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Platform Penginderaan Tertanam Real-Time untuk Klasifikasi Kesegaran Ikan Tuna secara Non-Destruktif: Fusi Multi-Sensor Hidung Elektronik dan Kolorimetri Digital

Real-Time Embedded Sensing Platform for Non-Destructive Tuna Freshness Classification: A Multi-Sensor Fusion of Electronic Nose and Digital Colorimetry

Erlina Nur Arifani[1*], Sevia Indah[2]

1 Department of Food Technology, Telkom University Purwokerto Campus, Indonesia
2 Department of Biomedical Engineering, Telkom University Purwokerto Campus, Indonesia

*[*1]Corresponding author: erlinanurarifani@telkomuniversity.ac.id*
[2]seviaindah@telkomuniversity.ac.id

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Abstrak

Metode tradisional untuk mengevaluasi kesegaran tuna seringkali dibatasi oleh subjektivitas manusia, biaya tinggi, dan prosedur laboratorium yang merusak. Hal ini menimbulkan tantangan bagi keamanan pangan, khususnya dalam mencegah akumulasi histamin beracun dan mengurangi penolakan ekspor. Studi ini bertujuan untuk menyelidiki sistem evaluasi kualitas yang cepat, non-destruktif, dan berbiaya rendah untuk tuna mentah menggunakan teknologi sensor modern terintegrasi. Sistem ini menggabungkan hidung elektronik yang menggunakan sensor gas MQ-136 dan MQ-137 untuk memantau emisi hidrogen sulfida (H2S) dan amonia (NH3) yang mudah menguap selama penyimpanan di udara terbuka, dikombinasikan dengan sensor warna terintegrasi yang digerakkan oleh arsitektur mikrokontroler. Pemodelan kinetik mengkonfirmasi bahwa konstanta laju (R2) NH3 dan H2S masing-masing sebesar 0,82. Kualitas tuna diklasifikasikan menjadi tiga fase: segar (0-10 jam), setengah segar (11-20 jam), dan busuk (21-30 jam). Bersamaan dengan itu, mikrokontroler menjalankan klasifikasi visual waktu nyata berdasarkan rentang Merah-Hijau-Biru (RGB) tertentu: segar (172 < R < 184, 70 < G < 104, 89 < B < 129), setengah segar (151 < R < 167, 32 < G < 64, 49 < B < 83), dan busuk (119 < R < 149, 0 < G < 28, 0 < B < 45). Platform penginderaan portabel dan objektif ini menyediakan kontrol kualitas dan keamanan waktu nyata berkecepatan tinggi di industri makanan.

Kata kunci: Keamanan pangan, MQ-136, MQ-137, Pemodelan kinetik, Sensor RGB, Kesegaran tuna, Orde nol.

Abstract

Traditional methods for evaluating tuna freshness are often constrained by human subjectivity, high costs, and destructive laboratory procedures. This presents a challenge to food safety, particularly in preventing toxic histamine accumulation and mitigating export rejections. This study aims to develop a rapid, non-destructive, and low-cost quality evaluation system for raw tuna using integrated modern sensor technologies.. The system incorporates an electronic nose utilizing MQ-136 and MQ-137 gas sensors to monitor volatile hydrogen sulfide (H_2S) and ammonia (NH_3) emissions during open-air storage, combined with an integrated color sensor driven by a microcontroller architecture. Principal Component Analysis (PCA) was used to model the sensor response kinetics, which confirmed a strong correlation in monitoring freshness decline (tuna) with a cumulative

explained variance (R^2) of 0.82. Kinetic modeling confirmed that both NH_3 and H_2S rate constant (R^2) of 0.82. Classified tuna quality into three phases: fresh (0-10 hour), semi-fresh (11-20 hour), and spoiled (21-30 hour). Concurrently, the microcontroller executed real-time visual classification based on specific Red-Green-Blue (RGB) range: fresh (172 < R < 184, 70 < G < 104, \$89 < B < 129), semi-fresh (151 < R < 167, 32 < G < 64, 49 < B < 83), and spoiled (119 < R < 149, 0 < G < 28, 0 < B < 45). This portable and objective sensing platform provides for high-speed, real-time quality control and safety in food industry. In conclusion, this portable and objective sensing platform provides a reliable, high-speed, and real-time solution for quality control and safety assurance in the food industry.

Keywords: food safety, mq-136, mq-137, rgb sensor, tuna freshness.

I. INTRODUCTION

In this modern era, technological innovation in food freshness testing devices holds great potential and has become one of the main pillars in safeguarding public health. Evaluating the viability of animal products is increasingly crucial alongside rising consumer awareness regarding food quality and safety [1]. Generally, the public yearns for healthy food whose freshness level can be easily monitored. Tuna is one of the marine commodities highly favoured by consumers due to its high nutritional value, delicious flavour, and practicality in processing. Nevertheless, tuna is highly susceptible to storage conditions and microbial contamination, which can accelerate the spoilage process [2].

Tuna spoilage and the accumulation of dangerous histamine represent a critical threat to food safety in Indonesia's rapidly growing seafood sector. To address this issue, advanced smart packaging utilizes pH-sensitive sensors that change colour in real-time to indicate spoilage long before toxins accumulate, thereby keeping consumers safe [3]. Once tuna is exposed to room temperature, bacteria convert the amino acid histidine into toxic histamine. This process can occur within just 8 to 20 hours. Histamine is heat-resistant (meaning cooking will not destroy it) and virtually odourless, making it impossible for consumers to detect using basic senses [4]. The odourless nature of histamine and the fundamental working principle of the electronic nose (e-nose). That histamine itself is odourless and cannot be directly ‘smelled’ or detected by either human olfaction or gas sensors. The bacteria that produce histamine also break down tuna proteins into odorous gases (NH3 and H2S). So, the e-nose detects these accompanying gases as an "alarm signal" that histamine is also being formed.

Humans can only detect a foul odour when the gas concentration is very high (it's too late). The MQ-136 & MQ-137 sensors can detect these gases at very low levels (ppm) long before the human nose notices them. As tuna spoils, volatile basic nitrogen compounds cause pH levels to rise. This shift triggers a visible color change in the packaging film. Biosensors: Advanced laboratories also utilize optical sensors and microchips that test for biogenic amines or gas alterations to precisely determine seafood safety controls [5]. Since histamine is the leading cause of tuna export rejections (frequently to Japan, the US, and the European Union), commercial export facilities in Bali and across Indonesia rely on rigorous laboratory testing prior to shipment. Daily Market Prices: In 2026, fresh and frozen tuna fillets in local markets range from IDR 52,900 to IDR 115,000 per kilogram [6]. Although smart sensor packaging has not yet been standardized for everyday wet markets, this innovation is being intensively researched to protect the growing number of domestic consumers as fish consumption increases.

A rapid, non-invasive, reagent-free, relatively inexpensive, and portable method would be ideal for veterinary authorities determining the freshness of fresh tuna on-site, or for consumers to check the freshness of the meat themselves [7]. Electronic nose (e-nose) technology represents an optimal solution for this purpose and has been widely utilized in food analysis in recent years [8]. It is proven that e-nose technology is a fast, simple, inexpensive, and non-destructive method for food quality assessment and control. Compared to analytical chemical and microbiological methods, e-nose technology offers an alternative approach for the rapid detection of volatile compounds [9].

The use of sensor technology has been proven to be developed and implemented across various fields of life, such as food, environmental monitoring, and medicine. The application of sensor technology to various types of tuna represents one of the primary application areas in the food industry [10]. However, MQ-136 and MQ-137 sensors have not been widely utilized for food quality assessment Rapid Quality Evaluation of Fresh Tuna [11].

Rapid quality evaluation of fresh tuna using an electronic nose. A sensor prototype incorporating a gas sensor system for evaluating the freshness of fresh tuna has been developed. In this journal, a rapid, simple, and inexpensive system for detecting fresh tuna spoilage is investigated, providing objective and reliable results. Quality changes in fresh tuna during storage were monitored by a sensor system utilizing MQ-136 and MQ-137 sensors and were compared with the results of traditional chemical measurements [12].

The selection of gas sensors was tested for the evaluation of ammonia and hydrogen sulphide, which primarily represent fish spoilage [13]. This study demonstrates that the correlation coefficient ($R^2 = 0.80$) between the sensor signals and traditional chemical methods is high. These results prove that the developed prototype has the potential to differentiate meat into fresh tuna, non-fresh tuna, and spoiled tuna.

Despite its high market demand, the quality of tuna declines rapidly after harvest if adequate preservation measures are not implemented. Under natural conditions, the fish typically begins to exhibit signs of spoilage, such as off-odors, within a short period of 8 to 10 hours [14]. Although its shelf life at room temperature is limited to approximately 12 hours, cold storage can significantly extend this period up to 15 days. Given that tuna sold in traditional markets has often been pre-processed or slaughtered, there is a critical need for research to accurately measure the freshness level of this commodity under such conditions.

Although freshness is traditionally assessed through sensory, chemical, and microbiological techniques, these methods often lack objectivity and safety in detecting toxic compounds. Recent findings indicate that pH monitoring is an effective metric for tuna freshness; however, the trend is moving toward high-speed, portable, and affordable diagnostic technologies. Modern sensor devices represent a breakthrough, replacing subjective human observations with integrated systems capable of analyzing aroma and color with superior efficiency and accuracy.

Despite the promising application of electronic noses in food safety, current methods for tuna freshness detection remain limited by single-modality sensing, which often struggles with environmental interference and false positives. Existing e-nose systems primarily rely on volatile gas analysis without corroborating visual degradation, while visual-only methods fail to detect invisible, highly toxic histamine accumulation. There remains a critical unsolved gap in developing a low-cost, multi-modal system that simultaneously cross-validates biochemical volatile emissions such as NH3 and H2S with macroscopic colorimetric changes in real-time. To address these limitations, this study proposes a multi-sensor fusion approach. The specific objectives of this research are: (1) to develop an integrated Electronic Nose and RGB sensing system for non-destructive tuna freshness monitoring; (2) to investigate the correlation between volatile gas concentrations and color degradation during spoilage; and (3) to classify tuna freshness into three distinct quality levels using threshold-based decision rules derived from integrated sensor measurements.

II. LITERATURE REVIEW

Ensuring seafood safety is a global priority, with quality standards stringently regulated by the Food and Agriculture Organization (FAO). However, conventional assessment techniques such as sensory inspections and chemical analyses frequently prove inadequate for large scale operations due to their inefficiency and subjective nature, underscoring the need for more advanced monitoring solutions [15]. As a highly perishable commodity, fish undergoes rapid quality degradation immediately after harvest. This decline is primarily attributed to high moisture content and nutrient density, which create a fertile environment for spoilage microorganisms [16]. The deterioration process is generally categorized into three mechanisms: autolysis (enzymatic breakdown), bacteriological activity, and various chemical transformations. Although preservation technologies have evolved to mitigate these effects, their implementation remains limited among traditional market traders, largely due to economic constraints [17].

While cold storage and freezing can effectively delay spoilage, the high operational costs associated with refrigeration equipment often exceed the financial capabilities of traditional market vendors. Consequently, fish sold in these environments remains highly vulnerable to rapid deterioration due to substandard handling, making consistent freshness monitoring absolutely critical. Tuna serves as a prime example of a widely traded species with substantial economic value. Since 2015, global demand for this fish has soared, driven by its high nutritional profile rich in protein, vitamins, and minerals—as well as its affordability. In regions like Purwokerto, this fish is a staple frequently found in traditional markets, further emphasizing the need for accessible quality assessment methods [18].

III. RESEARCH METHOD

Tuna Fish were sourced directly from Superindo in Purwokerto, Indonesia, to serve as the primary research samples. Upon procurement, the fish were securely packaged and transported to the laboratory in a fresh state to maintain quality. For the experimental procedure, 100 g portions of the samples were precisely weighed and transferred into petri dishes for systematic data acquisition.

3.1. Design of Detection Equipment

Detection system is a specialized gas sensing device controlled by an Arduino microcontroller. It employs NH3 and H2S sensors that leverage resistance-based semiconductor technology to quantify gas levels. As gases are released from the Tuna fish samples inside a 20 × 20 × 20 cm sealed acrylic enclosure, the sensors produce voltage outputs that the system converts into ppm units using calibration formulas. This data is then recorded in a computer database for further evaluation. The integration between the microcontroller and the computer ensures seamless serial data transfer, while the sensor performance characteristics are cross-referenced with manufacturer datasheets to ensure accuracy. This detection system can be seen in Figure 1.

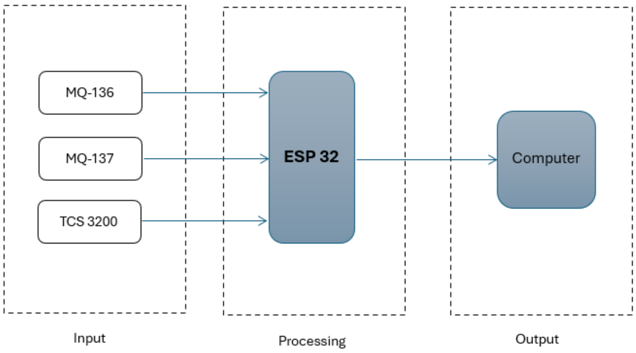


Figure 1. Block diagram of the gas detector device

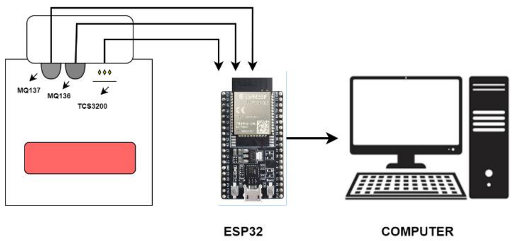


Figure 2. Diagrammatic representation of the sensor chamber, sample chamber, and sensor system Experimental Procedure, Sample Preparation

The experimental setup involved placing Tuna fish inside sensor-equipped acrylic containers. The MQ-136 and MQ-137 sensors captured the gaseous byproducts of the fish, resulting in real-time voltage changes within the system. The intensity of these signals, determined by the concentration of the volatiles, provided a reliable metric for determining the progression of spoilage in the samples. Diagram representation system can be seen in Figure 2.

To ensure statistical reliability, the experiment was conducted using multiple independent 100 g portions of raw tuna samples, with three replications performed for each freshness phase. Prior to data acquisition, the MQ-136, MQ-137, and TCS3200 sensors underwent a rigorous calibration process. The gas sensors were pre-heated for 24 hours to stabilize the semiconductor heating elements, followed by baseline calibration in clean ambient air. All measurements were conducted under controlled environmental conditions, maintaining a stable ambient temperature and relative humidity inside the test chamber. Data acquisition was performed continuously with a standard sampling interval and high ADC resolution. The TCS3200 sensor was fixed at a 2.5 cm clearance distance from the sample surface in a darkened chamber to prevent stray light interference. Freshness classification was executed using a threshold-based decision algorithm programmed into the microcontroller, which categorized the samples into three predefined phases (fresh, semi-fresh, spoiled) based on empirically derived RGB ranges and corresponding gas concentration limits.

IV. RESULTS AND DISCUSSION

The odorless nature of histamine and the basic working principle of the electronic nose (e-nose). Histamine itself is odorless and cannot be directly 'smelled' or detected by human olfactory organs or gas sensors. The bacteria that produce histamine also break down tuna proteins into odorous gases (NH_3 and H_2S). Thus, the e-nose detects these accompanying gases as an "alarm signal" that histamine is also being produced.

That putrefactive bacteria do two things simultaneously (synchronized): convert histidine to histamine and break down proteins into gas NH_3/H_2S. Sensor Phase & Bacteria Phase Correlation:

0–10 hours: Few bacteria → low gas → histamine is safe.

11–20 hours: Bacteria surge → gas rises sharply → histamine begins to form (crucial phase).

21–30 hours: Very high bacteria → pungent, putrid gas → histamine exceeds the safe limit (>50 ppm).

The color sensing unit was calibrated to ensure precise and accurate detection of the samples' chromatic attributes. Utilizing an integrated photodiode array, the TCS3200 sensor measures light reflected from the tuna's surface to generate RGB outputs.

Table 1. Fresh Tuna Fish

Time (Hour(s)	Red	Green	Blue	
1	177,666667	90,25	118,92	
2	183,00	103,58	129,08	
3	184,58	104,58	127,92	
4	183,33	102,17	124,33	
5	180,33	96,25	117,58	
6	177,67	89,33	109,83	
7	175,17	82,67	102,92	
8	172,17	76,33	96,00	
9	169,83	70,50	89,58	
10	167,25	64,83	83,92	

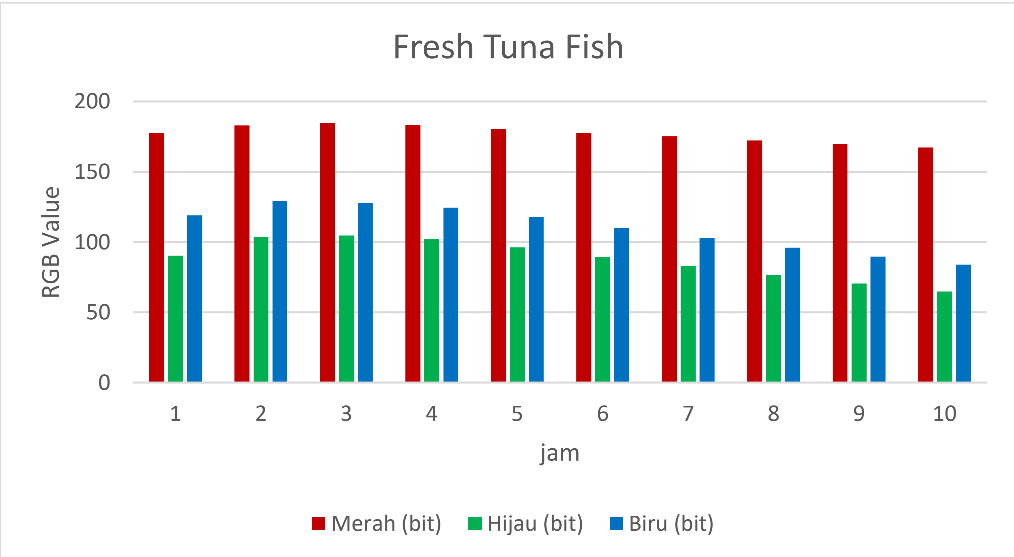


Figure 3. Fresh Tuna Fish.

The data in Table 1 reveals that the average RGB readings for fresh tuna remained stable for the first 10 hours, reflecting the natural state of the meat. While fresh market tuna typically presents a characteristic pink shade, visually differentiating it from early-stage spoilage is difficult because of their nearly identical color profiles. However, as the fish deteriorates, it noticeably turns into a paler, darker pink or a blackish hue. Data trends show that Red (R) values consistently outpaced Green (G) and Blue (B), with average intensities of 178, 90, and 112, respectively, validating the sensor metrics. This Fresh Tuna Fish can be seen in Table 1 and Figure 3.

An RGB distribution comparable to that of fresh fish, characterized by a prominent Red frequency, was maintained by the semi-fresh tuna according to the analysis of Table 2 and Figure 3. Mean values of 159 (R), 48 (G), and 66 (B) were yielded by the colorimetric data for samples subjected to ambient temperatures for 10 hours. The influence of room temperature was evidenced by a gradual transition toward a paler appearance compared to the initial fresh baseline. Additionally, a specific phase in the spoilage kinetics of the tuna was suggested by the stability observed in these average RGB values between the 11-hour and 20-hour marks.

Tabel 2. Fresh Half Tuna Fish

Time (Hour(s)	Red	Green	Blue	
11	164,75	59,58	78,42	
12	162,17	54,83	73,17	
13	159,58	50,00	68,25	
14	157,25	45,42	63,33	
15	154,83	40,83	58,17	
16	153,17	37,08	53,83	
17	151,50	32,67	49,42	
18	149,25	28,83	45,17	
19	147,92	26,33	42,25	
20	146,75	25,00	40,08	

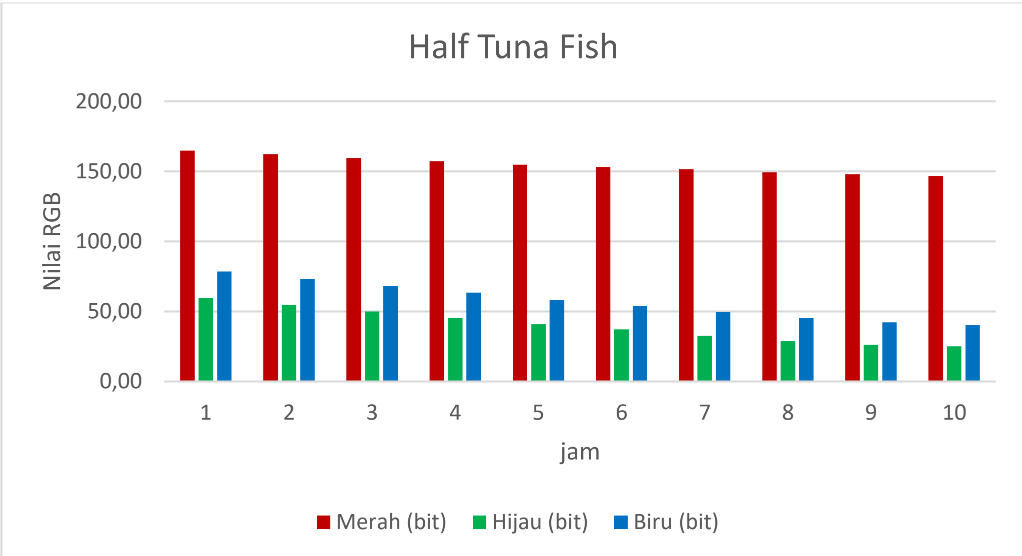


Figure 4. Fresh Half Tuna Fish

As tuna deteriorates, its color frequency drops significantly, yielding recorded averages of 137 (R), 13 (G), and 25 (B). Captured between 21 and 30 hours of ambient exposure, these data points deviate sharply from the color profiles of fresh fish. The samples assumed a characteristic brick-red appearance after 20 hours at room temperature, confirming that this chromatic shift can be utilized as a critical marker for advanced spoilage. An RGB distribution comparable to that of rotten fish, characterized by a prominent Red frequency, was maintained by the Rotten tuna according to the analysis of Table 3 and Figure 4.

Table 3. Rotten Tuna Fish

Hour(s)	Red	Green	Blue
21	145,25	23,08	38,58
22	143,75	21,50	37,08
23	141,50	19,08	34,42
24	140,08	16,25	30,92
25	136,75	11,58	26,17
26	134,00	3,92	18,17
27	130,75	0,00	10,00
28	125,17	0,00	0,92
29	121,92	0,00	0,00
30	119,08	0,00	0,00

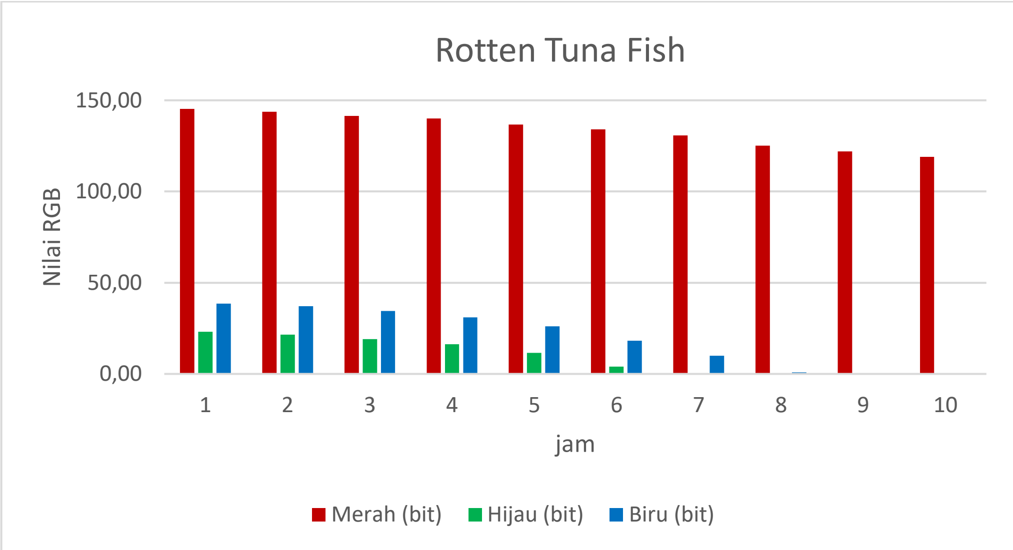


Figure 5. Rotten Tuna Fish.

The empirical data reveals a distinct correlation between the freshness levels of tuna and its corresponding color profile. Fresh Tuna display the most vibrant chromatic properties, noticeably outperforming the two subsequent stages of decay. This degradation trajectory is clearly demonstrated through a comparative analysis of fresh, semi-fresh, and spoiled samples, which is further validated by digital imaging. Although colorimetric data remains a critical tool for differentiating the distinct phases of muscle tissue degradation, the fluctuations observed in this study indicate that the macroscopic visual transitions in tuna freshness are relatively subtle.

Chromatic inputs modulate the internal resistance of the integrated color sensor, which translates these variations into a corresponding frequency output. However, the integrity of these readings remains highly susceptible to ambient illumination and distance variances. To counteract stray light contamination and secure high data fidelity, the entire sensing apparatus was enclosed in a controlled dark chamber. Furthermore, to satisfy the manufacturer's structural requirements, the operational clearance between the sensor substrate and the sample surface was locked at 2.5 cm.

4.1. Sensing Mechanism and Classification Thresholds

The optical sensing protocol employs a 3.5 mm^2 detection window coupled with a sequential filtering technique. Light reflected from the tuna surface is captured by individual red, green, and blue photodiodes, which an internal oscillator subsequently converts into a frequency-modulated square-wave signal. This transduction mechanism effectively translates the surface luminous intensity into quantifiable digital metrics, establishing the analytical baseline for tracking the post-harvest degradation trajectory of the fish from peak freshness to advanced spoilage. To automate this classification, the microcontroller architecture executes real-time data analysis based on the following specific RGB frequency thresholds:

- Fresh Tuna Fish: $172 < R < 184$, $70 < G < 104$, and $89 < B < 129$
- Semi-fresh Tuna Fish: $151 < R < 167$, $32 < G < 64$, and $49 < B < 83$
- Spoiled Tuna Fish: $119 < R < 149$, $0 < G < 28$, and $0 < B < 45$

These categorized freshness indicators are subsequently transmitted to a computer interface in a standardized RGB array format, accompanied by instantaneous auditory feedback from an integrated buzzer system to confirm the freshness classification.

4.2. MQ-136 and MQ-137 Gas Sensor Characterization

The operational sensitivity and response profiles of the MQ-136 and MQ-137 sensors were characterized to evaluate their capability in detecting biochemical shifts associated with meat quality degradation. A standardized experimental protocol was strictly maintained to guarantee reproducibility across all testing cycles. Structurally, the sensors were affixed to the ceiling of the airtight test chamber, directly overlying the tuna fish specimens. Upon introducing each sample into the enclosure, sensor output voltages were continuously acquired over a rigorous five-minute monitoring window. Following the established data collection framework, the experimental trials systematically commenced with baseline measurements of fresh tuna fish [19].

The sensitivity of MQ-136 and MQ-137 sensors to tuna quality transitions was assessed under a strict, standardized testing protocol to ensure cross-trial consistency. The sensors were integrated into the upper section of the test chamber, positioned directly over the tuna samples. Sensor voltage data was logged for a five-minute period, starting immediately after sample insertion. To align with predefined data collection procedures, testing chronologically began with fresh tuna specimens to establish baseline metrics.

Top-Mounted Sensors: Placing the MQ-136 and MQ-137 sensors at the top of the chamber with the sample below is a classic setup for Headspace Analysis. Because volatile compounds (such as ammonia and hydrogen sulfide gas) released by decaying fish are lighter than air and rise due to local ambient heat, the top-mounted configuration ensures that the gas accumulates efficiently around the sensor's heating element, maximizing sensitivity.

5-Minute Phase (Adsorption Phase): Initiating a 5-minute data acquisition period immediately after sample introduction captures the transient response (rise time) of the metal oxide semiconductor (MOS) sensor. During this 5-minute period, gas molecules adsorb onto the sensor surface, causing a measurable drop in resistance and a corresponding spike in output voltage. This phase is crucial for identifying the peak response or steady state of the system.

Fresh-to-Rot Timeline: Starting a test series with a fresh specimen is a vital scientific practice. This establishes a clean baseline voltage (V_0) before the chamber and sensor surfaces are at risk of being heavily contaminated by high concentrations of volatile organic compounds (VOCs) that would be emitted by semi-fresh or spoiled fish.

4.3. TGS 2602 Gas Sensor Characterization

The TGS 2602 gas sensor was evaluated to determine its responsiveness to the varying freshness levels of Tuna fish. To ensure experimental, a standardized testing was strictly maintained for each trial as follows: The testing was conducted within a hermetically sealed 20 cm^3 cubic chamber containing the gas sensor module. The sensor was positioned at the apex of the chamber, while the Tuna sample was placed at the base during the assessment. Voltage data acquisition was performed for a duration of 30 seconds, initiated immediately upon the sample's introduction into the enclosure. The experimental sequence commenced with fresh Tuna specimens, with all data logged according to established collection procedures.

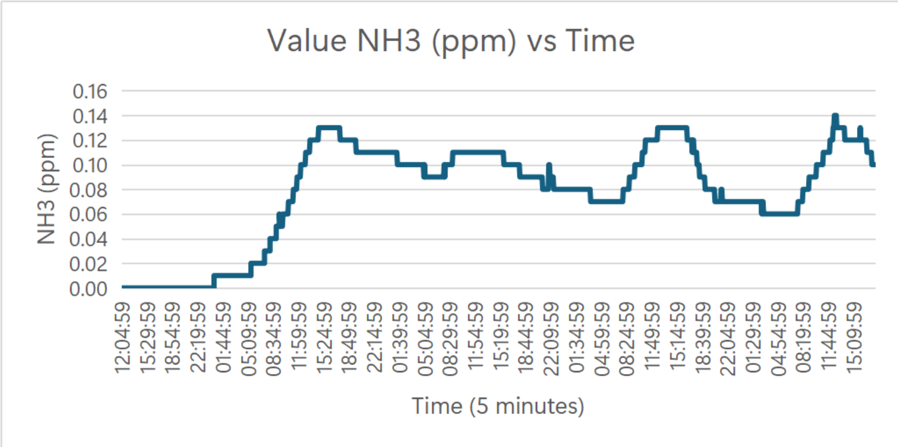


Figure 6. Change in the concentration of NH3 in meat stored at room temperature

To evaluate the TGS 2602 sensor's sensitivity to varying tuna freshness levels, a strict, uniform testing protocol was maintained across all trials. Testing took place within a hermetically sealed 20cm^3 cubic, where the sensor module was top mounted at the apex and the tuna sample rested at the base. Sensor voltage data was logged for 30 seconds, starting immediately after the sample was enclosed. Following predefined data acquisition procedures, testing chronologically began with fresh tuna specimens to establish a clean reference baseline.

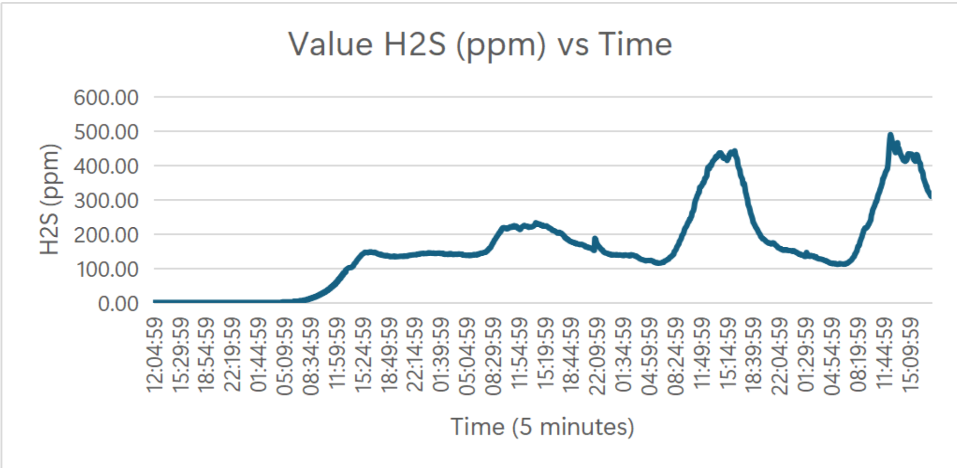


Figure 7. Change in the concentration of H2S in meat stored at room temperature

4.4. Kinetics of NH3 and H2S

The post-harvest degradation of tuna at ambient temperature is driven by simultaneous glycolytic and proteolytic pathways. Spoilage microorganisms metabolize glucose and lactate substrates into organic end-products, including ethanol and fatty acids. Concurrently, the catabolism of amino acids and nitrogenous compounds via secondary microbial metabolism generates volatile sulphides. Markedly elevated ammonia concentrations over extended storage periods serve as a key biochemical indicator of advanced spoilage and accelerated microbial proliferation. The liberation of both ammonia NH_3 and hydrogen sulphide H_2S is primarily mediated by the proteolytic activities of specific bacterial genera, namely *Bacillus*, *Clostridium*, and *Pseudomonas*. The corresponding temporal fluctuations in H_2S and NH_3 profiles for the monitored tuna fish are illustrated in Figures 6 and 7.

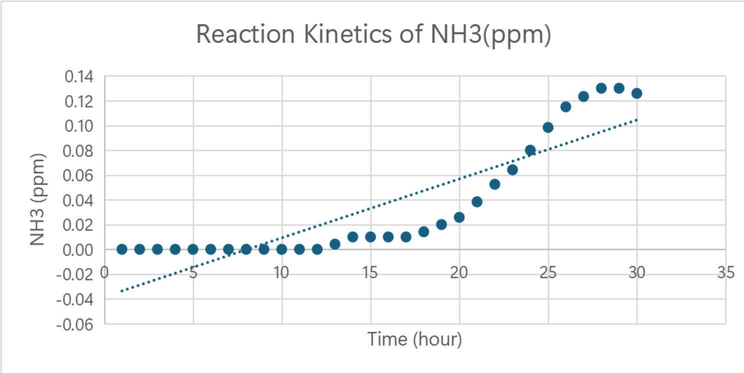
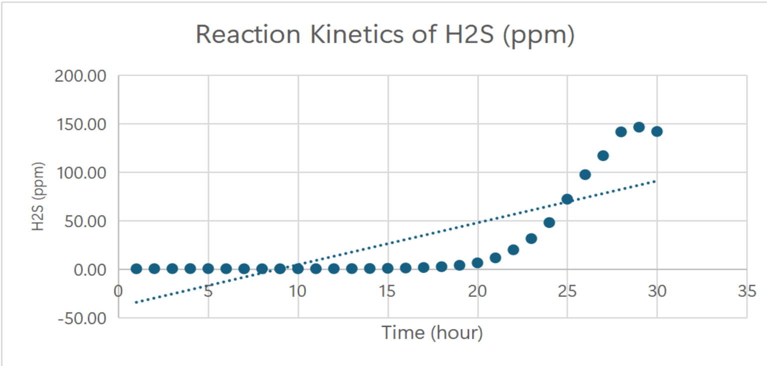


Figure 8. show how the concentrations of NH_3 gases changed in the Tuna Fish tested



Figures 9. show how the concentrations of H_2S gases changed in the Tuna Fish tested

The accumulation rates of ammonia (NH_3) and hydrogen sulfide (H_2S) were modeled using zero-order kinetics, plotting the progressive increase in volatile concentration (C) as a function of time (t), as illustrated in Figures 8 and 9. This mathematical framework aligns with established literature addressing the quality degradation kinetics of high-protein seafood during processing. Based on the experimental trajectories, the zero-order kinetic model exhibits high efficacy in predicting the gas release profiles of tuna, thereby providing a robust predictive tool for monitoring spoilage under ambient temperature conditions.

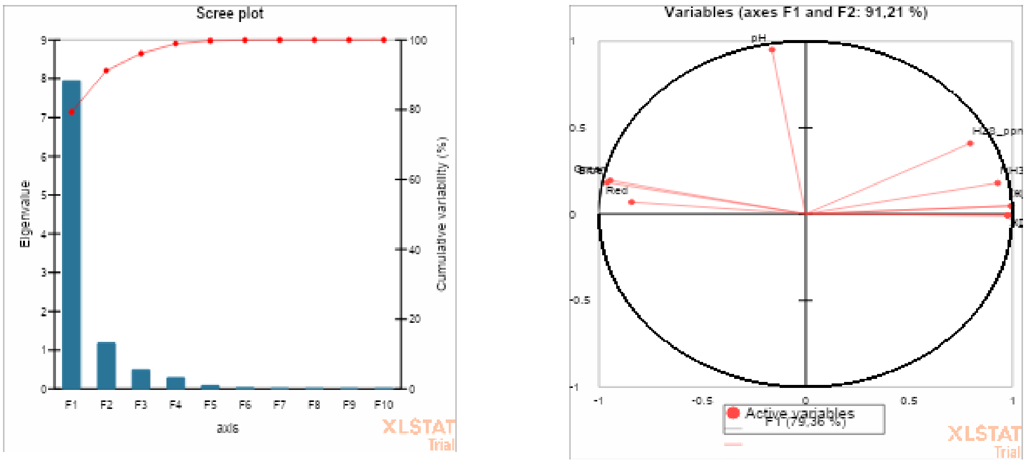


Figure 10. PCA plot of Salmon Fish samples during 96-hour storage

The computed rate constants (k) for volatile emissions were established at 0.38 for H_2S and 0.62 for NH_3. Freshness loss in tuna is primarily marked by off-odor development and increasing pH values, driven by the microbial breakdown of amino acids. This pathway yields specific by-products, namely hydrogen sulfide (H_2S), indoles, and volatile amines like ammonia. Consequently, these sulfurous compounds and amino acid derivatives serve as the critical chemical biomarkers required to accurately classify the fish's degradation stages.

Principal Component Analysis (PCA) was utilized to identify volatile NH_3 and H_2S markers in raw tuna stored under ambient conditions as seen in Figure 10. The shifting concentrations of these gases successfully classify the samples based on storage time. This allowed the tuna's freshness to be delineated into three temporal phases: fresh were aged for 0-10 hour, semi-fresh were aged for 11-20 hour, and spoiled were aged for 21-30 hour. The analytical data confirms that a steady accumulation of NH_3 and H_2S serves as a reliable indicator of the post-harvest transition from freshness to decay.

V. DISCUSSION

Post-harvest degradation in tuna is a multifaceted phenomenon initiated by endogenous autolysis and subsequently accelerated by microbial proliferation, culminating in rapid quality loss and diminished commercial viability [20]. Critical variables, including initial post-capture handling and thermal storage profiles, exert a decisive influence on the final state of the product. Although refrigeration technologies are widely deployed to mitigate tissue decay, the metabolic activity of psychotropic bacteria presents a persistent bottleneck for shelf-life extension. Consequently, given that freshness and spoilage serve as the definitive benchmarks of seafood safety, substantial scientific attention has shifted toward the development of high-precision evaluation methodologies. This focus is imperative to guarantee robust quality monitoring during the critical temporal window before the commodity renders itself unfit for human consumption [21].

Traditional organoleptic and sensory-based classifications of seafood freshness are frequently compromised by human subjectivity and inherent logistical bottlenecks. While quantitative chemical analyses provide an objective baseline, these analytical methods remain notoriously labor-intensive, cost-prohibitive, and difficult to scale across diverse marine species [22]. To transcend these classical limitations, the seafood processing sector urgently requires the development of novel, portable analytical technologies capable of delivering real-time data regarding tuna quality. The deployment of such objective sensing platforms is crucial to enable processing facilities to rapidly verify post-harvest freshness, thereby mitigating food safety risks and sustaining high market quality standards [23].

Commercial oxygen indicators predominantly rely on redox dye mechanisms to signal the presence of oxygen [24]. A typical formulation involves methylene blue acting as the redox dye, paired with a reducing agent in a basic solution. The system functions through a reversible color change; it remains colorless in oxygen-free environments due to the reducing agent but shifts to a visible hue upon exposure to oxygen, the principal advantages of these indicators include their low production costs and the ability to provide accessible, equipment-free monitoring for various applications [25].

The concurrent increase in volatile gas concentrations and the degradation of RGB values can be attributed to the synergistic biochemical breakdown of the tuna tissue. As post-harvest time increases, psychrotrophic bacteria initiate the proteolytic cleavage of amino acids and the reduction of sulfur-containing compounds, leading to the exponential emission of NH3 and H2S. This microbial metabolism simultaneously alters the tissue's structural integrity and pH level. The accumulation of basic volatile nitrogen compounds raises the surface pH, which directly impacts the myoglobin stability in the tuna muscle. The oxidation of bright-red oxymyoglobin into brownish metmyoglobin visually manifests as a sharp decline in the Red (R) frequency, shifting the sample's appearance from a vibrant pink to a paler, darkish hue[cite: 1]. Therefore, the digital colorimetry data strongly cross-validates the gas sensor readings, confirming that the macroscopic color shifts observed by the TCS3200 sensor are directly driven by the underlying biochemical spoilage kinetics detected by the MQ sensors

VI. CONCLUSION

Modern sensor technologies, such as pH-based smart packaging and electronic noses (e-noses) using MQ-136/MQ-137 sensors, have proven effective, cost-effective, and portable alternatives to traditional, subjective and expensive tuna freshness evaluation methods. Implementation of these innovations is crucial for preventing histamine poisoning, reducing export approval rates, and ensuring real-time quality in the domestic fisheries sector. A detection system based on MQ-136 and MQ-137 sensors successfully monitored H2S and NH3 gases in tuna during open storage. The device was able to categorize the freshness level of fish into three temporal phases: fresh (0-10 hours), not fresh (11-20 hours), and spoiled (21-30 hours). Kinetic modeling showed that the accumulation of NH3 and H2S gases followed a precise zero-order model with a uniform rate constant of 0.82, enabling the system to objectively classify tuna freshness levels. Visual data analysis was performed on a microcontroller using specific RGB parameter limits for fresh, semi-fresh, and spoiled conditions. The results for the color sensor on the microcontroller are: Fresh Tuna Fish: $172 < R < 184$, $70 < G < 104$, and $89 < B < 129$, Semi-fresh Tuna Fish: $151 < R < 167$, $32 < G < 64$, and $49 < B < 83$, Spoiled Tuna Fish: $119 < R < 149$, $0 < G < 28$, and $0 < B < 45$. This portable device innovation promises significant contribution as a fast and non-destructive evaluation instrument in the quality control line of the modern food industry.

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