

Non-Invasive Quality Assessment of Fresh Tuna via Integrated RGB Colorimetry and Volatile Organic Compound Sensing

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Abstract. Post-harvest tuna quality degrades rapidly due to autolysis and microbial decomposition, producing toxins such as histamine and harmful volatile compounds. Conventional organoleptic testing methods are subjective, whereas laboratory analyses are time-consuming and costly. This study aimed to develop a portable, non-invasive, rapid, and affordable analytical device by integrating an optical color sensor (TCS3200) and an electronic nose gas sensor array (MQ-136, MQ-137, and TGS 3200) to classify tuna freshness levels (fresh, semi-fresh, and spoiled) at room temperature. The color sensor was mounted at a fixed distance of 2.5 cm inside a dark chamber to measure RGB surface color degradation, while the gas sensor array was positioned at the top of the enclosed chamber to detect decomposition gases such as ammonia (NH₃) and hydrogen sulfide (H₂S). Gas release kinetics were analyzed using a zero-order reaction model, yielding rate constants (k) of 0.86 for NH₃ and 0.81 for H₂S. Pearson correlation analysis revealed a strong negative correlation between volatile gas concentrations and RGB color intensities (specifically H₂S against the Blue channel, $r = -0.82$, and the Green channel, $r = -0.80$), whereas pH parameters showed only a weak correlation ($r = 0.16-0.26$). RGB frequency thresholds proved effective for precisely categorizing freshness phases, supported by real-time audio feedback from a buzzer. These results demonstrate that integrating optical and volatile gas sensors offers significantly higher accuracy and sensitivity compared to pH-only testing, presenting great potential for implementation as a portable quality testing tool for veterinary authorities and the fishery industry.

Keywords: *Decomposition kinetics, electronic nose, Food freshness, MQ-136, MQ-137, TCS3200, Tuna fish.*

INTRODUCTION

The rapid expansion of cold chain logistics is largely driven by soaring global demand for fresh produce, beef, and dairy items. Because these perishable goods are highly sensitive to environmental fluctuations, maintaining their safety and quality during transit poses a major challenge. Storage failures can lead to rapid decay, severe financial losses, and consumer health risks. Similarly, premium seafood such as tuna and salmon is globally sought after for its exceptional flavor and nutritional value, yet its market value depends entirely on freshness [1]. Given that fish deteriorates quickly through biochemical and microbial processes, objective and accurate freshness evaluations are essential to uphold food safety standards. Traditional aquaculture, however, relies heavily on manual inspections by experts, a method that is costly, repetitive, and vulnerable to fatigue, oversight, and subjective variation. As the global tuna and salmon markets expand rapidly, delivering fast and consistent quality control has emerged as a critical hurdle [2].

Innovations in food freshness monitoring devices play a crucial role in safeguarding public health, particularly as growing consumer awareness heightens the focus on animal product quality. Modern consumers increasingly seek nutritious food options with easily verifiable freshness levels [3]. Tuna is widely recognized as a premier marine commodity owing to its exceptional nutritional profile, desirable flavor, and processing versatility. Nevertheless, it remains highly susceptible to ambient storage temperatures and microbial contamination, both of which can rapidly accelerate spoilage. In Indonesia, the expansion of the seafood sector faces a critical safety hurdle due to tuna deterioration and the hazardous accumulation of histamine. To mitigate this risk, advanced smart packaging utilizes pH sensitive colorimetric sensors to provide real-time indicators of degradation before toxic thresholds are reached. Exposure to ambient temperatures triggers bacterial decarboxylation of histidine into histamine within 8 to 20 hours. Because histamine is both heat-stable and odorless, conventional cooking cannot neutralize this compound, leaving consumers unable to identify contaminated fish through sensory evaluation alone.

The breakdown of tuna generates volatile basic nitrogenous compounds that elevate product pH, subsequently triggering a colorimetric response in smart packaging materials. To achieve high-precision quality assurance, advanced analytical laboratories deploy microchips and optical sensors to monitor biogenic amines and gaseous shifts. Because histamine buildup accounts for most rejections of Indonesian tuna exports to major international destinations like Japan, the US, and the EU, commercial exporters in key trading hubs such as Bali mandate rigorous pre-export testing. Domestically, 2026 market prices for fresh and frozen tuna fillets range from IDR 52,900 to IDR 115,000 per kilogram. Although smart packaging technologies have not yet seen widespread commercial adoption in traditional wet markets, ongoing research aims to implement them locally to support rising national fish consumption.

Veterinary authorities performing field inspections and consumers evaluating fish quality require a fast, portable, chemical-free, and non-destructive tool to test tuna freshness. Prototype Electronic Nose (E-nose) technology offers an ideal approach and has become increasingly popular in food analytics. Compared to traditional chemical and microbiological assays, E-nose systems provide a fast, affordable, and non-invasive method for profiling volatile organic compounds. While sensor technology is widely deployed across environmental, medical, and food safety applications including tuna species identification the specific use of MQ-136 and MQ-137 gas sensors for rapid tuna freshness evaluation remains largely unexplored [4].

Electronic nose technology utilizing specialized gas sensors offers an effective solution for the rapid freshness evaluation of raw tuna. This study investigates a straightforward, swift, and low-cost detection framework capable of producing objective, highly reproducible data regarding fish spoilage. Integrating MQ-136 and MQ-137 sensors, the system continuously monitored tuna quality dynamics throughout storage, directly comparing sensor outputs against standard chemical freshness parameters. The chosen gas sensors were evaluated for their efficacy in detecting ammonia and hydrogen sulphide, two primary gaseous markers of seafood deterioration. The study demonstrated a strong correlation coefficient (r) between the sensor array responses and conventional chemical testing protocols. These results indicate that the prototype system holds substantial promise for reliably categorizing meat samples into fresh, non-fresh, and spoiled tuna classes [5].

Despite robust consumer demand, post-harvest tuna undergoes rapid quality degradation when adequate preservation protocols are absent. Under ambient environmental conditions, early indicators of spoilage such as odors typically emerge within a narrow timeframe of 8 to 10 hours. Although room-temperature storage limits product shelf life to approximately 12 hours, cold chain preservation can significantly extend viability for up to 15 days. Because tuna commercialized in traditional wet markets frequently experiences prior handling or processing, conducting targeted research to accurately assess commodity freshness under these specific conditions is of paramount importance [6].

Traditional freshness assessments like sensory, chemical, and microbiological testing often lack objectivity and present safety hazards when screening for toxic metabolites [7]. While pH tracking offers a dependable gauge of tuna freshness, current demands lean toward fast, field-deployable, and affordable analytical technologies. Modern sensor platforms address this need by replacing subjective human evaluation with automated systems capable of rapid, high-precision color and odor profiling [8].

METHODS

Sample Preparation

Fresh tuna samples were acquired from Superindo (Purwokerto, Indonesia) and transported in secure packaging to the laboratory. Once received, 100 g sample portions were precisely weighed into petri dishes to carry out structured measurements.



Figure 1. Representation of the sensor chamber, sample chamber, and sensor system

Procedures

The detection system comprises a dedicated gas-sensing platform controlled by an Arduino microcontroller. Utilizing resistance-based semiconductor technology, the integrated MQ-136 and MQ-137 sensors quantify gaseous emissions released by tuna specimens enclosed within a sealed 1.5 L acrylic chamber. The setup converts raw sensor voltage outputs into parts-per-million (ppm) concentration values via calibrated mathematical formulas, subsequently logging these data points into a computer database through a seamless serial communication link. Operational accuracy and sensor reliability are maintained by validating performance parameters against manufacturer specifications.

Data analysis

Tuna fish were placed in sensor-integrated acrylic containers where MQ-136 and MQ-137 sensors continuously tracked volatile gas emissions. These emissions triggered real-time voltage changes proportional to gas concentration, providing a reliable measure to monitor sample spoilage over time.

RESULTS AND DISCUSSION

Colour in Tuna Fish

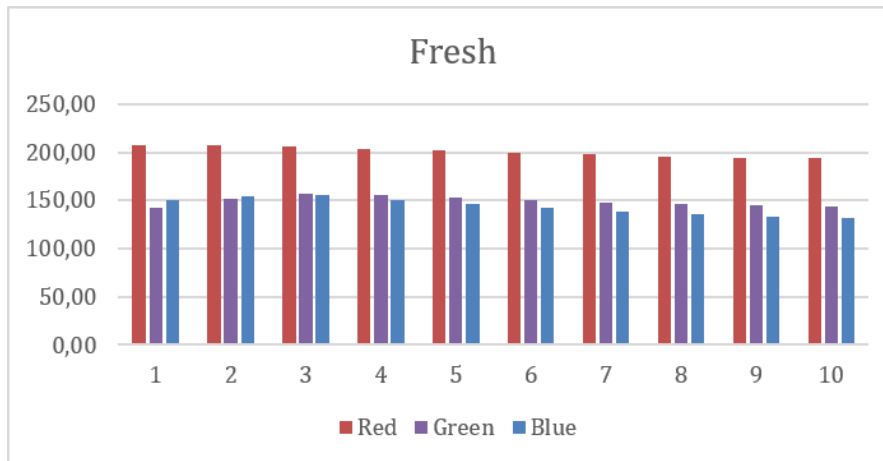


Figure 1. Tuna Fresh

Surface chromatic properties were measured using a calibrated TCS3200 photodiode sensor. As shown in Figure 1, the fresh tuna displayed stable colour profiles over the first 10 hours, consistent with myoglobin-dense muscle tissue. Mean RGB readings were recorded at 203.01 (Red: 196.50–207.50), 151.38 (Green: 142.17–156.33), and 147.10 (Blue: 136.58–155.67). The predominant red intensity relative to Green and Blue ($R > G > B$) validated sensor accuracy and reflected the characteristic appearance of fresh tuna. These high baseline luminance levels demonstrate that light reflectance is highest during early preservation before gradually decreasing with fish spoilage.

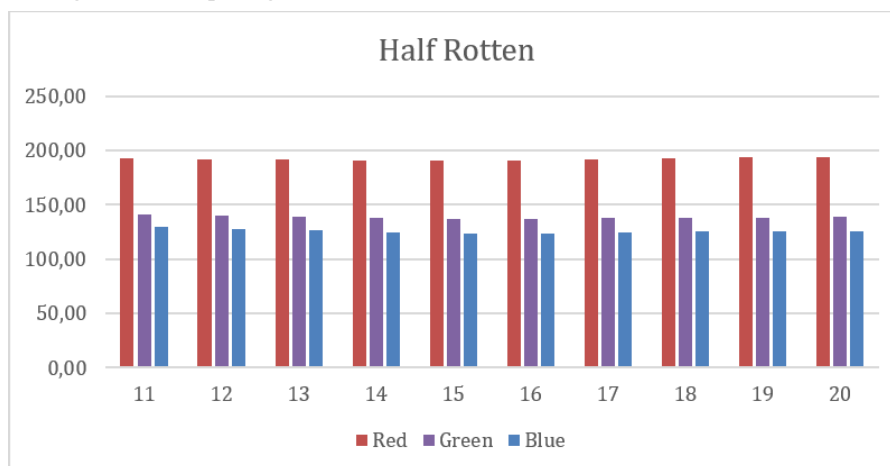


Figure 2. Fresh Half Tuna

Analysis of the colorimetric data for the half-fresh (moderately degraded) tuna phase (hours 11 to 20 of ambient exposure) demonstrates a noticeable shift in spoilage kinetics, characterized by a gradual attenuation across all RGB spectrums. Empirical measurements yield mean intensities of 192.53 for Red (range: 190.75–195.17), 141.05 for Green (range: 137.42–146.25), and 128.07 for Blue (range: 123.50–134.92). This downward trend reflects the onset of pigment oxidation—specifically the conversion of oxymyoglobin to metmyoglobin under room temperature—which visually transitions the muscle tissue toward a paler appearance compared to the fresh baseline. Despite the overall reduction in luminance, the dominant red frequency ($R > G > B$) is preserved throughout this transitional period. Furthermore, the steady and controlled rate of decline across these 10 data points confirms the presence of a distinct plateau phase in the quality degradation kinetics prior to advanced spoilage.

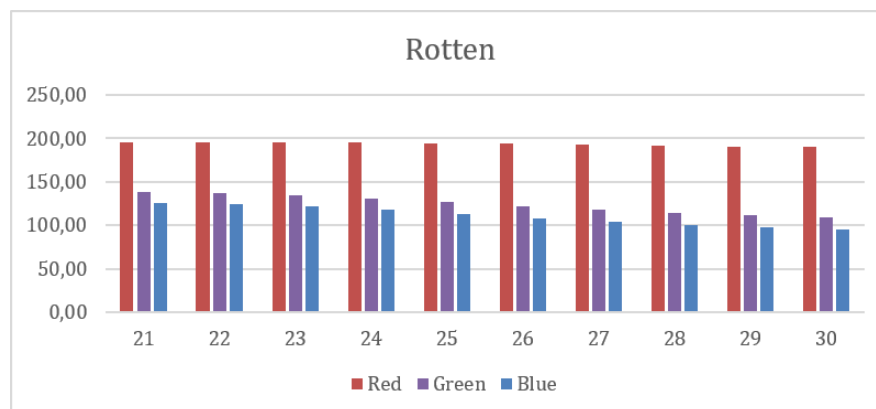


Figure 3. Rotten Tuna

Colorimetric evaluation during advanced deterioration (hours 21 to 30 of ambient exposure) demonstrates a marked departure from the initial chromatic baseline of fresh tuna. As evidenced by the empirical dataset, average readings for the Green (G) and Blue (B) channels decreased significantly to 136.63 (range: 130.67–138.83) and 124.08 (range: 117.67–126.33), respectively, whereas the Red (R) channel stabilized at a higher mean of 193.81 (range: 190.92–195.92). This substantial decline in Green and Blue wavelengths relative to Red induces a visible color shift toward a dark brick-red or brownish hue past the 20-hour mark at room temperature. Ultimately, this pronounced chromatic divergence confirms that the RGB spectral ratio serves as an effective qualitative metric for identifying advanced tuna spoilage.

These empirical findings demonstrate a clear correlation between tuna freshness and its surface chromatic profile. Fresh tuna exhibits peak color intensity, significantly exceeding the optical values recorded during subsequent stages of tissue decay. This progressive degradation pattern remains evident across fresh, half-fresh, and spoiled samples, a trend independently corroborated by digital image processing. However, while colorimetric metrics provide an essential framework for differentiating stages of muscle breakdown, the subtle nature of the observed data variations indicates that macro-level visual changes in tuna freshness remain relatively nuanced.

The integrated TCS3200 color sensor operates by modulating its internal resistance in response to chromatic inputs, thereby converting color variations into proportional frequency outputs. To mitigate the sensor's inherent sensitivity to ambient illumination fluctuations and measurement distance variations, the complete sensing module was enclosed within a custom dark chamber to eliminate stray light interference. Furthermore, a constant working distance of 2.5 cm was maintained between the sensor photodiode array and the sample surface, adhering strictly to the manufacturer's structural recommendations to ensure high data fidelity.

Sensing Mechanism and Classification Thresholds

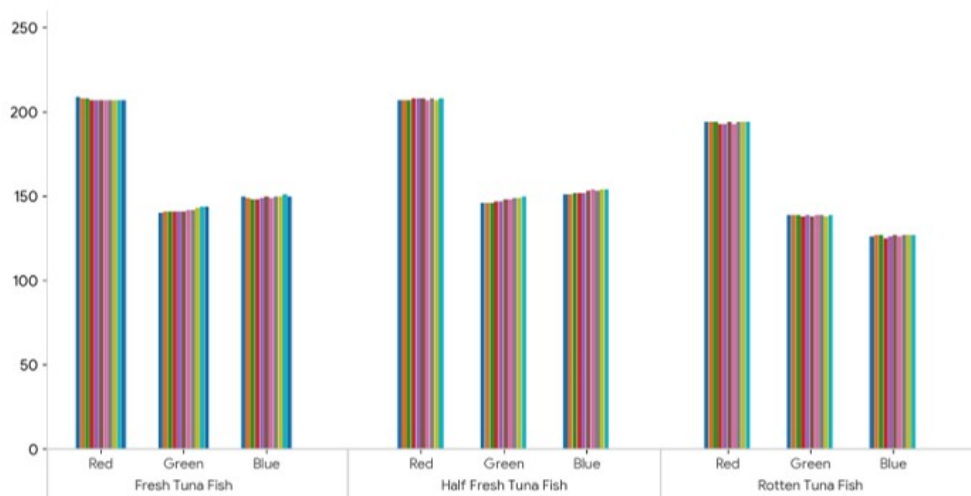


Figure 4. Overall Fresh, Fresh Half, and Rotten Tuna Fish

The optical detection protocol employs a 3.5 mm² detection window combined with a sequential filtering technique to assess color changes on the tuna sample's surface. Light reflected from the tuna flesh is captured individually by red, green, and blue photodiodes, which are subsequently converted by an internal oscillator into frequency-defined square-wave signals. This transduction mechanism effectively translates surface

luminance intensity into a quantifiable digital metric, while establishing an analytical baseline for monitoring the fish's post-harvest degradation trajectory from peak freshness to advanced stages of spoilage. To automate classification, the microcontroller architecture performs real-time data analysis based on the following RGB frequency thresholds:

The optical sensing protocol classifies tuna freshness based on specific RGB frequency thresholds: fresh samples exhibit values of R: 196.50–207.50, G: 142.17–156.33, and B: 136.58–155.67; semi-fresh specimens measure R: 190.75–195.17, G: 137.42–146.25, and B: 123.50–134.92; while spoiled tuna registers R: 190.92–195.92, G: 130.67–138.83, and B: 117.67–126.33. These categorized freshness indicators are subsequently transmitted to a computer interface in a standardized RGB array format, accompanied by real-time acoustic feedback from an integrated buzzer module to provide instantaneous verification of the classification outcomes.

MQ-136 and MQ-137 Gas Sensor Characterization

Characterization of the MQ-136 and MQ-137 gas sensors focused on assessing their performance in monitoring biochemical indicators during tuna deterioration. Ensuring consistent and repeatable measurements across testing cycles was achieved by adhering to a standardized testing procedure. The sensor array was mounted at the top of an airtight test vessel directly above the tuna samples. Continuous recording of the output voltage proceeded for five minutes immediately after sealing the enclosure, beginning with initial baseline data collection on fresh tuna tissue.

Standardized characterization of the MQ-136 and MQ-137 gas sensors ensured high data consistency during tuna freshness evaluations. Mounted in the top section of the chamber directly above the samples, the sensors recorded output voltage for five minutes following insertion. Trial procedures systematically began with fresh tuna specimens to capture essential baseline readings prior to monitoring subsequent decay stages.

Mounting the MQ-136 and MQ-137 sensors on the ceiling of the testing enclosure optimizes standard headspace gas sampling. Because volatile degradation products such as ammonia and hydrogen sulfide possess a lower density than air and naturally ascend due to ambient thermal convection, this overhead configuration facilitates rapid gas accumulation around the active sensing elements, thereby maximizing measurement sensitivity.

The five-minute adsorption phase captures the transient rise time of the MOS sensor right after sample introduction. As volatile gas molecules bind to the sensor surface, decreasing electrical resistance drives a corresponding voltage increase. Monitoring this timeframe is essential to determine peak signal levels and assess the system's steady-state performance.

Experimental trials were systematically initiated with fresh specimens to establish a reliable baseline voltage (V_0). By acquiring reference metrics prior to introducing semi-fresh or spoiled samples, potential surface and chamber contamination caused by high volatile organic compound (VOC) emissions was effectively minimized.

TGS 2602 Gas Sensor Characterization

Characterization of the TGS 2602 gas sensor was conducted to evaluate its response profiles across varying levels of tuna freshness. To maintain high experimental reproducibility, a standardized measurement protocol was strictly followed. The sensor module was installed on the ceiling of a hermetically sealed cubic chamber (10cm x 10cm x 10cm), with the tuna specimen placed at the bottom. Voltage acquisition was recorded continuously over a 30 second window immediately following sample introduction. In accordance with established procedures, testing systematically began with fresh tuna samples to acquire baseline reference data.

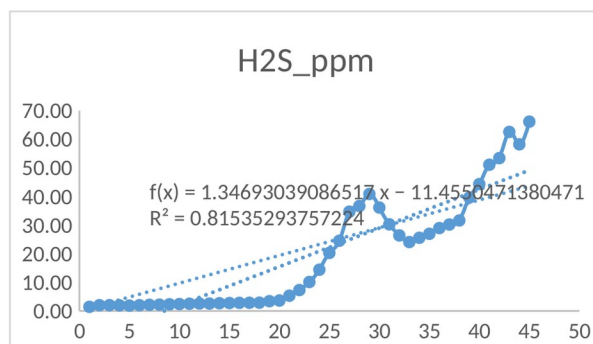


Figure 5. Kinetic Reaction for H2S

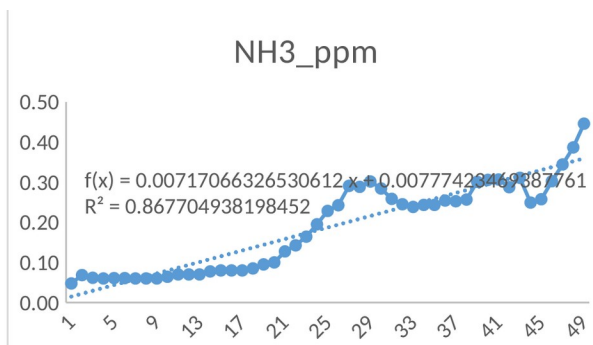


Figure 6. Kinetic Reaction for NH3

Kinetics of NH3 and H2S

Zero-order reaction kinetics effectively characterized the release of ammonia (NH_3) and hydrogen sulfide (H_2S) over time during tuna storage. Based on Figures 6 and 7, linear equations described the temporal concentration accumulation, expressed as ($R^2 = 0.8154$) for (H_2S) and ($R^2 = 0.8677$) for (NH_3). In agreement with standard kinetic models for high-protein marine tissues, this linear approach serves as an accurate analytical metric for tracking quality deterioration at room temperature.

The rate constants (k) for volatile gas generation were determined as $k_{\text{H}_2\text{S}} = 1.3469$ ppm/h and $k_{\text{NH}_3} = 0.0072$ ppm/h corresponding to the slopes of zero-order linear regressions (Figures 6 and 7). Microbial degradation of amino acids serves as the primary driver of tuna spoilage, causing off-odors, an elevated pH, and the concurrent release of hydrogen sulfide (H_2S), indoles, and ammonia (NH_3). These sulfurous and amine compounds function as crucial chemical biomarkers for identifying and differentiating specific stages of seafood freshness [9].

The kinetics of ammonia (NH_3) and hydrogen sulfide (H_2S) accumulation reflect the post-mortem deterioration of room-temperature stored tuna, which progresses through coupled glycolytic and proteolytic degradation pathways. Initial bacterial metabolism converts glucose and lactate into ethanol and organic acids, whereas subsequent nitrogenous catabolism yields volatile sulfur compounds. Significant elevations in ammonia concentration serve as a definitive biochemical index of advanced tissue decay and microbial proliferation. The release of (NH_3) and (H_2S) is predominantly catalyzed by proteolytic bacteria belonging to the *Bacillus*, *Clostridium*, and *Pseudomonas* genera, with Figures 1 and 2 illustrating the temporal tracking of these gas profiles throughout the monitoring period[10].

Principal Component Analysis

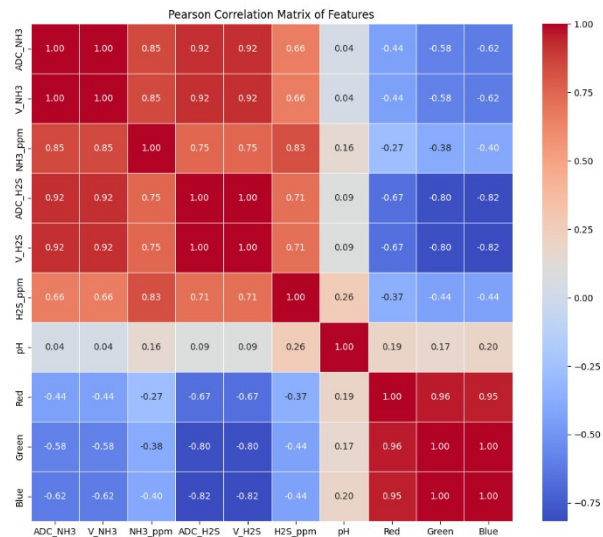


Figure 7. Pearson correlation matrix

The Pearson correlation matrix confirms a perfect positive linear relationship ($r = 1.00$) between ADC digital output values and measured voltage (V) for both NH₃ and H₂S sensors, verifying the fidelity of the hardware signal conversion setup. Gas concentration levels (ppm) demonstrate strong positive correlations with raw sensor signals $r = 0.71-0.85$. Simultaneous volatile emissions induce high inter-sensor correlation ($r = 0.83-0.92$), whereas optical color channels (Red, Green, Blue) display near-perfect collinearity ($r = 0.95-1.00$) driven by the uniform reduction in muscle surface luminance. Marked inverse correlations between gas sensor signals and optical channels—most notably H₂S against Blue ($r = -0.82$) and Green ($r = -0.80$)—quantify the inverse coupling between volatile degradation products and surface reflectance. Conversely, pH exhibits only weak correlation coefficients ($r = 0.16-0.26$), validating that a multimodal fusion of optical and gas-sensing modalities achieves significantly higher sensitivity and diagnostic accuracy for tuna freshness classification than pH evaluation alone.

Discussion

The post-mortem degradation of tuna progresses through early endogenous autolysis followed by intense microbial activity, causing rapid sensory decay and loss of commercial value. Immediate post-harvest handling and thermal storage profiles predominantly dictate final tissue integrity [11]. Although cold chain logistics are routinely employed to suppress spoilage kinetics, psychotropic bacterial growth poses an ongoing challenge to shelf-life extension [12]. Consequently, high-precision detection techniques are actively being developed to establish robust quality assurance frameworks before the fish transitions to an inedible state. Traditional sensory and organoleptic evaluations of seafood freshness are frequently constrained by subjective human judgment and operational bottlenecks [13]. Although quantitative chemical assays establish an objective benchmark, these laboratory methods remain labour-intensive, cost-prohibitive, and difficult to scale across diverse marine species. To overcome these conventional limitations, the seafood processing industry increasingly necessitates portable analytical technologies capable of delivering rapid, real-time quality metrics for tuna [14]. Deploying such objective sensing platforms is essential for enabling processing facilities to verify post-harvest freshness efficiently, thereby mitigating food safety hazards and maintaining market quality standards [15].

Redox dye mechanisms form the operational foundation for most commercial oxygen indicators. Typically comprising methylene blue and a reducing agent dissolved in an alkaline solution, the system exhibits a reversible color transition, remaining colorless under anoxic conditions and developing a distinct chromophore upon oxygen exposure. The primary advantages of these indicator systems include low production costs and the capability for visual, non-instrumental monitoring in practical smart packaging applications.

CONCLUSION

This study successfully demonstrates that integrating a TCS3200 optical colour sensor with an Electronic Nose gas sensor array comprising MQ-136, MQ-137, and TGS 2602 sensors provides an objective, rapid,

non-destructive, and highly reproducible platform for evaluating tuna freshness without chemical reagents. Post-mortem tuna degradation at ambient temperature follows zero-order reaction kinetics, with volatile gas generation rate constants (k) established at 0.0072 ppm/h for ammonia (NH_3) and 1.3469 ppm/h for hydrogen sulphide (H_2S), both of which inversely correlate with RGB surface colour attenuation caused by myoglobin oxidation. By utilizing real-time RGB frequency thresholds, the system effectively automates the classification of tuna meat into fresh, semi-fresh, and spoiled categories, supported by immediate visual and auditory feedback. Furthermore, Pearson correlation analysis confirms that combining volatile gas and optical reflectance profiles yields far superior sensitivity ($r=0.80-0.82$) for tracking early spoilage stages than traditional pH testing ($r = 0.16-0.26$). Ultimately, this portable multi-sensor prototype offers a robust, field-deployable solution for veterinary authorities and commercial seafood exporters to streamline quality assurance, prevent histamine toxicity, and reduce export rejections.

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