Journal of Technomaterial Physics
Journal homepage: https://talenta.usu.ac.id/JoTP

Real-Time Ethanol Monitoring System for Palm Sap Fermentation Using a MiCS-5524 Gas Sensor and Arduino Uno

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ARTICLE INFO

Article history:
Received 10 December 2025
Revised 26 December 2025
Accepted 31 December 2025
Available online 31 December 2025

E-ISSN: 2656-0755
P-ISSN: 2656-0747

How to cite:
D. R. D. K. Siregar, M. S. Surbakti, Fadhli, Zakaria, Susilawati, H. Akbar, "Real-Time Ethanol Monitoring System for Palm Sap Fermentation Using a MiCS-5524 Gas Sensor and Arduino Uno," Journal of Technomaterial Physics, vol. 08, no. 01, pp. 1-7, Feb. 2026, doi: 10.32734/jotp.v8i1.23866.

ABSTRACT

This study aims to develop a real-time alcohol monitoring instrument for palm sap fermentation using the MiCS-5524 gas sensor integrated with an Arduino Uno. The system consists of the MiCS-5524 sensor, an Arduino Uno microcontroller, and a 16×2 I2C LCD for real-time display. Sensor calibration was performed using ethanol solutions at 10%, 20%, 30%, 40%, 50% and 60% to establish a linear regression model relating sensor resistance to ethanol concentration. Fermentation monitoring was carried out for 72 hours, with measurements taken every 24 hours. Sensor outputs were converted from ADC values into voltage, resistance, and ethanol concentration using the calibration equation. The calibration yielded a strong linear correlation (R^2 = 0.982). Fermentation tests showed a consistent increase in ethanol concentration, reaching 53.9% after 72 hours. Comparison with a digital alcohol meter produced relative errors ranging from 2.8% to 6.4%, demonstrating good accuracy, low drift, and stable sensor response. Overall, the developed instrument effectively measures ethanol concentration in palm sap fermentation in real time. Its simple configuration, low cost, and reliable performance make it suitable for small-scale palm sap processing, quality control, and laboratory applications. Further improvements, such as environmental compensation and IoT-based monitoring, are recommended to enhance system performance.

Keywords: MiCS-5524, Arduino Uno, Palm Sap, Ethanol, Gas Sensor, Fermentation.

ABSTRAK

Penelitian ini bertujuan untuk mengembangkan sebuah instrumen pemantauan kadar alkohol secara real-time pada fermentasi air nira menggunakan sensor gas MiCS-5524 yang terintegrasi dengan Arduino Uno. Sistem ini terdiri atas sensor MiCS-5524, mikrokontroler Arduino Uno, dan LCD I2C 16×2 untuk menampilkan data secara real-time. Kalibrasi sensor dilakukan menggunakan larutan etanol dengan konsentrasi 10%, 20%, 30%, 40%, 50% dan 60% untuk menghasilkan model regresi linier yang menghubungkan resistansi sensor dengan konsentrasi etanol. Pemantauan fermentasi dilakukan selama 72 jam dengan pengukuran setiap 24 jam. Keluaran sensor dikonversi dari nilai ADC menjadi tegangan, resistansi, dan konsentrasi etanol menggunakan persamaan kalibrasi. Hasil kalibrasi menunjukkan korelasi linier yang kuat dengan koefisien determinasi (R^2 = 0,982). Pengujian fermentasi menunjukkan peningkatan konsentrasi etanol yang konsisten, mencapai 53,9% setelah 72 jam. Perbandingan dengan alkoholmeter digital menghasilkan error relatif antara 2,8% hingga 6,4%, yang menunjukkan akurasi yang baik, drift rendah, dan respons sensor yang stabil. Secara keseluruhan, instrumen yang dikembangkan mampu mengukur konsentrasi etanol pada

http://doi.org/10.32734/jotp.v8i1.23866

fermentasi air nira secara real-time dengan efektif. Konfigurasi sistem yang sederhana, biaya rendah, dan performa yang reliabel menjadikannya cocok untuk pengolahan nira skala kecil, pengendalian kualitas, dan aplikasi penelitian laboratorium.

Kata kunci: MiCS-5524, Arduino Uno, Nira Sawit, Etanol, Sensor Gas, Fermentasi.

1. Introduction

Palm sap is a valuable agricultural commodity widely utilized in Indonesia, particularly as a raw material for producing palm sugar, palm vinegar, fermented beverages, and other traditional food products. Its relatively high sugar content (10–15%) makes it highly susceptible to rapid fermentation immediately after tapping. This fermentation process is driven primarily by the metabolic activity of Saccharomyces cerevisiae, which converts glucose into ethanol and carbon dioxide through a series of biochemical [1-2]. Such biochemical transformations significantly alter the physical and chemical properties of palm sap, including a marked increase in alcohol content, which in turn affects product quality and shelf life [3].

Monitoring ethanol concentration in palm sap is essential because fermentation progresses rapidly under tropical climatic conditions. Previous studies have shown that alcohol levels may rise substantially within only 6–24 hours of open storage [4]. For small-scale industries, farmers, and microenterprises that rely on fresh sap, delayed detection of rising ethanol levels may lead to deterioration of raw materials and economic losses. Consequently, a low-cost, responsive, and field-deployable alcohol monitoring system capable of real-time measurement is urgently needed [5]. Although conventional analytical methods such as distillation, spectrophotometry, and gas chromatography provide high accuracy, they require complex instrumentation, trained personnel, substantial operational costs, and long analysis times, limiting their practicality for field applications [6-7].

Metal oxide semiconductor (MOS) gas sensors, including the MQ-3, MQ-6, and TGS-2620, have been widely employed for detecting alcohol vapor in beverages and fermented products [8-10]. Despite offering high sensitivity and affordability, MOS sensors are susceptible to environmental variations in temperature and humidity, sensor drift, and gas cross-interference, which collectively compromise long-term measurement accuracy [11]. Recent findings indicate that the MiCS-5524 sensor exhibits superior performance over earlier MOS-based sensors, providing high sensitivity to ethanol and other volatile organic compounds (VOCs), low power consumption, and compact structural design attributes favorable for portable monitoring devices [12-13]. Although the MiCS-5524 has been applied in cigarette smoke detection systems, IoT-based air quality monitoring, and electronic-nose applications [14-16]Its application for multi-day fermentation monitoring of palm sap remains underexplored.

Existing literature further indicates that research on palm sap fermentation has largely focused on chemical characterization, microbiological analysis, or detection systems employing MQ-series sensors, with limited consideration of the MiCS-5524 sensor, which offers potentially greater stability and sensitivity for ethanol detection [2], [17]. Moreover, few studies have integrated MiCS-5524 with an Arduino Uno microcontroller and a real-time display for low-cost monitoring suitable for small-scale industrial contexts [13], [18]. This research gap demonstrates the need for a portable, economical, and continuous monitoring instrument capable of tracking the dynamic progression of palm sap fermentation.

Accordingly, this study aims to design and develop an alcohol detection instrument for palm sap based on the MiCS-5524 sensor integrated with an Arduino Uno. The proposed system is expected to provide real-time alcohol measurements with high sensitivity to variations in ethanol concentration and serve as a practical, affordable, and user-friendly solution for small-scale industry and laboratory applications.

2. Methods

2.1. Research Design

This study employed an experimental approach aimed at designing and evaluating an alcohol detection instrument for palm sap using the MiCS-5524 sensor integrated with an Arduino Uno microcontroller. The research procedure consisted of several stages, including hardware design, software development, sensor calibration using standard ethanol solutions, and performance testing of the instrument on palm sap samples undergoing natural fermentation. Each stage was conducted systematically to ensure the reliability and accuracy of the developed system.

2.2. Hardware Design

The hardware design of the instrument consists of three main components: the MiCS-5524 gas sensor, the Arduino Uno microcontroller, and a 16×2 I2C LCD module for real-time data display. The MiCS-5524 sensor functions as the primary ethanol detector, operating based on changes in semiconductor resistance when exposed to ethanol vapor. The sensor was mounted inside a sealed test chamber to ensure stable exposure to vapor emitted during palm sap fermentation. The Arduino Uno serves as the central processing unit, responsible for acquiring analog voltage signals from the sensor, performing analog-to-digital conversion, and processing the values into measurable outputs. A load resistor (R_L = 10 kΩ) was connected in series with the sensor to form a voltage divider circuit, allowing the calculation of sensor resistance changes. The 16×2 I2C LCD module was integrated to display the measured voltage, sensor resistance, and ethanol concentration in real time.

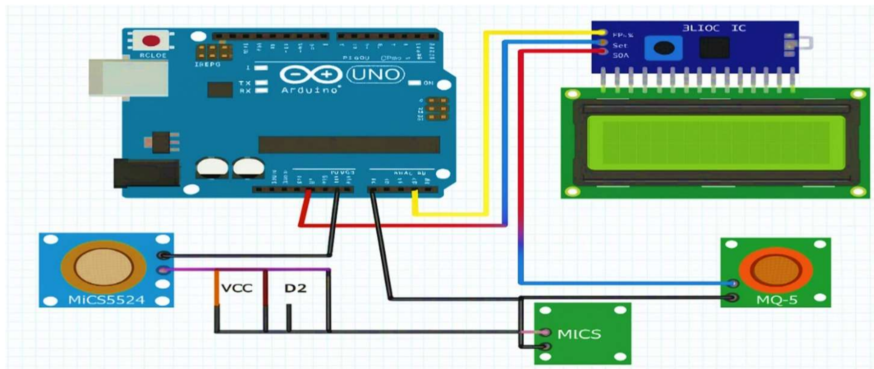

Figure 1. Hardware design scheme for alcohol level detector.

All components were assembled on a prototyping board as shown in the scheme shown in Figure 1, with power supplied through a 5 V DC source. The hardware design ensured portability, low power consumption, and operational stability during long-term fermentation measurements.

2.3. Software Development

Software for the alcohol monitoring system was developed using the Arduino IDE. The program was designed to perform continuous data acquisition, ADC-to-voltage conversion, resistance calculation based on the voltage-divider model, and ethanol concentration estimation using the calibration equation. The software also manages data visualization on the LCD and serial communication for additional data logging. The initial data in the form of ADC values from the Arduino Uno is converted into sensor output voltage using equation (1).

$$V_{out} = \frac{ADC}{1023} \times 5\,V \tag{1}$$

The output voltage is used to calculate the sensor resistance based on the voltage divider configuration, using equation (2).

$$R_s = R_L\left(\frac{5}{V_{out}} - 1\right) \tag{2}$$

Figure 2 illustrates the software flowchart. The program starts with system initialization, including the Arduino Uno, MiCS-5524 gas sensor, LCD, and serial communication. The system then continuously reads the sensor output, processes the signal to determine ethanol concentration using the calibration model, and displays the results on the LCD while simultaneously transmitting the data to the serial monitor. This cycle is repeated continuously to support real-time monitoring throughout the fermentation process. The software flowchart does not include a termination stage because the system is designed for continuous real-time monitoring throughout the fermentation period.

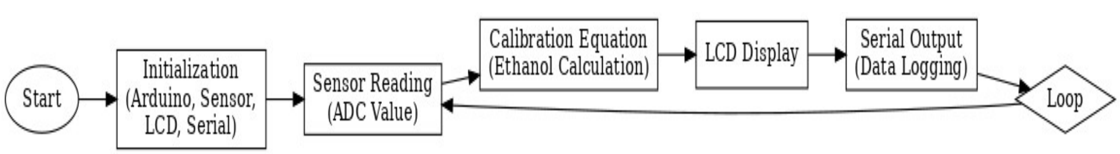

Figure 2. Flowchart of the software design.

2.4. Sensor Calibration

Calibration was conducted to determine the mathematical relationship between sensor resistance and ethanol concentration. Standard ethanol solutions with concentrations of 10%, 20%, 30%, 40%, 50%, and 60% were prepared by diluting 70% ethanol. For each concentration, three repeated measurements were taken to obtain an average sensor output. The sensor was placed inside a sealed calibration chamber containing the standard ethanol solution. After vapor equilibrium was reached, the Arduino recorded ADC outputs, which were processed into voltage and resistance values. A linear regression model was then developed by Equation (3).

$$y = aR_s + b \tag{3}$$

where y is ethanol concentration (%), and a and b are regression constants derived from calibration data.

2.5. Fermentation Testing

Fermentation testing was performed using freshly tapped palm sap samples placed in sealed fermentation containers. The instrument was positioned above the sap surface to detect ethanol vapor produced during natural fermentation. Measurements were recorded every 24 hours over a 72-hour period to observe changes in ethanol concentration. For each measurement interval, the system displayed voltage, resistance, and ethanol concentration values in real time. These data were also logged through the serial monitor for further analysis. Three palm sap samples collected on different days were tested to evaluate sensor consistency and repeatability. The fermentation process was carried out at ambient room temperature (25–28 °C) under typical tropical conditions.

2.6. Data Processing and Analysis

Raw ADC data were converted into voltage, resistance, and ethanol concentration using the equations described in the calibration stage. The processed data were plotted to observe the temporal trend of ethanol formation during fermentation. Instrument accuracy was evaluated by comparing ethanol concentration readings with those obtained from a digital alcohol meter. Absolute and relative errors were computed as in Equation (4) and (5).

$$Absolute\ error = (X_{instrument} - X_{reference}) \tag{4}$$

$$Relative\ error = \frac{Absolute\ error}{X_{instrument}} \times 100\% \tag{5}$$

This analysis provided insights into sensor accuracy, stability, and sensitivity during long-term monitoring.

3. Results and Discussions

3.1. Sensor Calibration Results

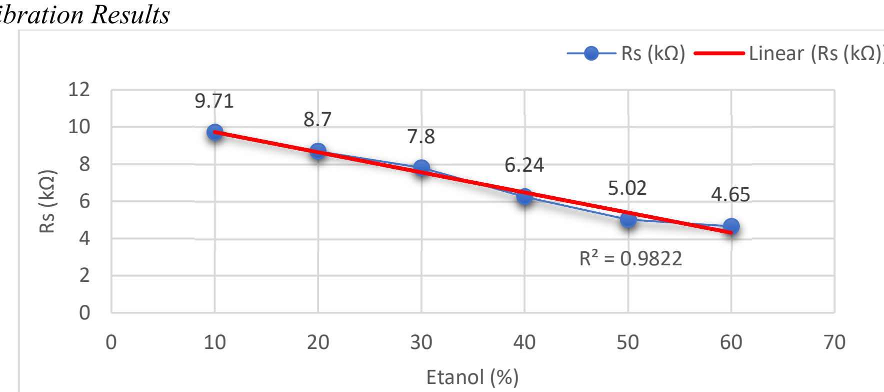

Figure 3. Calibration curve showing the relationship between sensor resistance (R_s) and ethanol concentration.

The resulting calibration curve is presented in Figure 3, illustrating the relationship between sensor resistance (R_s) and ethanol concentration. The regression analysis yielded a coefficient of determination of R^2 = 0.982, indicating that 98.2% of the variation in ethanol concentration can be explained by changes in sensor resistance. This high R^2 value confirms a strong linear correlation and demonstrates the reliability of the sensor for ethanol concentration measurement. This strong correlation demonstrates that the MiCS-5524 sensor possesses a reliable and proportional response to ethanol concentration variations. This result further confirms the accuracy and responsiveness of the calibration model in estimating ethanol concentration under high vapor conditions.

These findings align with recent studies showing that the MiCS-5524, modern metal-oxide semiconductor (MOS) and composite gas sensors can achieve high sensitivity and stable ethanol detection detection [19-22]. Compared with earlier MOS sensors such as MQ-3 and MQ-6, the MiCS-5524 shows improved stability and reduced drift, making it more suitable for continuous fermentation monitoring.

3.2. Real-Time Fermentation Monitoring

The instrument was used to monitor ethanol formation during a 72-hour palm sap fermentation period, with measurements recorded at 24-hour intervals. Figure 4 presents the ethanol concentration measured by the MiCS-5524-based instrument across three different sap samples collected on Saturday, Sunday, and Monday. Overall, the results show a consistent and substantial increase in ethanol concentration throughout the fermentation process, although notable differences were observed across sampling days.

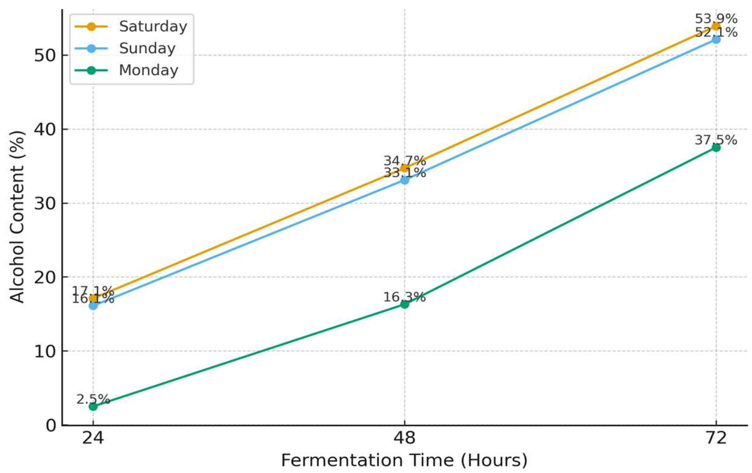

Figure 4. Graph of Alcohol Content Changes During Fermentation

During the first 24 hours, ethanol levels in the Saturday and Sunday samples were relatively high, reaching 17.1% and 16.1%, respectively. In contrast, the Monday sample exhibited a much lower concentration of 2.5%. This discrepancy is likely due to differences in sap freshness, as the Saturday and Sunday samples may have undergone partial spontaneous fermentation prior to measurement. In contrast, the Monday sample was fresher and had not yet initiated significant microbial activity.

On the second day of fermentation, all samples exhibited a sharp increase in ethanol concentration. The Saturday sample increased to 34.7%, the Sunday sample to 33.1%, and the Monday sample rose from 2.5% to 16.3%. This indicates that the fermentation process had entered the exponential phase, characterized by intensive activity of Saccharomyces cerevisiae in converting sugars into ethanol. During the final 72-hour measurement, ethanol levels continued to increase but at a slower rate compared to the previous phase. This reduced rate of increase is attributed to the declining availability of fermentable sugars and the rising ethanol concentration, which begins to inhibit microbial activity. The Saturday sample reached the highest ethanol content at 53.9%, followed by the Sunday sample at 52.1%, while the Monday sample reached 37.5%. These results indicate that although all samples exhibited strong fermentation activity, initial sap freshness significantly influenced the rate and extent of ethanol production.

This overall trend aligns with the natural biochemical progression of palm sap fermentation as reported in earlier studies [2], [23], where high sugar content (10–15%) and tropical temperature conditions promote vigorous microbial activity and rapid ethanol accumulation. Throughout the fermentation period, the instrument demonstrated stable response behavior, rapid reaction to vapor changes, and minimal signal drift, confirming its suitability for real-time monitoring.

3.3. Accuracy Evaluation Against Digital Alcohol Meter

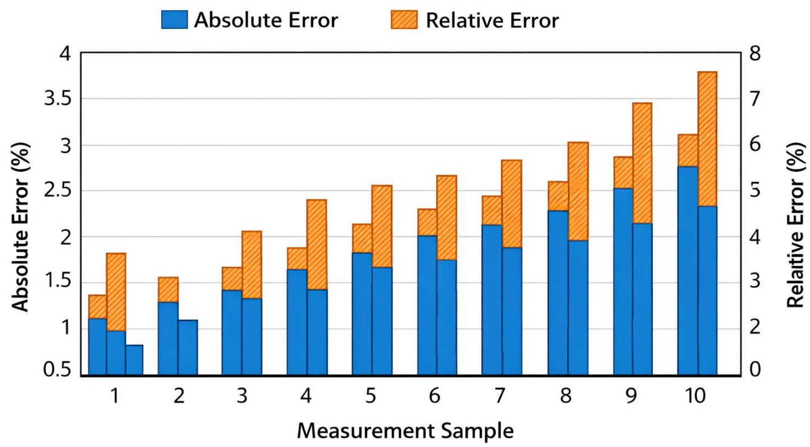

Figure 5. Absolute and Relative Error Comparison Between the Proposed System and A Commercial Digital Alcohol Meter.

Performance evaluation was carried out by comparing the measurements obtained from the developed instrument with those from a commercial digital alcohol meter. The comparison results are shown in Figure 5, which presents the absolute and relative error values for each measurement point. The results showed that the absolute error between the two devices ranged from 0.8% to 3.4%, while the relative error ranged from 2.8% to 6.4%. These values fall within the acceptable tolerance range for MOS-based sensors, consistent with previous studies employing MQ and TGS sensors, which reported relative errors of 5–12% [9], [11]. In addition to measurement accuracy, the MiCS-5524 demonstrated stable readings throughout the monitoring period without extreme fluctuations, indicating minimal sensor drift. The sensor also exhibited a rapid response to changes in ethanol concentration, particularly during the exponential phase of palm sap fermentation.

These characteristics are essential for real-time monitoring applications, especially in small-scale palm sap processing, where rapid and reliable information on fermentation status is required. Overall, the instrument demonstrated strong performance in terms of accuracy, stability, and response time, enabling it to follow fermentation dynamics effectively. Based on these performance indicators, the instrument is considered appropriate for real-time monitoring of palm sap fermentation. It is suitable for use by farmers, small-scale palm sap processors, and laboratory researchers involved in food fermentation studies.

4. Conclusion

This study successfully developed a real-time ethanol monitoring system based on a MiCS-5524 gas sensor integrated with an Arduino Uno. The calibration results demonstrated a strong linear relationship between sensor output and ethanol concentration, confirming the reliability of the system. Accuracy evaluation against a commercial digital alcohol meter showed that the proposed system achieved acceptable error levels, indicating its feasibility for practical fermentation monitoring applications. The developed system offers a low-cost, real-time, and portable solution for monitoring palm sap fermentation and has potential for further development in the food and beverage fermentation industries.

Acknowledgments

The authors express gratitude to the staff and colleagues of the Electronica and Instrumentation Laboratory at Universitas Syiah for their contributions to the calibration and fermentation testing processes, as well as for the facilities and technical support provided throughout this research.

References

[1] I. Desak, P. Galuh, W. Putri, D. Andrianto, and A. H. Kuspranoto, "Rancang Bangun Detektor Alkohol Pada Makanan Dan Minuman Berbasis Data Logger Design of Alcohol Detectors in Food and Beverages Based on Data Logger," *Med. Trada J. Tek. Elektromedik Polbitrada*, vol. 3, no. 1, pp. 14–20, 2022.

[2] N. Hanifah, R. N. Setiadi, Y. Yanuar, V. A. Rosandi, and L. Umar, "Deteksi Kadar Etanol Pada Makanan Tradisional Lemang Tapai Menggunakan Mikrobial Biosensor," *J. Online Phys.*, vol. 8, no. 3, pp. 109–114, 2023, doi: 10.22437/jop.v8i3.27517.

[3] M. K. Negara, R. Wirawan, and N. Qomariyah, "Rancang Bangun Sistem Monitoring Gas Alkohol Pada Fermentasi Ketan Berbasis Sensor Tgs 2620," *ORBITA J. Kajian, Inov. dan Apl. Pendidik. Fis.*, vol. 6, no. 2, p. 235, 2020, doi: 10.31764/orbita.v6i2.3166.

[4] W. Widyastuti, "Validasi Alat Penelitian Hidung Elektronik dengan Senyawa Alkohol Standar," *Indones. J. Lab.*, vol. 3, no. 1, p. 20, 2020, doi: 10.22146/ijl.v3i1.60822.

[5] M. Fahrizal Rahman, Farihin Lazim, and Akhlis Munazilin, "Sistem Deteksi Dan Monitoring Alkohol Pada Nafas Pengemudi Travel Berbasis Internet of Things," *STORAGE J. Ilm. Tek. dan Ilmu Komput.*, vol. 4, no. 3, pp. 158–165, 2025, doi: 10.55123/storage.v4i3.5608.

[6] I. Irkham, F. N. Zalfadilah, M. I. H. L. Zein, W. Khaerani, S. N. Zakiyyah, and Y. W. Hartati, "Electrochemical Sensor and Biosensor Detection of Ethanol in Beverage Samples," *J. Adv. Technol. Multidiscip.*, vol. 4, no. 1, pp. 34–43, 2025, doi: 10.20473/jatm.v4i1.71985.

[7] P. Sinambela, I. Hendrawan, and ..., "Rancang Bangun Detektor Kadar Etanol Pada Minuman Menggunakan Sensor Mq3 Berbasis Nodemcu Esp8266," *... Konf. Nas. Soc. ...*, no. 2019, pp. 351–356, 2023.

[8] A. I. Ikhsan, "Rancang Bangun Alat Deteksi Alkohol Dengan Menggunakan Sensor MQ3 Berbasis Arduino NANO V3," *J. Inov. Fis. Indones.*, vol. 11, no. 3, pp. 81–87, 2022.

[9] A. Firdaus, U. Rahmiatun, I. Artikel, and G. Artikel, "Pembuatan Alat Deteksi Gas Berbasis Arduino Menggunakan Sensor Gas MQ-6 dan MQ-3," vol. 03, no. 01, pp. 21–25, 2023, doi: 10.18592/alkawnu.v3i1.8560.

[10] S. Pratama and M. A. Auliq, "Rancang Bangun Alat Deteksi Alkohol Pada Urin Menggunakan Sensor Array," *J. Tek. Elektro dan Komputasi*, vol. 6, no. 1, pp. 69–76, 2024, doi: 10.32528/elkom.v6i1.7217.

[11] M. Ismail and S. A. Dwi Prasetyowati, "Gas Detection and Classification Using Neural Network Based Gas Sensors," *J. Rekayasa Elektr.*, vol. 19, no. 2, pp. 59–63, 2023, doi: 10.17529/jre.v19i2.30974.

[12] M. W. Aminullah, Dina Fitria, Imam Akbar, and Rama Denata, "Development of an IoT-Integrated Cigarette Smoke Detection System Using MiCS-5524 Sensor," *Int. J. Res. Vocat. Stud.*, vol. 4, no. 1, pp. 40–45, 2024, doi: 10.53893/ijrvocas.v4i1.243.

[13] Y. Wu, M. Lei, and X. Xia, "Research Progress of MEMS Gas Sensors: A Comprehensive Review of Sensing Materials," *Sensors*, vol. 24, no. 24, 2024, doi: 10.3390/s24248125.

[14] B. H. Daulay, S. A. Pasaribu, M. F. Hirzi, C. Author, and B. Hasian, "Design of The Smoke Level Measuring Device and Cigarette Smoke Control Device in The Smoking Area on Campus," 2025.

[15] Y. Zhou, Z. Zhang, Y. He, P. Gao, H. Zhang, and X. Ma, "Integration of electronic nose, electronic tongue, and colorimeter in combination with chemometrics for monitoring the fermentation process of Tremella fuciformis," *Talanta*, vol. 274, p. 126006, 2024, doi: https://doi.org/10.1016/j.talanta.2024.126006.

[16] Y. Feng *et al.*, "Real-time and on-line monitoring of ethanol fermentation process by viable cell sensor and electronic nose," *Bioresour. Bioprocess.*, vol. 8, no. 1, 2021, doi: 10.1186/s40643-021-00391-5.

[17] Y. Li *et al.*, "Can Electronic Nose Replace Human Nose?─An Investigation of E-Nose Sensor Responses to Volatile Compounds in Alcoholic Beverages," *ACS Omega*, vol. 8, no. 18, pp. 16356–16363, 2023, doi: 10.1021/acsomega.3c01140.

[18] S. Kontogiannis, M. Tsoumani, G. Kokkonis, C. Pikridas, and Y. Kotseridis, "Proposed SmartBarrel System for Monitoring and Assessment of Wine Fermentation Processes Using IoT Nose and Tongue Devices," *Sensors*, vol. 25, no. 13, pp. 1–34, 2025, doi: 10.3390/s25133877.

[19] C. Zhang, Z. Zhang, Y. Tian, L. Yu, and H. Wang, "An Ultrasensitive Ethanol Gas Sensor Based on a Dual-Nanoparticle In2O3/SnO2 Composite," *Sensors*, vol. 24, no. 23, 2024, doi: 10.3390/s24237823.

[20] W. Park, Y. Kang, X. Jin, D. Lee, S. J. Hwang, and J. Kim, "Ultra-sensitive ethanol detection using a chemiresistive SnO2 thin-film gas sensor functionalized with RuO2 nanosheets," *Microsystems Nanoeng.*, vol. 11, no. 1, 2025, doi: 10.1038/s41378-025-01055-6.

[21] M. Khan *et al.*, "Ethanol-Gas-Sensing Performances of Built-in ZrO2/Co3O4 Hybrid Nanostructures," *Sensors*, vol. 23, no. 23, 2023, doi: 10.3390/s23239578.

[22] H. Chen, H. Chen, J. Chen, and M. Song, "Gas Sensors Based on Semiconductor Metal Oxides Fabricated by Electrospinning: A Review," *Sensors*, vol. 24, no. 10, 2024, doi: 10.3390/s24102962.

[23] S. Das and J. P. Tamang, "Fermentation Dynamics of Naturally Fermented Palm Beverages of West Bengal and Jharkhand in India," *Fermentation*, vol. 9, no. 3, 2023, doi: 10.3390/fermentation9030301.