineering, Universiti Kuala Lumpur, Malaysian Institute of Industrial Technology, Kuala Lumpur, Malaysia

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ABSTRACT

The demand for processed frozen food has increased due to its rich flavors, long shelf life, and convenience. This trend was noticeable during the COVID-19 pandemic as it reduced the need for frequent grocery shopping and minimized virus exposure. However, processed frozen food is still prone to spoilage over time. This study aims to monitor the quality of processed frozen food, including beef, chicken, and fish, over 24 hours using three primary sensors known as MQ4, MQ136, and MQ137. These sensors detect the main gases produced during food spoilage, which are methane (CH_4), hydrogen sulphide (H_2S), and ammonia (NH_3), respectively, and are integrated with the ESP32 microcontroller. Each sample was analyzed using 100 g of meat placed in a sealed container, with ambient temperature and humidity levels being monitored. The pattern of gas production can be viewed on ThingSpeak, and a notification is sent via Telegram when the threshold value is reached. This study is conveniently used to identify the typical conditions under which processed frozen food is most likely to be spoiled. The result shows that the MQ137 sensor is the most sensitive in detecting early spoilage stages, which indicates the ammonia gas in high temperature and humidity levels.

Corresponding Author:

Nur Hazahsha Shamsudin
Department of Engineering Technology, Faculty of Electrical Technology and Engineering
Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, Durian Tunggal, Melaka, Malaysia
Email: nurhazahsha@utem.edu.my

1. INTRODUCTION

The degradation process in the quality of food is associated with its smell, appearance, texture, and taste. Spoiled food can be linked to foodborne diseases, and it is estimated that millions of patients and thousands of deaths are associated with this disease annually, according to the World Health Organization (WHO) and disease control and prevention (CDC) [1]-[3]. Deteriorated frozen food mostly produces NH_3 and H_2S. These gases are harmful to the environment because they reduce oxygen levels in water bodies and contribute to the greenhouse gas (GHG) crisis [4]-[7]. Spoiled frozen food also becomes food waste, where methane gas is likely to be produced. Methane is a powerful GHG with a global warming potential 28 times greater than that of carbon dioxide (CO_2) over a 100-year period that can cause climate change [8], [9]. Methane was the least produced gas during the analysis, as it is produced when food is putrid.

Numerous researchers have analyzed the food spoilage using various methods, emphasizing the importance of accurate food quality assessment. In conventional approaches, physical inspection and odour detection often rely on human sensory evaluation, which poses risks due to exposure to toxic gases and spoiled food odours [10]-[12]. To enhance the quality of the food quality assessment, many studies have been published concerning the use of electronic noses that mimic the human sense of smell. The improvisation is to address the challenges in conventional methods.

There are various types of sensors that were used to evaluate the quality of the frozen food. A global gas sensor (GGS) series was used for applications requiring enhanced durability or specific performance characteristics, but their higher cost and complexity may be drawbacks for beginners or budget-conscious users [13]. Buratti *et al*. [14], conductive metal oxide (CMO) sens-based sensors (CCS) are made for early detection, providing advanced air quality monitoring, though they may exhibit slower response times at low gas concentrations. An amperometric sensor that measures electrical currents generated during chemical reactions has shown limitations in lifespan and sensitivity due to electrode degradation over time was referenced in [15]. In comparison, studies in [16]-[19] used Taguchi gas sensors (TGS), which are more expensive and have higher power consumption, making them less cost-effective for certain applications. Indeed, studies [18], [19] also use various types of MQ series gas sensors. While prior studies primarily investigated on data acquisition and system optimization, with limited consideration of user-centered functionality. This highlights a clear research gap, which this study addresses by enhancing end-user accessibility, interaction, and practical applicability. It highlights a real-time monitoring on the production of gases from processed frozen food spoilage inclusion of the CH_4, H_2S, and NH_3 gases.

Therefore, this study introduces a low cost, convenient and portable system that utilized sensing devices to monitor the quality of the processed frozen food, allowing users to track food degradation over time and make informed consumption decisions. This system is programmed by using the Arduino IDE software integrated with the ESP32 module, and the reading is displayed on the liquid crystal display (LCD). Not only the collection of data's are plotted in ThingSpeak, the potential freshness degradation is notified via the Telegram once the threshold value is achieved, indicating the real-time reading for each sensor utilized in the system.

2. METHOD

2.1. System operation

Figure 1 illustrates the circuit setup with microcontroller. By initializing hardware and programming using Arduino IDE, the coding is integrated to the microcontroller as all the sensors are connected to it.

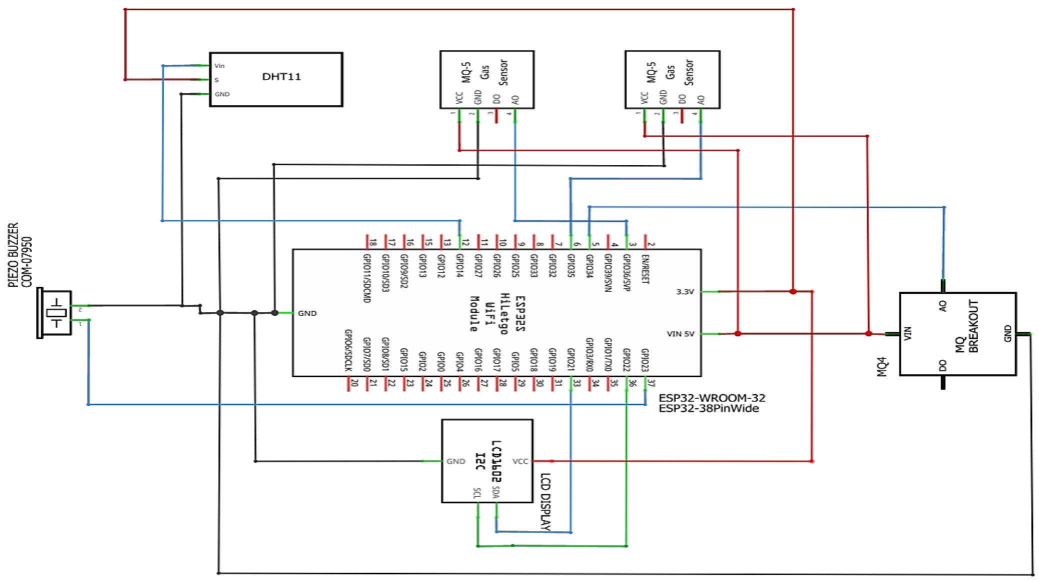


Figure 1. Circuit setup with microcontroller

The circuit connection is important to make sure that every component is connected with the microcontroller to receive all the commands which were written and uploaded in the ESP32 microcontroller.

This experiment has been done by placing 100 g of meat in a sealed container after all the sample was defrosted for one hour at ambient temperature. Then, the data is recorded every hour for 24 hours. The information is displayed on the LCD and ThingSpeak.

2.2. System operation

A custom 3D-printed airtight container is fabricated to execute the experiment and obtain accurate results as shown in Figure 2. The container is designed with four holes in the lid to accommodate the sensors, ensuring proper placement for reliable data collection. The sides are made of acrylic sheet, providing transparency to observe any visible changes in the food samples throughout the 24-hour experiment. During 24-hour testing, the ESP32 and its connected sensors are typically powered by a DC power supply with careful attention to voltage and current requirements to ensure stable operation throughout the test period. Every possible gap or openings is sealed to prevent external gas interference, as maintaining an airtight environment is crucial for ensuring precise and consistent sensor readings.

In the calibration stage, the mathematical model of the MQ gas sensors must be introduced. The mathematical model for MQ gas sensors typically follows a power law relationship between the sensor resistance and gas concentration. Different MQ sensors have unique sensitivities and responses to various gases. Calibration have been performed for each specific sensor type and target gas combination to ensure accurate measurements [20].

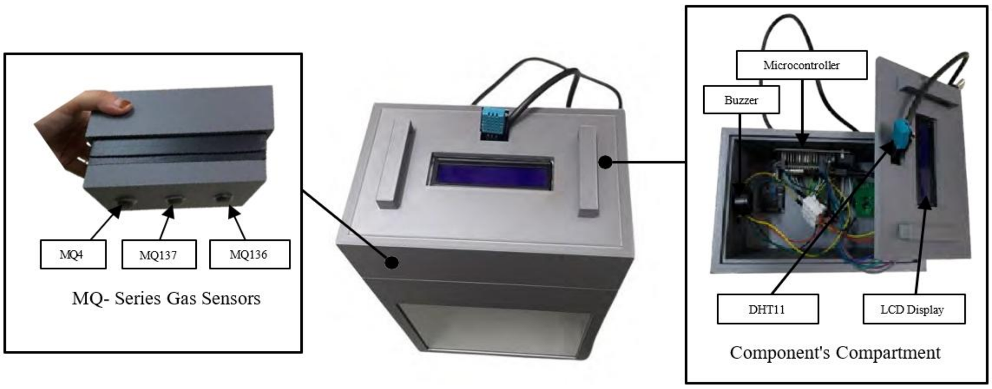


Figure 2. Hardware implementation

3. RESULTS AND DISCUSSION

3.1. CH4, H_2S, NH_3, and gasses detection

In food spoilage, certain gases are commonly produced because of microbial activity and chemical reactions, making them key indicators for detecting spoilage. Previous studies have identified three primary gases which are CH4, H_2S, and NH_3 as the most significant byproducts of food spoilage. Ammonia is produced from the breakdown of proteins and hydrogen sulphide with its distinct odour, is released during the decomposition of sulphur-containing compounds. Meanwhile, methane is produced by anaerobic bacteria during the decomposition of organic matter. By selecting specific gas sensors tailored to detect these gases, the system can more accurately monitor spoilage processes. This targeted approach not only improves the precision of the analysis but also saves time and resources by eliminating the need for trial and error with a broader range of sensors, ensuring more reliable and focused results for food quality monitoring. Figure 3 (in Appendix) depicts the manually plotted graph for voltage reading for each food sample where Figure 3(a) beef meat, Figure 3(b) chicken meat, and Figure 3(c) fish meat.

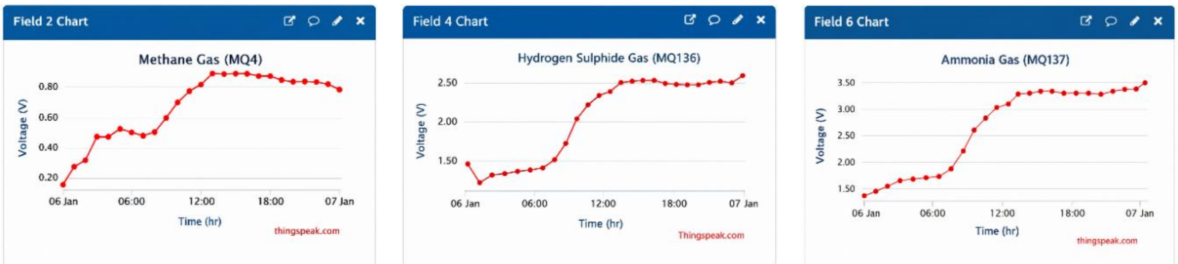
The spoilage analysis of 100 g beef patty, beef nugget, and beef sausage over a 24-hour period revealed NH_3 and H_2S as the primary spoilage indicators, with CH_4 showing minimal relevance. NH_3 exhibited the highest response across all samples, peaking at 70 ppm and 3.53 V for beef nugget, 70 ppm and 3.53 V for beef patty, and 70 ppm and 3.51 V for beef sausage. H_2S followed closely, reaching 69 ppm and 3.50 V in beef nugget, 59 ppm and 2.96 V in beef patty, and 71 ppm and 3.58 V in beef sausage. CH_4 remained below 20 ppm with voltage responses under 1.00 V, confirming its limited role in spoilage detection. Beef patties and nuggets exhibit the most visible spoilage signs due to their high myoglobin content, muscle density, and fat composition. As oxidation progresses, the red color fades to brown or green, while microbial activity leads to sliminess and surface discoloration. Additionally, fat oxidation contributes to rancidity and a strong odor, making spoilage easily identifiable through changes in color, texture, and smell [21].

As for chicken meat in Figure 3(b) which also consists of nugget, chicken patty, and chicken sausage, NH_3 and H_2S consistently identified as key spoilage indicators, while CH_4 exhibited minimal significance. Among the tested samples, NH_3 recorded the highest concentration, reaching 80 ppm with 4.01 V in chicken nugget, 65 ppm with 3.30 V in chicken patty, and 73 ppm with 3.66 V in chicken sausage. H_2S also demonstrated significant spoilage activity, peaking at 78 ppm with 3.94 V in chicken nugget, 62 ppm in 3.12 V in chicken patty, and 72 ppm in 3.65 V in chicken sausage. Meanwhile, CH_4 remained below 20 ppm with voltage responses under 1.00 V, confirming its negligible role in spoilage detection. Chicken meat undergoes moderate spoilage changes due to its lower myoglobin content and softer muscle tissue. Unlike beef, its color change is less pronounced, often turning slightly greyish and discoloration. However, its higher moisture content and loose muscle fibers promote bacterial growth, leading to a slimy texture and a strong sour or sulphureous odor from bacterial byproducts like H_2S [22]. While spoilage is noticeable, it is less visually distinct than in beef.

In Figure 3(c), the fish meat was analyzed with NH_3 and H_2S emerging as primary spoilage indicators, while CH_4 exhibited minimal relevance. Fish cake recorded lower gas emissions, with H_2S and NH_3 peaking at 51 ppm with 2.56 V and 50 ppm with 2.51 V, respectively, indicating that spoilage progression remained moderate. Crab stick displayed a higher spoilage response, with NH_3 reaching 89 ppm with 4.47 V and H_2S at 79 ppm in 3.98 V, reinforcing their role as key markers. Meanwhile, squid ball demonstrated the most pronounced spoilage, as H_2S peaked at 86 ppm with 4.33 V, followed by NH_3 at 79 ppm with 3.98 V, suggesting significant microbial activity. CH_4 remained below 25 ppm with voltages under 1.30 V across all samples, confirming its limited contribution to spoilage detection. This correlation stems from microbial protein degradation during spoilage. Additionally, fish meat spoils less visibly than beef or chicken due to its low myoglobin content and high-water composition, making spoilage more noticeable by odor rather than color or texture changes [23], [24].

3.2. Internet of things

In this study, internet of things (IoT) integration allows continuous monitoring of gas levels and environmental conditions, which is temperature and humidity levels by using sensors that are connected to the ESP32 microcontroller. Data is visualized on platforms like ThingSpeak for remote tracking and analyzed to identify spoilage indicators as shown in Figure 4 for; CH_4 (Figure 4(a)), H_2S (Figure 4(b)), and NH_3 (Figure 4(c)). As shown, the data plotted manually for every one hour for 24-hour interval is the same as the graph generated in ThingSpeak which validates the use of IoT applications. Otherwise, Telegram can be used to know the exact value of the reading remotely at the moment and a notification will be sent when the threshold value is achieved.



(a) (b) (c)

Figure 4. ThingSpeak plotted graph for beef patty; (a) CH_4, (b) H_2S, and (c) NH_3

It is found that the integration of the Telegram application correlates with improved real-time user interaction and system responsiveness as displayed in Figure 5, compared with ThingSpeak, which is largely limited to gas concentration trends visualizations [25]. The proposed method in this study tended to have an inordinately higher proportion of user-centric IoT functionality, as IoT was embedded primarily for real-time monitoring, notifications, and actionable feedback rather than for post-experimental analysis. Unlike previous studies [16], [17], [26], where IoT platforms were used mainly for data collection and algorithm evaluation, this approach shifts the emphasis toward practical end-user application, effectively bridging technical sensing performance and user interaction.

3.3. Sensor response analysis

Based on the experimental data, the sensing response and response time were calculated for each target gas. The calculated results are presented in Tables 1 to 3. These parameters are crucial in evaluating gas sensor performance in terms of detection capability and responsiveness under the specified experimental conditions.

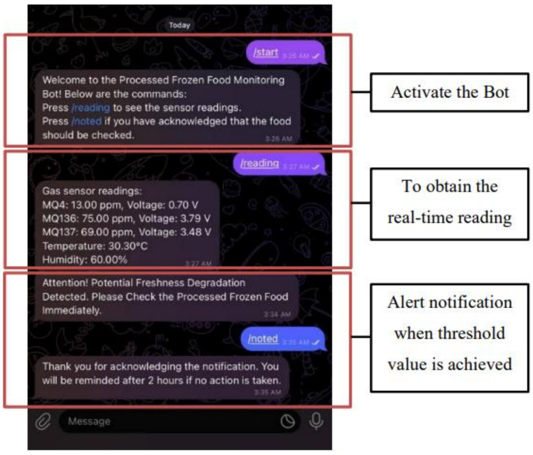


Figure 5. Telegram notifications and commands

Table 1. Beef meat response analysis

	Sensing response			Time response (hour)		
	Nugget	Patty	Sausage	Nugget	Patty	Sausage
CH_4	0.95	1.61	1.07	21	23	24
$H2_S$	1.92	2.04	1.55	18	15	22
NH_3	2.26	2.05	1.85	18	15	23

Table 2. Chicken meat response analysis

	Sensing response			Time response (hour)		
	Nugget	Patty	Sausage	Nugget	Patty	Sausage
CH_4	2.40	1.12	0.97	22	19	22
$H2_S$	2.80	1.49	1.70	20	21	16
NH_3	2.80	1.51	1.82	20	20	21

Table 3. Fish meat response analysis

	Sensing response			Time response (hour)		
	Fish cake	Crab stick	Squid ball	Fish cake	Crab stick	Squid ball
CH_4	1.00	1.09	1.13	21	23	23
$H2_S$	1.18	1.23	1.27	20	20	21
NH_3	1.10	1.23	1.61	20	23	21

Table 1 compares the sensing responses of CH_4, H_2S, and NH_3 for beef meat products, including nuggets, patties, and sausages. Among them, patties exhibited the highest responses for CH_4 with 1.61, H_2S with 2.04, and NH_3 with 2.05, indicating strong gas detection sensitivity. NH_3 consistently exhibited responses above 2.0, highlighting its strong detectability. As for the response times, sausages had the longest delays for CH_4 and NH_3, while patties showed the shortest response for H_2S and NH_3 with 15 h. These findings confirm the superior sensitivity of the sensor to NH_3 for detecting spoilage in beef products.

Table 2 presents the sensing response for chicken meat products which also consists of nuggets, patties, and sausages. Nuggets exhibited the highest detection capability, with responses of 2.40 for CH_4, 2.80 for both H_2S, and NH_3, while sausages had the lowest CH_4 response followed by H_2S and NH_3. The sensor response time for nuggets and sausages required 22 hours for CH_4 detection, while patties responded faster at 19 hours. For H_2S, sausages had the shortest time which is 16 hours, whereas nuggets and patties required 20 hours and 21 hours, respectively. NH_3 detection times were similar across all samples in the range of 20 to 21 hours. These findings shows that nuggets are the most sensitive to gas detection, and NH_3 remains the most effectively detected gas, reinforcing its suitability for spoilage monitoring in chicken meat products.

Table 3 present the sensing and time response of CH_4, H_2S, and NH_3 for fish meat products including fish cakes, crab sticks, squid balls. Crab sticks showed the highest CH_4 response, while squid balls exhibited the strongest sensitivity to H_2S and NH_3. Fish cakes consistently had the lowest responses for all gases. In terms of detection time, crab sticks had the longest response for CH_4 in 23 hours, whereas fish cakes responded fastest. H_2S and NH_3 detection times were similar across all food sample, ranging from 20 to 21 hours, except for H_2S in crab sticks took 2 hours longer. Overall, the sensors demonstrated higher sensitivity to NH_3 and H_2S, with squid balls being the most emitted spoilage indicator gas throughout the experiment.

The response analysis in Tables 1 to 3. are derived from the plotted graphs of emitted gases. The data indicates that both H_2S and NH_3 are the primary spoilage gases detected. Notably, the highest sensing and time response for NH_3 confirms that the MQ137 sensor is the most sensitive for detecting spoilage across all three meat categories, while MQ136 is particularly effective for detecting H_2S in fish meat.

NH_3 and H_2S were consistently identified as the primary spoilage indicators across beef, chicken and fish samples, with NH_3 generally showing the highest concentrations and sensor responses. This aligns with expectations, as these gases are common byproducts of protein breakdown during meat spoilage. Response analysis showed that the MQ137 sensor (for NH_3) was generally the most sensitive across all meat types, while the MQ136 (for H2S) performed particularly well for fish samples. The mean and standard deviation values for NH_3 from the experiment to be found as 55.50 and 17.39, respectively are within the ranges observed in real-world studies, reflecting typical variability due to operational and environmental changes. Specifically, the environmental conditions during the experiments were stable, with a temperature of 30.30±0.53 °C and relative humidity of 61.38±2.04%, confirming consistent testing conditions were applied to evaluate the significance of sensor sensitivity variations across different target gases.

Monitoring spoilage gases in frozen food is essential for ensuring safety and quality. The specific thresholds for the CH_4, NH_3, and H_2S vary depending on the type of frozen food and storage conditions. Generally, CH_4 levels above 50 ppm, NH_3 above 20 ppm, and H_2S above 10 ppm are considered indicative of potential spoilage [20], [27]. These thresholds are based on industry standards and regulatory guidelines set by food safety authorities to maintain product quality and protect consumer health.

3.4. Comparison with prior studies

Table 4 compares this system with prior studies, highlighting the need for a more practical and user-oriented food quality monitoring solution. The proposed study integrates selected MQ gas sensors with humidity and temperature sensing to target critical spoilage-related gases, improving detection accuracy while maintaining low cost.

Unlike earlier systems that employed on higher-cost TGS sensors or multiple MQ sensors without prioritizing critical spoilage indicators [16], [17], [26], our study incorporates IoT-enabled real-time monitoring via ThingSpeak and automated user alerts through Telegram. Prior works relied on DAQ–LabVIEW platforms [26], controlled test chambers with Bluetooth monitoring [17], or advanced concepts such as intelligent packaging and digital twins [16], which, despite their effectiveness, faced limitations in cost, signal robustness, portability, hardware dependency, or user accessibility. This study addresses these gaps by offering a cost-effective, portable, and user-centered solution for maintaining food quality and safety.

Table 4. Comparison with previous studies

Studies parameter	[16]	[17]	[26]	This study
Gas sensor	Figaro TGS and 852 AMS CCS811	TGS2602, TGS2620, MQ136, and MQ137	Nanocomposite	MQ4, MQ136, and MQ137
Most sensitive gas detected	Carbon monoxide (CO), hydrogen (H_2), and NH_3	Alcohol (C2H5OH), NH_3, and H_2S	NH_3	NH_3
Reading value	-	H2S-5.23 ppm NH3-7.8 ppm	100 ppm	90 ppm
Weight sample (g)	10	25	20	100
Humidity and temperature	Available	Not available	Not available	Available
IoT	Intelligent packaging and digital time	Bluetooth communication	DAQ Card and LabView	ThingSpeak application

4. CONCLUSION

This paper presents an improved system featuring an IoT interface for analyzing the quality of processed frozen food, specifically designed for food technology (FoodTech) applications. The system offers a user-friendly interface suitable for all end-users and holds significant potential for small industries by moving away from conventional sensory evaluation methods and costly devices. The integration of IoT technology allows for remote monitoring, reducing the need for sensory evaluations that could pose long-term health risks. Future study may look into focusing on incorporating artificial intelligence (AI) to predict food quality by analyzing physical changes in frozen food that could significantly enhance the system's capabilities. This advancement would allow for more accurate, automated assessments, reducing human error and further improving food safety and quality monitoring. The system could be integrated into cold chain logistics and smart packaging in several ways, such as real-time monitoring in transit (via sensors and IoT connectivity), smart packaging, warehouse management or even automated inventory management. Overall, this study provides a solid foundation for developing more advanced, user-friendly food quality monitoring systems using gas sensors and IoT technology.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Aina Hayani Amran		✓	✓			✓			✓		✓			
Nur Hazahsha Shamsudin	✓	✓		✓	✓		✓			✓	✓	✓	✓	
Siti Asma Che Aziz						✓	✓			✓				✓
Siti Amaniah Mohd Chachuli	✓	✓	✓	✓				✓	✓			✓		
Nur Fazira Haris			✓		✓			✓		✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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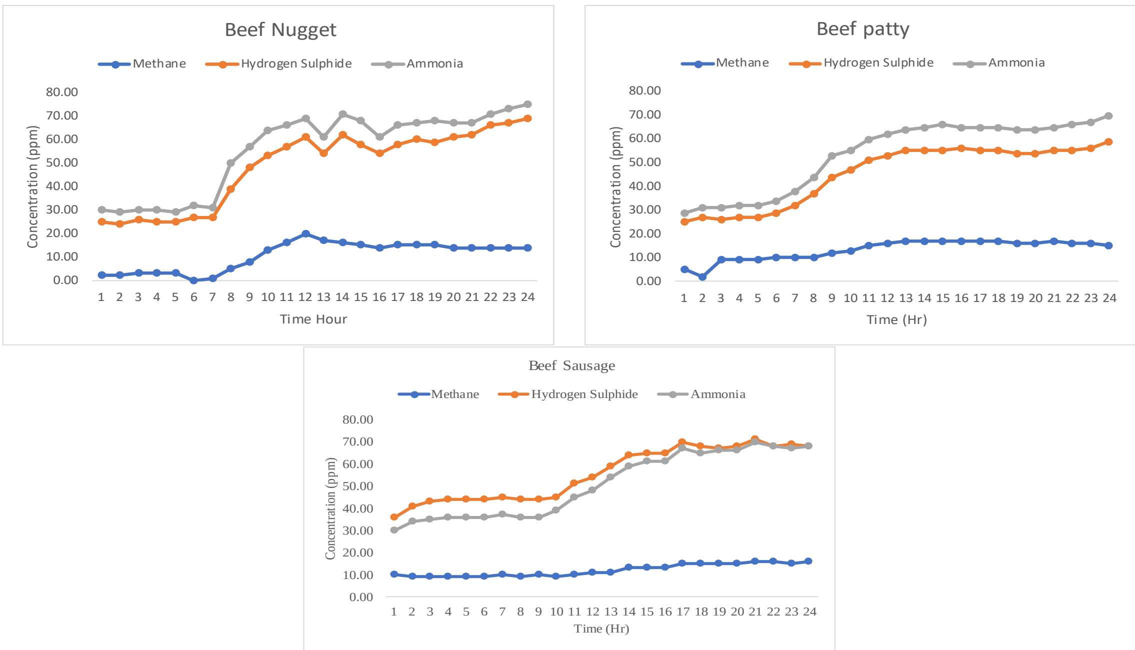
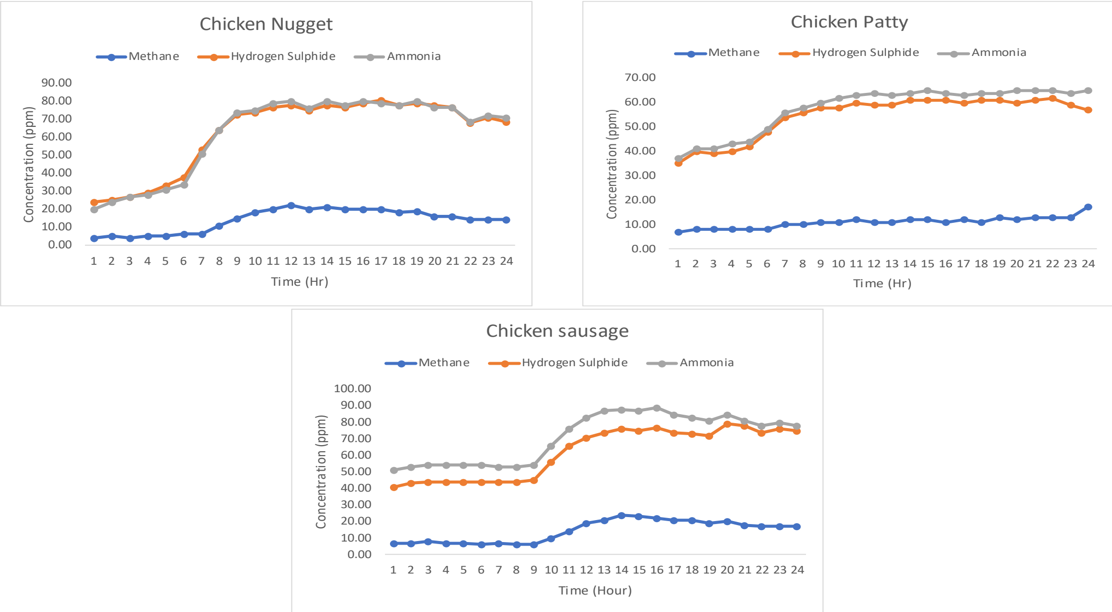
APPENDIX

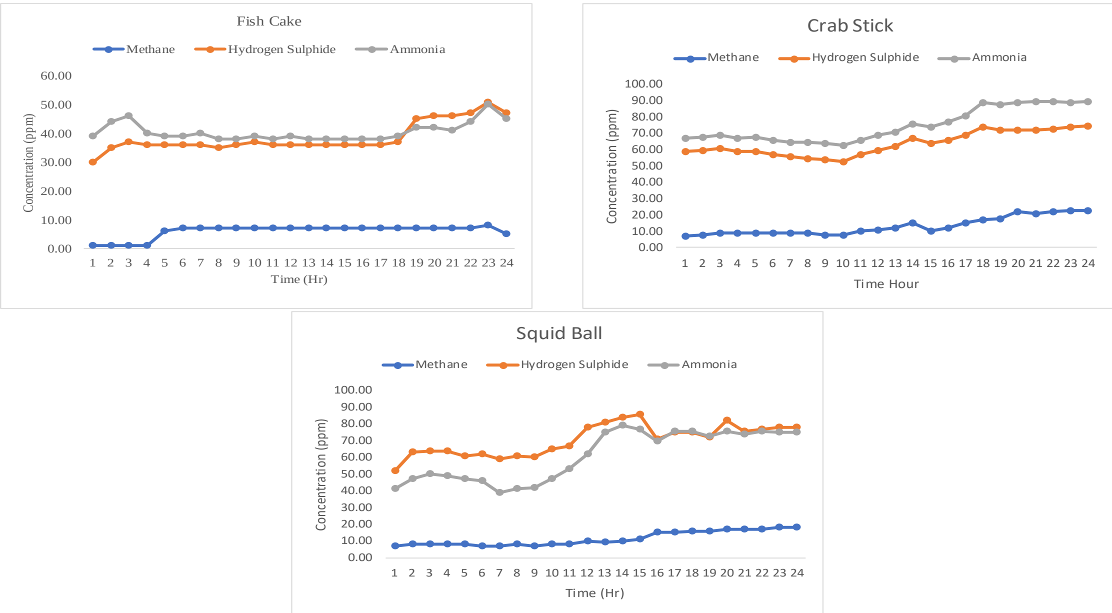


(a)

Figure 3. Manually plotted graph for; (a) beef meat



(b)



(c)

Figure 3. Manually plotted graph for; (b) chicken meat and (c) fish meat *(continued)*

BIOGRAPHIES OF AUTHORS

Aina Hayani Amran received B.Eng. degree in electrical engineering from Universiti Teknikal Malaysia Melaka, Malaysia, in 2008. Her research interests include gas sensors and food quality. She can be contacted at email: hayaniamran29@gmail.com.

Nur Hazahsha Shamsudin received a B.Eng. degree in electrical engineering from Universiti Teknologi Mara, Malaysia, in 2008, M.Eng. from Universiti Malaya in 2012, and Ph.D. degree from Universiti Putra Malaysia in 2022. Currently, she is a senior lecturer at the Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka. She has professional certification of Registered Energy Manager Type 1 and 2 from Energy Commission of Malaysia. Her research interests include gas sensors, solar energy, power quality, and nanomaterial. She can be contacted at email: nurhazahsha@utem.edu.my.

Siti Asma Che Aziz received her B.Eng. (Hons) in Electrical, Electronics and System Engineering from Universiti Kebangsaan Malaysia, Bangi, Malaysia in 2008. Then persue her Master of Science in Electrical, Electronics and System Engineering from Universiti Kebangsaan Malaysia, Bangi, Malaysia in 2011. Currently she is a lecturer at the Faculty of Electronics and Computer Technology and Engineering Universiti Teknikal Malaysia Melaka. Her research interests lie at the intersection of fiber optics, optical networks, photonics, and sensing materials. She can be contacted at email: sitiasma@utem.edu.my.

Siti Amaniah Mohd Chachuli received a B.Eng. degree in electrical and electronic engineering from Universiti Kebangsaan Malaysia, Malaysia, in 2008, M.Eng. from Universiti Malaya in 2012, and Ph.D. degree in sensor technology from Universiti Putra Malaysia in 2020. Currently, she is a senior lecturer at the Faculty of Electronics and Computer Technology and Engineering, Universiti Teknikal Malaysia Melaka. Her research interests include thin and thick film gas sensors, nanomaterials, and material characterization. She can be contacted at email: sitiamaniah@utem.edu.my.

Nur Fazira Haris received a B.Eng. degree in electrical engineering from Universiti Teknologi Mara, Malaysia, in 2008, M.Eng. from Universiti Malaya in 2013. Currently, she is a lecturer at the Instrumentation and Control Engineering, Universiti Kuala Lumpur, Malaysian Institute of Industrial Technology (UniKL MITEC), 81750 Masai, Johor, Malaysia. Her research interests include renewable energy and control and automation. She can be contacted at email: nurfazira@unikl.edu.my.