

Measurement of Temperature, CO₂ Concentration, and Humidity in Food Spoilage Gas Using an Electroplated SnO₂ Resistive Sensor

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Abstract:

Food spoilage is accompanied by changes in environmental parameters, including temperature, carbon dioxide (CO₂) concentration, and relative humidity, which can influence the electrical response of metal oxide semiconductor sensors. This study aimed to fabricate an SnO₂ resistive sensor by electroplating and evaluate its electrical response to environmental variations during food spoilage. The SnO₂ sensing layer was deposited on a Cu substrate by electroplating at 6.0 V and an electrolyte temperature of 40 °C, followed by thermal oxidation. The fabricated sensor was tested in a sealed chamber containing a food sample undergoing natural spoilage, while temperature, CO₂ concentration, relative humidity, and sensor resistance were simultaneously monitored. The results showed that the sensor resistance generally decreased with increasing temperature, CO₂ concentration, and relative humidity. Regression analysis revealed a strong relationship between sensor resistance and temperature ($R^2 = 0.8729$), whereas relative humidity showed a moderate relationship ($R^2 = 0.5669$). The resistance response to CO₂ concentration also exhibited a distinct nonlinear trend associated with the progression of food decomposition. These findings indicate that temperature and CO₂ concentration exert a stronger influence on the electrical response of the electroplated SnO₂ sensor than relative humidity. The fabricated sensor therefore demonstrates potential as a low-cost resistive sensing platform for monitoring environmental changes associated with food spoilage.

1. Introduction

Food spoilage is a complex process driven by microbial activity and biochemical reactions that continuously alter the environmental conditions surrounding food products (Snyder et al., 2024; Odeyemi et al., 2020). Among the most important indicators of spoilage are temperature, relative humidity, and carbon dioxide (CO₂) concentration. Temperature affects microbial growth rates and enzymatic reactions, whereas humidity influences water availability required for microbial metabolism (Preetha and Narayanan, 2020; Hoffmann et al., 2021). Meanwhile, CO₂ is one of the major gaseous by-products generated during microbial decomposition and is widely recognized as an indicator of spoilage progression (Snyder et al., 2024; Ramadan et al., 2025). Therefore, simultaneous monitoring of these parameters is essential for evaluating food freshness and enabling real-time spoilage detection (Ramadan et al., 2025).

Metal oxide semiconductor sensors have attracted considerable attention for environmental monitoring because their electrical properties are highly sensitive to changes in surrounding conditions (Nam et al., 2024). Among these materials, SnO₂ is widely recognized for its excellent chemical stability, high sensitivity, and suitability for gas sensing applications (Sayago et al., 2024). The sensing mechanism of SnO₂ is governed by adsorption-desorption reactions between gas molecules and oxygen species

adsorbed on the sensor surface, which modify charge transfer and electrical resistance (Paolucci et al., 2022). Consequently, simultaneous variations in temperature, humidity, and gas concentration can significantly influence the sensing characteristics of SnO₂-based resistive sensors.

Electroplating provides a simple, scalable, and cost-effective technique for fabricating SnO₂ sensing layers with controllable thickness and surface morphology (Hernandez et al., 2023). Our previous study demonstrated that an electroplated SnO₂ sensor fabricated at an applied voltage of 4.5 V with electrolyte temperatures of 30 and 60 °C exhibited excellent responsiveness to CO₂ concentration ($R^2 = 0.9823$), moderate sensitivity to temperature ($R^2 = 0.6694$), and negligible response to relative humidity during food spoilage (Setiawan et al., 2025). These findings confirmed that the electroplating conditions strongly influence the sensing characteristics of SnO₂ layers and suggested that further optimization of the fabrication parameters is required to achieve simultaneous detection of multiple environmental variables.

Despite these advances, the resistive response of electroplated SnO₂ sensors under optimized electroplating conditions has not been systematically investigated for the simultaneous monitoring of temperature, relative humidity, and CO₂ concentration during food spoilage. In particular, the influence of increasing the deposition voltage from 4.5 V to 6.0 V while employing an intermediate electrolyte temperature of 40 °C remains unclear. Addressing this knowledge gap is important for improving the practical applicability of low-cost SnO₂ sensors in real-time food freshness monitoring.

Therefore, this study fabricated an SnO₂ sensor by electroplating at an applied voltage of 6.0 V and an electrolyte temperature of 40 °C, followed by thermal oxidation, and investigated its resistive response to simultaneous variations in temperature, relative humidity, and CO₂ concentration during food spoilage. The results were further compared with those of our previous study to evaluate the influence of the modified electroplating conditions on the sensing performance of the fabricated SnO₂ sensor.

2. Literature Review

Food spoilage is a complex process resulting from microbial growth, enzymatic reactions, and physicochemical changes occurring during food storage. During microbial metabolism, organic compounds are continuously degraded, producing heat, carbon dioxide (CO₂), water vapor, and various volatile compounds. Consequently, temperature, relative humidity, and CO₂ concentration change progressively as spoilage advances, making these environmental parameters reliable indicators of food freshness and quality (Snyder et al., 2024; Odeyemi et al., 2020). Because these variables originate from the same microbial activity, simultaneous monitoring provides a more comprehensive assessment of food spoilage than monitoring a single parameter alone.

Temperature directly affects microbial growth kinetics and metabolic activity. An increase in temperature generally accelerates microbial proliferation and biochemical reactions, leading to faster deterioration of food quality and safety (Hoffmann et al., 2021; da Costa et al., 2022). Relative humidity also plays a significant role because water availability strongly influences microbial metabolism and enzymatic activity. High humidity conditions promote microbial growth and accelerate degradation processes, whereas humidity variations alter the physicochemical properties of food products and influence the release of volatile compounds associated with spoilage (Seilov et al., 2025). Carbon dioxide is another important parameter because it is continuously produced during microbial respiration and decomposition. Consequently, increasing CO₂ concentration is widely recognized as an early indicator

of microbial activity and food deterioration. Several studies have demonstrated that simultaneous monitoring of temperature, relative humidity, and CO₂ significantly improves the reliability of food spoilage detection systems and enables real-time assessment of food freshness (Kiaitsi et al., 2025; Ramadan et al., 2025).

Metal oxide semiconductor sensors have attracted considerable attention for monitoring environmental changes because their electrical properties are highly sensitive to surface reactions. Among these materials, SnO₂ is one of the most extensively studied n-type semiconductors owing to its excellent chemical stability, high sensitivity, and low fabrication cost (Sayago et al., 2024; Kumar et al., 2023). The sensing mechanism of SnO₂ is governed by adsorption–desorption reactions occurring on the sensor surface. Adsorbed oxygen species capture electrons from the conduction band, forming an electron-depletion layer. Variations in temperature, humidity, and gas concentration modify this adsorption equilibrium, resulting in changes in electron transfer and electrical resistance (Meng et al., 2022; Alam et al., 2022). Thus, changes in the environmental conditions generated during food spoilage can be detected through measurable variations in the resistance of an SnO₂ sensing layer.

Humidity and temperature further influence the sensing performance of SnO₂ by modifying surface adsorption processes and charge carrier transport mechanisms. Water molecules adsorbed on the sensor surface can form hydroxyl groups and alter oxygen adsorption, whereas increasing temperature enhances adsorption–desorption kinetics and carrier mobility. Meanwhile, CO₂ molecules interact with adsorbed oxygen species, modifying the surface charge distribution and electrical conductivity of the sensing layer (Suematsu et al., 2018; Suematsu et al., 2018). This interaction between environmental parameters and surface reactions constitutes the theoretical basis for employing resistive SnO₂ sensors in food spoilage monitoring.

In a previous study (Setiawan et al., 2025), an SnO₂ sensor was fabricated using an electroplating process at an applied voltage of 4.5 V and an electrolyte temperature of 30 °C. The fabricated sensor exhibited excellent sensitivity toward CO₂, with the resistance–CO₂ relationship following a quadratic function. However, its response to temperature was relatively weak, and the influence of relative humidity on sensor resistance was not investigated. These findings indicate that the electroplating parameters strongly influence the sensing characteristics of SnO₂ layers and that further optimization is required to achieve simultaneous monitoring of multiple environmental variables.

Based on this research gap, the present study employed modified electroplating conditions by increasing the applied voltage to 6.0 V and the electrolyte temperature to 40 °C. These conditions were selected to investigate whether modifying the electroplating process could improve the resistive response of the fabricated SnO₂ sensor to simultaneous variations in temperature, relative humidity, and CO₂ concentration during food spoilage, thereby enhancing its applicability for real-time food freshness monitoring.

3. Experimental Methods

The experimental procedure followed the workflow illustrated in Figure 1.

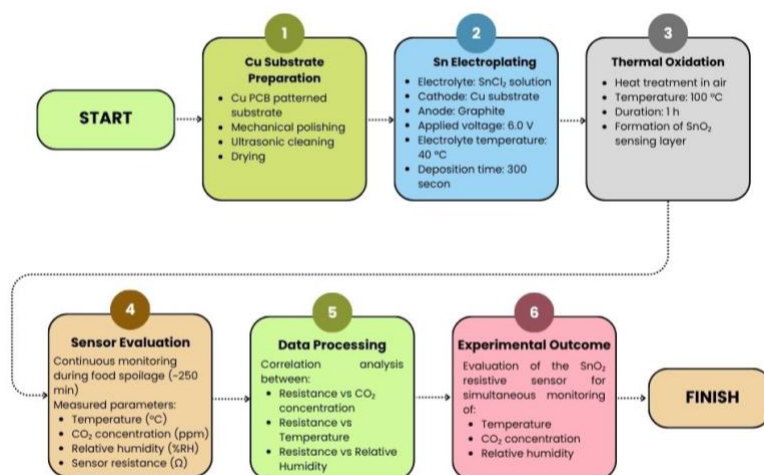


Figure 1. Flowchart of the experimental procedure for fabrication and evaluation of the electroplated SnO_2 resistive sensor during food spoilage.

3.1. Substrate Preparation

Prior to the electroplating process, printed circuit board (PCB) substrates were prepared to ensure proper adhesion and uniform deposition of the sensing layer. Each substrate was cut into rectangular strips measuring 10.0 cm × 1.3 cm and mechanically polished using fine sandpaper to remove surface oxidation and improve surface roughness. The substrates were then cleaned with a detergent solution and rinsed with distilled water to eliminate residual contaminants. To further enhance cleanliness, the substrates were treated using an ultrasonic cleaner to remove microscopic impurities. After ultrasonic cleaning, the substrates were rinsed with ethanol and distilled water to remove organic residues and cleaning agents. Finally, the substrates were dried using a hot air dryer under ambient laboratory conditions to ensure complete moisture removal prior to the electroplating process, thereby providing a clean and uniform surface for thin-film deposition (Majer-Baranyi et al., 2023).

3.2. Electroplating Process

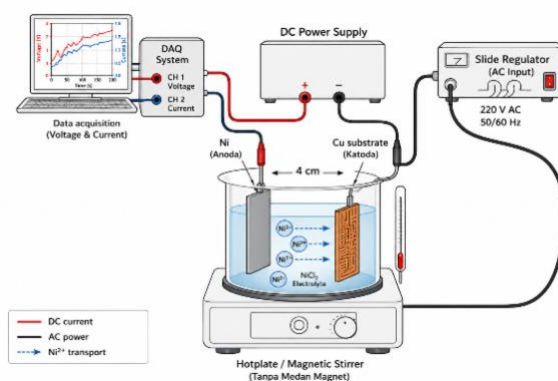


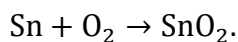
Figure 2. Schematic diagram of the electroplating setup

Figure 2 illustrates the schematic diagram of the electroplating setup used in this study. For the electroplating process, the Cu/Sn films were deposited in a laboratory-scale electroplating reactor using a graphite rod as the anode and the prepared copper substrate as the cathode, with an inter-electrode distance of 4 cm. Both electrodes were immersed in an electrolyte consisting of 14.9 g of SnCl_2 dissolved in 500 mL of distilled water. The electrolyte temperature was maintained at 40 °C using a digital hot plate magnetic stirrer (MS 400) throughout the deposition process to ensure uniform temperature distribution.

Electroplating was performed at a constant voltage of 6.0 V for 5 min. Following deposition, the coated samples were dried for 15 min to ensure complete solvent evaporation, after which their mass and sheet resistance were remeasured. After electroplating, the coated samples were rinsed with distilled water and ultrasonically cleaned in distilled water for 5 min to eliminate residual electrolyte and surface contaminants. The samples were subsequently dried using a hot-air dryer until completely free of moisture. Each dried sample was then wrapped in clean tissue paper, sealed in a zip-lock plastic bag, and stored in a dry box before further characterization and electrical testing.

3.3. Thermal Oxidation

Following the electroplating process, the deposited Cu/Sn samples were thermally oxidized in air at 100 °C for 1 h. This mild thermal treatment promoted controlled oxidation of the electroplated Sn layer, leading to the formation of a thin surface tin-oxide (SnO_x) layer while minimizing excessive oxidation, film cracking, and delamination caused by thermal stress. At this relatively low temperature, oxidation was primarily confined to the near-surface region, where oxygen molecules diffused into the deposited Sn layer and reacted according to



Thermal oxidation of Sn in air promotes the formation of tin oxide through the diffusion and reaction of oxygen with the deposited Sn surface. Previous studies have reported the formation of tin-oxide structures by thermal oxidation of deposited Sn films at temperatures as low as 100 °C for 1 h. However, the oxidation state and stoichiometry of thermally formed tin oxide strongly depend on the oxidation temperature, oxygen availability, film morphology, and processing conditions. Low-temperature oxidation may therefore produce oxygen-deficient or mixed tin-oxide states rather than a fully stoichiometric crystalline SnO_2 phase. Thermal oxidation of Sn in air promotes the formation of tin oxide through the diffusion and reaction of oxygen with the deposited Sn surface. Previous studies have reported the formation of tin-oxide structures by thermal oxidation of deposited Sn films. However, the oxidation state and stoichiometry of thermally formed tin oxide strongly depend on the oxidation temperature, oxygen availability, film morphology, and processing conditions. In the present study, the thermally oxidized sensing layer is referred to as SnO_2 following the material designation adopted in the sensor fabrication framework and previous related studies. Nevertheless, because phase-sensitive characterization such as XRD, Raman spectroscopy, or XPS was not performed, complete stoichiometric conversion to crystalline SnO_2 cannot be conclusively confirmed. The possible presence of oxygen-deficient or mixed tin-oxide states should therefore be considered when interpreting the electrical sensing response.

Although oxidation at 100 °C is limited compared with high-temperature oxidation, the resulting surface oxide provides chemically stable active sites for oxygen adsorption and gas–surface interactions. These adsorption–desorption processes modulate the electron concentration within the sensing layer, producing measurable changes in electrical resistance during exposure to variations in temperature, CO_2 concentration, and relative humidity.

3.4. Sample Weighing and Film Thickness Estimation

Before mass determination, the specimens were rinsed thoroughly with distilled water, subjected to ultrasonic cleaning, and completely dried to reduce possible contributions from electrolyte residues and surface moisture. The mass of each specimen was measured using an Ohaus PR224 analytical balance with a readability of 0.1 mg. Five consecutive measurements were performed, and the variation in the measured mass was used to estimate the random uncertainty associated with the weighing procedure.

The effective thickness of the deposited SnO_x sensing layer, t , was estimated gravimetrically from the mass gain of the substrate after deposition and thermal oxidation using the following relation (Bay & Celik, 2025; Beniwal & Sunny, 2019)

$$\delta_{\text{SnO}_2} = \frac{M_{\text{Cu/SnO}_2} - M_{\text{Cu}}}{\rho A} = \frac{\Delta m}{\rho A} \quad (1)$$

where M_{Cu} is the initial mass of the Cu substrate, $M_{\text{Cu/SnO}_2}$ is the mass of the coated sample after deposition and thermal oxidation, Δm denotes the corresponding mass increment, ρ is the assumed density of SnO₂ (6.95 g cm⁻³), and A is the coated surface area (4.50 cm²).

The uncertainty in the gravimetrically estimated film thickness was evaluated by propagating the uncertainties associated with the measured mass increment and coated area. Accordingly, the standard uncertainty in thickness, s_δ , was calculated as

$$s_\delta = \sqrt{\left(\frac{1}{\rho A} s_{\Delta m}\right)^2 + \left(\frac{\Delta m}{\rho A^2} s_A\right)^2} \quad (2)$$

where $s_{\Delta m}$ and s_A are the standard uncertainties associated with the mass increment and coated area, respectively. The coated area was obtained from the measured deposition width and length. An instrumental reading uncertainty of ± 0.05 mm was assigned to each linear dimension. The corresponding area uncertainty was calculated as

$$s_A = \sqrt{(ls_p)^2 + (ps_l)^2} \quad (3)$$

where p and l represent the width and length of the coated region, respectively, while s_p and s_l are their corresponding measurement uncertainties. The reported thickness uncertainty therefore represents the propagated random uncertainty arising from the gravimetric and dimensional measurements. Possible systematic contributions associated with spatially non-uniform deposition, incomplete surface coverage, residual surface species, and Cu-substrate roughness were not separately quantified. These factors may introduce additional uncertainty into the estimated SnO₂ layer thickness.

3.5. Measurement: The Sheet Resistance

The sheet resistance of the samples was characterized using a JG-FPP four-point probe (FPP). Measurements were performed both before electroplating (Cu substrate) and after electroplating and thermal oxidation (Cu/SnO₂ sample) to evaluate the electrical contribution of the deposited sensing layer. The four-point probe method was employed to minimize contact resistance and provide reliable measurements of the electrical properties of the thin film. The sheet resistance (or sheet resistance) was calculated according to

$$R_s = \frac{\pi V}{\ln 2 I}, \quad (4)$$

where V is the measured voltage (V) and I is the applied current (A). For each sample, the measurement was repeated five times under identical conditions, and the reported sheet resistance is expressed as the mean value $\pm$ standard deviation ($R_s \pm SD$).

The electrical contribution of the deposited sensing layer was evaluated by comparing the sheet resistance of the Cu substrate before deposition ($R_{s,\text{Cu}}$) with that of the Cu/SnO_x sample after electroplating and thermal oxidation ($R_{s,\text{Cu/SnO}_2}$). The difference between these two values reflects the influence of the deposited SnO_x layer on the overall electrical transport characteristics of the fabricated.

3.6. Measurement of Temperature, CO₂ Concentration, Relative Humidity, and Sensor Resistance

Food samples consisting of vegetable salad were placed inside a sealed acrylic chamber and allowed to undergo natural decomposition under ambient laboratory conditions. The sealed chamber was designed to retain the gases generated during spoilage while minimizing the influence of the surrounding

environment. During the decomposition process, the fabricated SnO_x resistive sensor and the environmental sensors were positioned inside the chamber to ensure that all sensors were exposed to the same gaseous atmosphere.

The experimental setup used for monitoring the food spoilage process is illustrated in Figure 3. Environmental parameters and the electrical response of the fabricated sensor were simultaneously monitored throughout the experiment using an integrated data acquisition system (Ghasemi-Varnamkhasti et al., 2018).

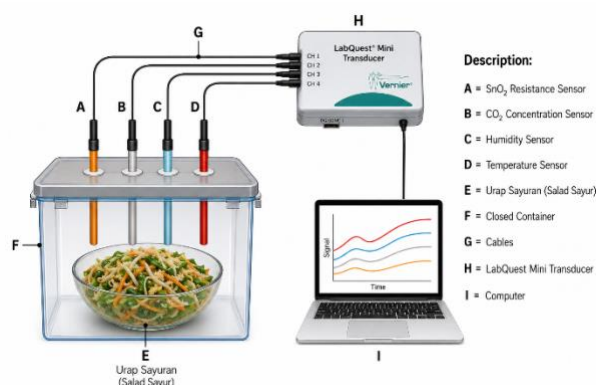


Figure 3. Schematic diagram of the food spoilage monitoring system using the fabricated SnO_2 resistive sensor.

Temperature ($^{\circ}\text{C}$) was measured using a TCA-BTA thermocouple, relative humidity (%RH) using an RH-BTA sensor, and carbon dioxide concentration (ppm) using a CO_2 -BTA sensor. The electrical characteristics of the fabricated sensor were simultaneously measured by recording the voltage using a VP-BTA voltage probe and the current using a DCP-BTA current probe. All sensors were connected to a LabQuest Mini data acquisition interface, and the experimental data were continuously recorded using Logger Pro software, which provided real-time numerical and graphical displays.

Data acquisition was performed continuously throughout the food spoilage process with a sampling rate of 10 measurements min^{-1} (one measurement every 6 s). At each sampling time, temperature, relative humidity, CO_2 concentration, voltage, and current were recorded simultaneously. The electrical resistance of the fabricated sensor was subsequently calculated using Ohm's law,

$$R = \frac{V}{I}, \quad (5)$$

where R is the sensor resistance (Ω), V is the measured voltage (V), and I is the measured current (A). The synchronized acquisition of environmental parameters and electrical resistance enabled direct evaluation of the sensor response to the evolving conditions during food spoilage.

3.7. Data Analysis

In the first stage, the temporal evolution of the environmental parameters and the electrical response of the fabricated SnO_x sensor during the food spoilage process was investigated. Temperature ($^{\circ}\text{C}$), carbon dioxide (CO_2) concentration (ppm), relative humidity (%RH), and sensor resistance (Ω) were continuously monitored for approximately 260 min. Time-dependent plots were then constructed to identify the evolution of each environmental parameter and the corresponding electrical response of the fabricated sensor during food decomposition. In the second stage, the relationships between the sensor resistance and each environmental parameter were quantitatively evaluated. Scatter plots of resistance as

a function of temperature, CO₂ concentration, and relative humidity were constructed, followed by regression analysis to determine the mathematical relationship between the variables. The regression model for each parameter was selected according to the experimental data trend using the least-squares fitting method. The coefficient of determination (R^2) was used to evaluate the goodness-of-fit of each regression model. By comparing the resulting R^2 values, the relative strength of the individual associations between sensor resistance and each environmental parameter was evaluated. Because the environmental variables changed simultaneously, the analysis was not intended to identify an independent dominant causal factor.

4. Result

4.1. Physical Parameters of the Fabricated Sample

The physical parameters of the fabricated sensor are summarized in Table 1. The measured dimensions, mass, estimated film thickness, and sheet resistance confirm the successful deposition of the sensing layer on the Cu substrate. These parameters are important because the film thickness and electrical properties of the deposited layer directly influence charge transport, gas adsorption behavior, and ultimately the sensing performance toward changes in temperature, CO₂ concentration, and relative humidity during food spoilage.

Table 1. Physical parameters of the fabricated Cu/SnO₂ sensor before and after electroplating and thermal oxidation.

Parameter	Specification / Value
Substrate	: Cu plate, 15.5 cm × 2 mm × 0.3 mm
Cu mass	: 2.4555 g
Coating material	: SnO ₂
Cu/SnO ₂ mass	: 2.4577 g
SnO ₂ coating thickness	: 36.05 μm
Cu sheet resistance	: 11.128 ± 0.18 Ω/sq
Cu/SnO ₂ sheet resistance	: 11.41 ± 0.27 Ω/sq

4.2. Sensor Electrical Response to Environmental Variations during Food Spoilage

Data acquisition was conducted for 260 min with a sampling rate of 10 measurements per minute. The system recorded humidity (%RH), CO₂ concentration (ppm), temperature (°C), and electrical parameters including voltage (V) and current (A). Figure 8 presents the time-dependent variations of environmental parameters and sensor resistivity during the food spoilage process.

Figure 4(a) shows the variation in temperature as a function of time. The temperature gradually increased throughout the food spoilage process, from approximately 32.5 °C at the beginning of the experiment to approximately 33.2 °C after 260 min. The relationship between temperature and time was well described by a linear regression model with a coefficient of determination of $R^2 = 0.9963$, indicating that more than 99% of the temperature variation was explained by the regression model. This result demonstrates that the temperature increased steadily during food decomposition, reflecting the progressive biological activity occurring inside the sealed chamber. Figure 4(b) shows the variation in CO₂ concentration as a function of time. The CO₂ concentration exhibited an exponential increase throughout the food spoilage process. During the initial stage, the CO₂ concentration remained nearly constant at approximately 1100–1300 ppm, followed by a rapid increase after approximately 150 min, reaching more than 5500 ppm at the end of the experiment. The exponential regression model provided an excellent fit to the experimental data ($R^2 = 0.99$), indicating that the increase in CO₂ concentration was strongly associated with the progression of food decomposition. This behavior is attributed to

intensified microbial respiration and organic matter degradation, which continuously generated carbon dioxide within the closed chamber.

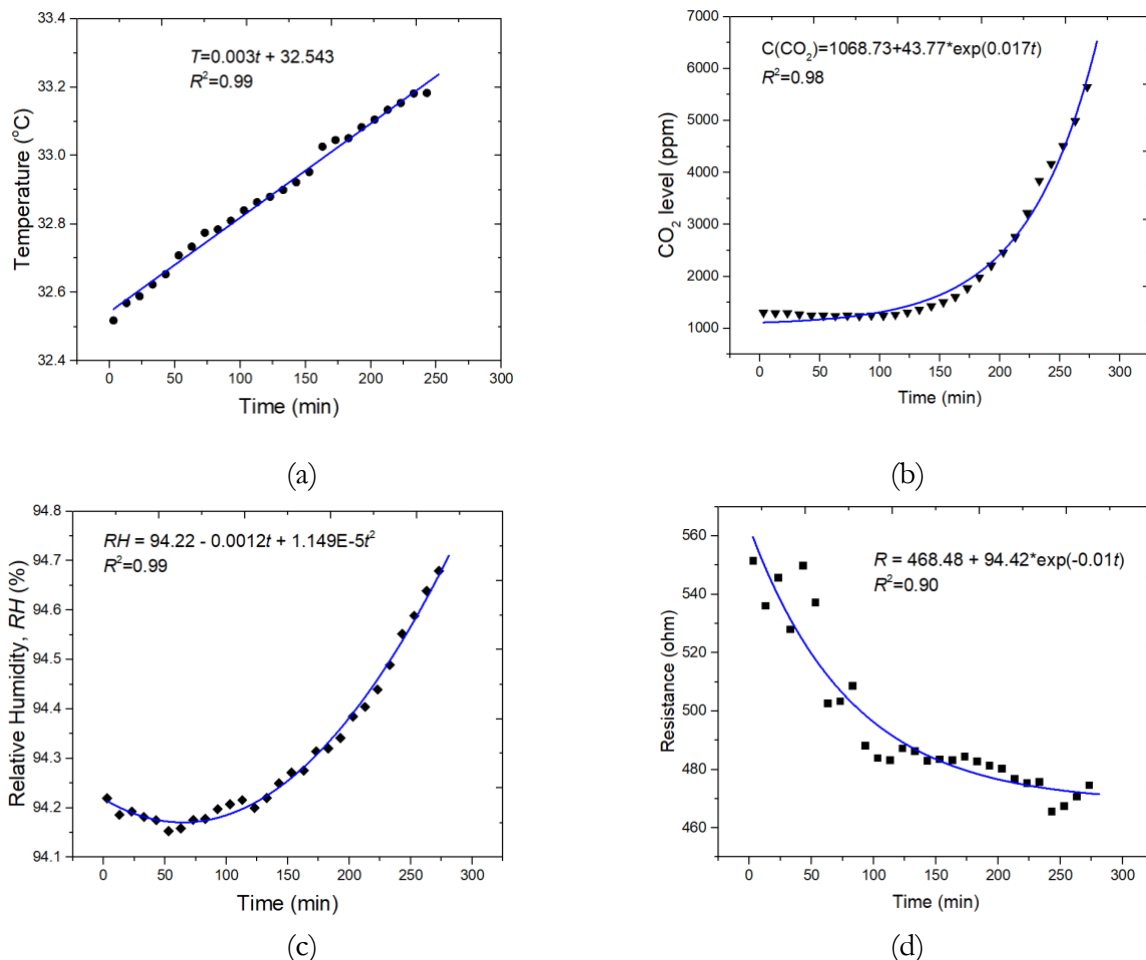


Figure 4. Time-dependent variations of temperature, CO₂ concentration, humidity, and SnO₂ sensor resistivity.

Furthermore, Figure 4(c) illustrates the variation in relative humidity as a function of time. illustrates the variation in relative humidity during food spoilage. The relative humidity decreased slightly during the initial stage and subsequently increased gradually, reaching approximately 94.7% RH at the end of the experiment. The experimental data were well fitted by a quadratic regression model with $R^2 = 0.9940$, demonstrating excellent agreement between the model and the measured data. The gradual increase in humidity is likely associated with moisture released from the food matrix and microbial metabolic activity during the decomposition process. Figure 4(d) shows the variation in sensor resistance as a function of time, showing the electrical resistance of the fabricated SnO₂ sensor decreased exponentially with increasing monitoring time, as shown in Figure 4(d). The resistance decreased from approximately 550 Ω at the beginning of the experiment to about 470 Ω after 260 min. The most significant decrease occurred during the early stage of the experiment, followed by a gradual stabilization. The exponential regression model yielded a coefficient of determination of $R^2 = 0.8961$, indicating that approximately 90% of the experimental variation could be explained by the fitted model. The observed decrease in sensor resistance suggests an increase in the electrical conductivity of the SnO₂ sensing layer in response to the simultaneous increase in CO₂ concentration, temperature, and relative humidity during food spoilage. The simultaneous increase in temperature, CO₂ concentration, and relative humidity observed during food spoilage is consistent with previous reports describing microbial metabolism and

biochemical degradation as coupled processes that generate heat, CO₂, and water vapor (Snyder et al., 2024; Odeyemi et al., 2020). The pronounced exponential increase in CO₂ after approximately 150 min particularly supports previous findings that CO₂ accumulation can serve as an indicator of intensified microbial activity and spoilage progression (Ramadan et al., 2025). In contrast to studies that monitor these parameters using separate sensing elements, the present results show that the electrical resistance of the SnO₂ layer evolves concurrently with the combined environmental changes occurring in the spoilage chamber. This agreement supports the use of the fabricated resistive layer as a cross-sensitive platform for tracking the overall evolution of the food-spoilage environment.

Overall, the results demonstrate that food spoilage is characterized by a gradual increase in temperature, CO₂ concentration, and relative humidity, accompanied by a corresponding decrease in the electrical resistance of the fabricated SnO₂ sensor. These findings indicate that the electroplated SnO₂ sensor exhibits a clear to environmental changes associated with food decomposition, demonstrating its potential as a low-cost sensing platform for real-time food spoilage monitoring.

4.3. Relationship between Sensor Resistance and Environmental Parameters

4.3.1 Relationship Between Sensor Resistance and Temperature

Figure 9 illustrates the relationship between the electrical resistance of the fabricated SnO₂ sensor and temperature.

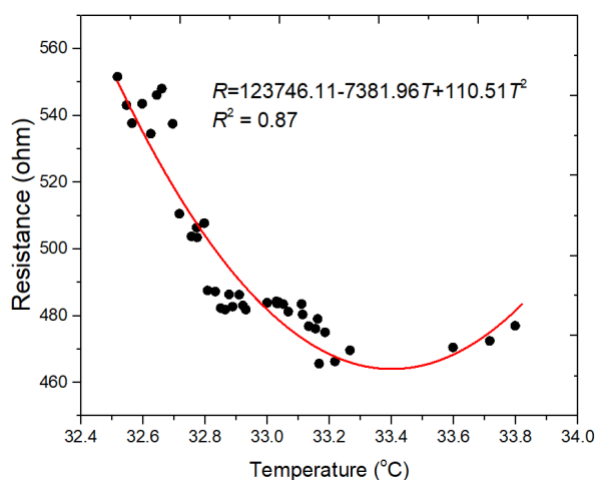


Figure 5. Relationship between SnO₂ sensor resistance and temperature.

The sensor resistance decreased as the temperature increased from approximately 32.5 °C to 33.4 °C, followed by a slight increase at higher temperatures. The experimental data were best described by a second-order polynomial regression model with a coefficient of determination of $R^2 = 0.8729$, indicating that approximately 87.3% of the variation in sensor resistance was explained by temperature. The initial decrease in resistance can be attributed to enhanced charge carrier mobility induced by increasing thermal energy, whereas the slight increase observed at elevated temperatures may be associated with changes in the surface adsorption–desorption equilibrium of gas molecules on the SnO₂ sensing layer.

The observed temperature-dependent resistance behavior is consistent with previous studies reporting that temperature affects charge-carrier transport and surface adsorption–desorption kinetics in tin-oxide-based sensing materials (Meng et al., 2022; Alam et al., 2022). Increasing thermal energy can enhance carrier mobility and modify the equilibrium of adsorbed oxygen species, thereby changing the electrical resistance of the sensing layer. More importantly, the present temperature–resistance relationship ($R^2 = 0.8729$) is stronger than that reported in our previous electroplated SnO₂ sensor

fabricated at 4.5 V and 30 °C ($R^2 = 0.6694$) (Setiawan et al., 2025). This contrast suggests that the modified electroplating conditions may have altered the electrical transport and surface characteristics of the deposited layer. However, because the sensing-layer microstructure was not independently characterized, the specific structural origin of this improvement cannot yet be conclusively established.

4.3.2 Relationship Between Sensor Resistance and CO₂ Concentration

Figure 6 presents the variation in sensor resistance as a function of CO₂ concentration.

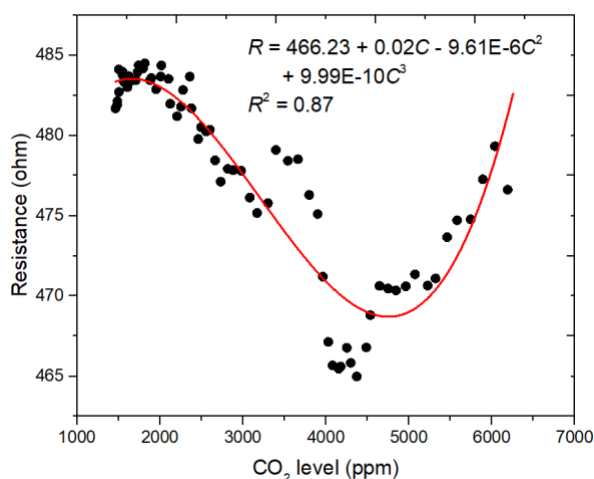


Figure 6. Relationship between SnO₂ sensor resistance and CO₂ concentration.

The resistance exhibited a nonlinear response, gradually decreasing with increasing CO₂ concentration until reaching a minimum at approximately 4500–5000 ppm, after which it increased slightly at higher concentrations. A third-order polynomial regression model provided a satisfactory fit to the experimental data, yielding a coefficient of determination of $R^2 = 0.8755$. This nonlinear behavior suggests that the interaction between CO₂ molecules and the SnO₂ surface is concentration dependent. At moderate CO₂ concentrations, gas adsorption promotes charge transfer and reduces the sensor resistance, whereas saturation of active adsorption sites at higher concentrations may alter the surface reaction kinetics, resulting in a slight increase in resistance.

The nonlinear resistance response to CO₂ is generally consistent with the surface-reaction mechanism reported for tin-oxide-based resistive sensors, in which gas molecules interact with adsorbed oxygen species and modify surface charge transfer and electrical conductivity (Paolucci et al., 2022; Suematsu et al., 2018). However, the present third-order relationship ($R^2 = 0.8755$) differs from our previous study, where the resistance–CO₂ response followed a quadratic relationship with a higher coefficient of determination ($R^2 = 0.9823$) (Setiawan et al., 2025). The lower correlation obtained here does not necessarily indicate poorer sensing behavior, because CO₂ varied simultaneously with temperature and relative humidity during natural food spoilage. Instead, the difference suggests a stronger contribution of cross-sensitivity under the present experimental conditions. Thus, the modified fabrication conditions appear to broaden the environmental response of the sensing layer, although at the expense of a less isolated resistance–CO₂ relationship.

4.3.3 Relationship Between Sensor Resistance and Relative Humidity

Figure 7 shows the relationship between sensor resistance and relative humidity. The resistance generally decreased as the relative humidity increased to approximately 94.6% RH, followed by a slight increase at higher humidity levels. The experimental data were fitted using a fourth-order polynomial model with a

coefficient of determination of $R^2 = 0.5669$, indicating a moderate goodness-of-fit. Compared with temperature and CO_2 concentration, relative humidity exhibited a weaker influence on the electrical resistance of the fabricated SnO_2 sensor. Nevertheless, the observed decrease in resistance with increasing humidity suggests that adsorbed water molecules contributed to the electrical conduction process by modifying the surface chemistry and charge transport mechanisms of the SnO_2 sensing layer.

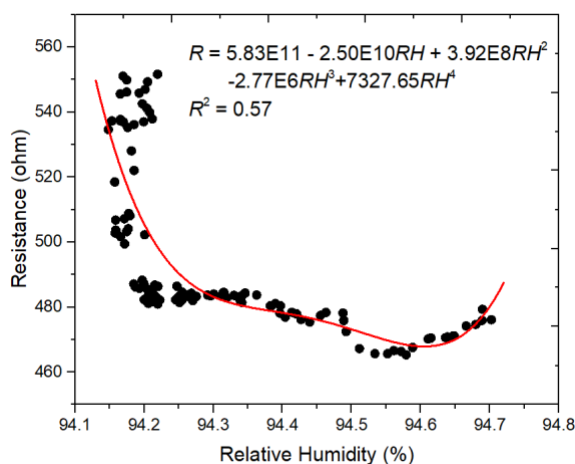


Figure 7. Relationship between SnO_2 sensor resistance and humidity.

More broadly, this study contributes to the understanding of surface interactions, molecular adsorption, and charge-transport mechanisms in SnO_2 -based oxide semiconductors under dynamically changing environmental conditions. The distinct resistance responses of a single sensing layer to temperature, relative humidity, and CO_2 concentration provide a basis for further development of multiparameter sensing from the perspective of materials physics and electrical transport. In physics education, the integration of materials physics, semiconductor transport, sensing, and real-time data acquisition provides a contextual framework for research- and project-based learning addressing real-world challenges such as food spoilage and food loss.

5. Discussion

5.1. Interpretation of Findings

The observed decrease in resistance with increasing humidity suggests that adsorbed water molecules contributed to the electrical conduction process by modifying the surface chemistry and charge transport mechanisms of the SnO_2 sensing layer. Unlike our previous study, in which the electroplated SnO_2 sensor fabricated at 4.5 V showed negligible sensitivity to relative humidity during food spoilage, the present sensor, fabricated at 6.0 V, exhibited a measurable resistance response to humidity, although the correlation remained weaker than those obtained for temperature and CO_2 concentration. This improvement suggests that the modified electroplating conditions influenced the electrical response of the SnO_2 sensing layer under the combined environmental conditions associated with food spoilage.

Overall, comparison of the three relationships reveals that the fabricated SnO_2 sensor does not respond equally to all environmental parameters. The strongest relationship was observed between resistance and temperature, whereas CO_2 produced a distinct nonlinear resistance response, and relative humidity exhibited a weaker and non-monotonic relationship. These differences demonstrate that the electrical response of the sensor is governed by multiple physical mechanisms, including thermally

activated charge transport and surface adsorption–desorption processes. The novelty of the present study lies in evaluating these responses simultaneously under an actual food-spoilage environment rather than under individually controlled temperature, CO₂, or humidity conditions. Accordingly, the fabricated sensor is more appropriately considered a multi-parameter resistive sensing platform with cross-sensitive responses than a highly selective single-gas sensor.

This behavior is consistent with previous reports that adsorbed water molecules can form surface hydroxyl species and modify oxygen adsorption and charge transport in tin oxide-based materials (Suematsu et al., 2018). At high relative humidity, increased water adsorption and competing surface interactions may contribute to a non-monotonic electrical response, which may partly explain the resistance minimum observed near 94.6% RH.

5.2. Implications

From the perspective of physics, these findings contribute to a better understanding of coupled charge-transport and surface adsorption phenomena in metal-oxide semiconductors subjected to dynamically changing environmental conditions. The different resistance responses observed for temperature, CO₂ concentration, and relative humidity indicate that electrical conduction in the electroplated SnO₂ layer is governed by multiple physical mechanisms operating simultaneously, including thermally activated carrier transport, adsorption–desorption equilibrium, and humidity-assisted surface conduction. These results provide additional experimental evidence for understanding charge transport in non-equilibrium sensing environments, where several environmental variables evolve concurrently rather than independently.

Furthermore, this study demonstrates that modifying electroplating parameters can significantly influence the electrical response characteristics of SnO₂ sensing layers without requiring complex nanostructure engineering or expensive fabrication techniques. Consequently, the present work provides a useful experimental basis for future studies investigating the relationships among electroplating conditions, microstructure, electronic transport, and sensing performance of metal-oxide semiconductor materials.

5.3. Limitations of the Study

Several limitations should be considered when interpreting the findings of this study. First, the fabricated SnO₂ sensor was evaluated using only a single type of food sample (vegetable salad). Different food matrices may produce distinct volatile compounds, microbial growth patterns, and CO₂ generation rates, which could influence the sensor response. Therefore, the applicability of the proposed sensor should be further validated using a wider range of food products.

Second, although temperature, relative humidity, and CO₂ concentration were monitored simultaneously, these variables were not independently controlled. Consequently, the individual contribution of each environmental parameter to the electrical response of the SnO₂ sensor could not be quantitatively separated because the sensor was exposed to their combined effects during the natural spoilage process.

Third, this study evaluated only the resistance response of the electroplated SnO₂ sensor. Other important sensing characteristics, including sensitivity, selectivity toward different gases, response and recovery times, repeatability, long-term stability, and detection limit, were not investigated. Moreover, the influence of the modified electroplating parameters (6.0 V and 40 °C) on the microstructure and physicochemical properties of the sensing layer was not characterized using complementary techniques such as SEM, XRD, or XPS. Future studies should address these aspects to provide a more

comprehensive understanding of the sensing mechanism and to further improve the practical applicability of electroplated SnO₂ sensors for food spoilage monitoring.

6. Conclusion

A SnO₂ resistive sensor was successfully fabricated by electroplating at an applied voltage of 6.0 V and an electrolyte temperature of 40 °C, followed by thermal oxidation. During food spoilage, the fabricated sensor exhibited a measurable electrical response characterized by a general decrease in resistance with increasing temperature, CO₂ concentration, and relative humidity. Regression analysis showed that sensor resistance was more strongly associated with variations in temperature and CO₂ concentration than with relative humidity. Compared with our previous electroplating conditions of 4.5 V and 30 °C, the modified fabrication conditions produced a measurable resistance response to relative humidity in addition to the responses associated with temperature and CO₂ variations. These findings demonstrate the potential of the electroplated SnO₂ resistive sensor as a low-cost sensing platform for monitoring environmental changes associated with food spoilage. However, because temperature, CO₂ concentration, and relative humidity varied simultaneously during the natural spoilage process, their individual contributions to the sensor response could not be independently separated. Future studies should therefore focus on sensor selectivity, repeatability, long-term stability, and the relationship between electroplating parameters, sensing-layer microstructure, and sensing performance.

Author Contributions

Ridlo Hajatulloh: conceptualization, methodology, experimentation, data collection, data analysis, and original draft writing. **Moh. Toifur:** supervision, conceptual framework, and manuscript review and editing. **Aliaman Aliaman:** experimental design and technical guidance during electroplating and sensor characterization. **Indra Budi Setiawan:** data analysis and interpretation. **Okimustava Okimustava:** data processing, visualization, and manuscript editing. **Eko Susanto:** validation, scientific review, and final revision of the manuscript. All authors have read and approved the final version of the manuscript.

Ethical Statement

This study was conducted in a laboratory setting and did not involve human participants or animal subjects. Therefore, ethical approval was not required. All procedures were carried out in accordance with standard scientific research ethics and safety guidelines.

Declaration of AI use

The authors used generative AI tools for language editing and improving the clarity of the manuscript. The authors take full responsibility for the final content of the manuscript.

Conflict of Interest

The authors declare that there are no conflicts of interest, either financial or non-financial, that could influence the results or interpretation of this study.

Supplementary Materials and Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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