JOURNAL OF AUTOMOTIVE AND
MECHANICAL APPLIED TECHNOLOGY

Vol. 3 No 1, 2026, pp. 43-53 https://journal.uny.ac.id/publications/jamat https://doi.org/10.21831/jamat.v3i1.3035

Arduino and IoT-Based LPG Gas Leak Detection Systems: A Focused Review of Sensors, Architectures, and Reliability Issues

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ARTICLE INFO

Article history:

Received	11.03.2026
Revised	17.04.2026
Accepted	09.05.2026

Keywords:
LPG gas leak; Arduino; Internet of Things; MQ sensor; Safety monitoring

ABSTRACT

Liquefied petroleum gas (LPG) leakage remains a major safety concern in households, restaurants, and micro, small, and medium enterprises because leaked combustible gas can accumulate rapidly and trigger fire or explosion. This paper presents a focused review of Arduino- and Internet of Things (IoT)-based LPG gas leak detection systems, emphasizing sensing technologies, embedded architectures, alert mechanisms, performance indicators, and reliability limitations. In response to reviewer concerns, the literature base was expanded from a small set of local prototype papers to more than fifty international peer-reviewed studies from Scopus-indexed journals and proceedings, covering metal oxide semiconductor sensors, MEMS gas sensors, wireless sensor networks, IoT security, low-power communication, signal processing, and TinyML-based gas detection. The synthesis shows that MQ-series sensors remain dominant in low-cost prototypes because of their availability and simple analog interface; however, their practical reliability is constrained by cross-sensitivity, humidity and temperature dependence, heater power consumption, aging, baseline drift, and insufficient calibration. IoT integration improves remote awareness through Wi-Fi, GSM, LoRa, Zigbee, or cloud dashboards. However, it also introduces latency, network outage, service availability, data integrity, and cybersecurity issues. Recent studies indicate that multi-sensor fusion, calibrated testing, edge intelligence, and reliability-oriented design provide a more credible pathway than threshold-based prototypes alone. Future LPG safety systems should therefore combine robust sensing, standardized performance reporting, local fail-safe alarms, secure IoT communication, energy-aware operation, ergonomic installation, and long-term field validation before large-scale household or industrial deployment.

1. Introduction

Liquefied petroleum gas (LPG) is widely used as a compact fuel in domestic kitchens, restaurants, and small production environments. Although convenient, LPG is hazardous when it leaks from cylinders, valves, regulators, hoses, or stove connections. The risk is not only the presence of gas, but the delayed recognition of gas accumulation before ignition. For this reason, embedded early-warning systems have become a popular research direction for low-cost safety monitoring.

The broader Internet of Things (IoT) literature shows that sensor nodes, communication protocols, cloud dashboards, and mobile applications can transform stand-alone instruments into distributed monitoring systems [1-8]. In the context of gas safety, this enables local alarms, remote warnings, historical logging, and maintenance alerts. However, safety-critical IoT devices must be evaluated more rigorously than ordinary demonstration prototypes because false negatives, false positives, communication failures, or sensor drift can undermine user confidence.

Low-cost LPG leak detection studies typically use metal oxide semiconductor (MOS) sensors such as MQ-2, MQ-5, or MQ-6. The international gas-sensor literature has long emphasized that MOS sensors are sensitive and inexpensive, but their outputs are affected by heater temperature, humidity, oxygen concentration, interfering gases, aging, and sensor-to-sensor variability [9-18]. Therefore, a review of Arduino- and IoT-based LPG detectors should not only list previous prototypes but also connect prototype findings to the broader gas-sensor, wireless monitoring, and IoT reliability literature.

Previous manuscript versions relied heavily on descriptive summaries and a limited number of references. The present revision strengthens the paper by adding more than fifty international peer-reviewed references, reorganizing the review method, condensing the comparative table, and adding redrawn figures adapted from published literature. The review addresses four questions: (1) which embedded and IoT architectures are dominant in LPG leak detection systems; (2) how MQ-series and alternative gas sensors are used and limited; (3) which performance indicators should be reported for meaningful comparison; and (4) what future work is required for reliable, secure, and deployable LPG safety systems.

2. Methodology

This paper is positioned as a focused review with structured coding rather than a full systematic review or meta-analysis. The term comprehensive review was removed because the objective is to synthesize technology trends, limitations, and future directions in Arduino- and IoT-based LPG detection systems, not to claim exhaustive coverage of every gas-sensing publication. The workflow was redrawn with reference to structured review reporting logic such as PRISMA 2020 [19], while the synthesis remains narrative because the reviewed studies report heterogeneous metrics (**Fig. 1**).

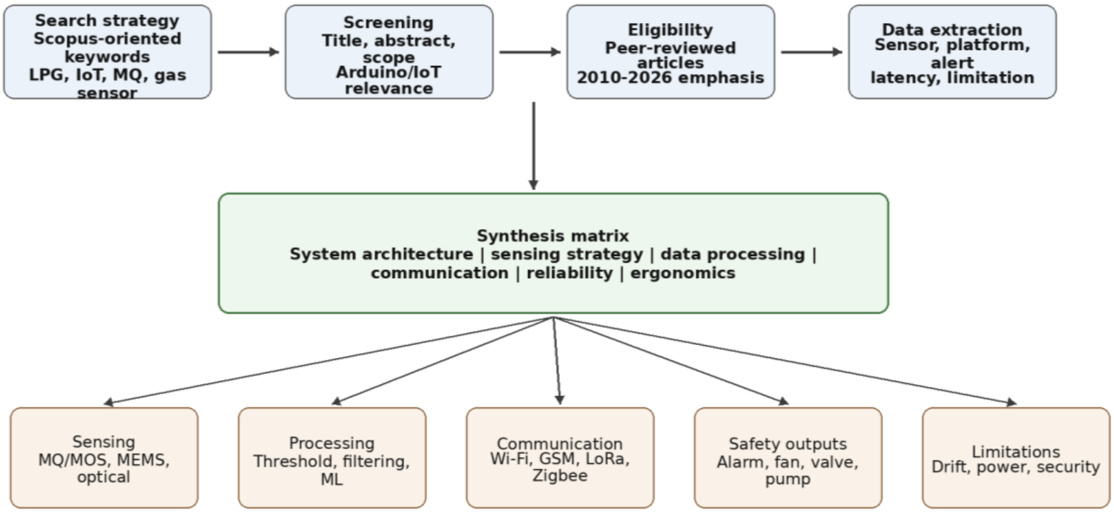

Figure 1. Structured review workflow and synthesis dimensions [19]

The expanded literature search prioritized Scopus-indexed international journals and conference proceedings on IoT, gas sensors, wireless sensor networks, safety monitoring, metal oxide semiconductor sensors, signal processing, sensor drift, and cybersecurity. Search terms included combinations of: LPG leak detection, gas leakage detection, combustible gas detector, MQ-2, MQ-6, Arduino, ESP8266, ESP32, NodeMCU, Raspberry Pi, Internet of Things, IoT gas sensor, wireless gas detection, MEMS gas sensor, gas sensor drift, cross-sensitivity, LoRaWAN, GSM notification, TinyML gas detection, and IoT security.

Documents were included when they addressed at least one of the following aspects: LPG or combustible-gas detection; gas-sensor material behavior; sensor calibration and stability; embedded or IoT-based monitoring; wireless communication for safety systems; data processing or machine learning for gas classification; or cybersecurity and reliability of IoT nodes. Documents were excluded when they were unrelated to combustible gas safety, lacked technical relevance to sensing or communication, or only repeated generic Arduino implementation without extractable technical insight.

Table 1. Expanded international literature coverage and synthesis role

Theme	Representative international references	Contribution to the present review
IoT architecture and general framework	[1-8]	Defines sensor-node architecture, cloud connectivity, interoperability, and application-layer monitoring.
MOS and gas-sensor fundamentals	[9-17], [32-40], [49-54]	Explains sensitivity, selectivity, calibration, drift, heater dependence, humidity effects, and material-level limitations.
Signal processing, drift, and AI	[18-20], [43], [44], [47]	Supports discussion of Kalman filtering, pattern recognition, TinyML, and sensor-array intelligence.
Wireless communication and LPWAN	[21-25]	Supports comparison of Wi-Fi/GSM-based prototypes with LoRa, NB-IoT, Zigbee, and WSN approaches.
Cybersecurity and IoT reliability	[26-31], [42], [48]	Supports the added discussion on authentication, access control, data integrity, and service availability.
Local LPG/Arduino prototype studies	[55-65]	Provides direct LPG leak-detection examples, compared with the international literature.

Each publication was coded using seven categories: application domain, sensing technology, controller platform, signal-processing method, communication channel, alert or mitigation mechanism, and reported limitation. Because the reviewed studies use non-uniform experimental conditions, quantitative meta-analysis was not performed. Instead, the review compares trends, identifies reporting gaps, and proposes standardized performance indicators for future LPG safety devices.

3. Result and Discussion

3.1. Literature expansion and analytical positioning

The expanded reference base changes the manuscript from a descriptive summary of several prototypes into a broader technology review. International references indicate that LPG detection should be treated as a combination of sensing science, embedded system design, communication reliability, and human-centered safety deployment. This wider framing is important because a prototype that activates a buzzer in a laboratory does not automatically become a dependable safety system in a kitchen, restaurant, or industrial setting.

The literature also indicates that the label "IoT-based" should not be applied merely because a device can send a notification. A credible IoT-based gas safety system requires clear device identification, reliable communication, data handling, alert prioritization, maintenance strategy, and resilience against network or cyber failures. Therefore, the discussion below separates the gas-sensing problem from the communication and deployment problem.

3.2. Sensing strategy and MQ-series limitations

MQ-2, MQ-5, and MQ-6 sensors dominate low-cost Arduino prototypes because they are inexpensive, widely available, and easy to interface with via analog or digital modules. MQ-2 is broadly responsive to flammable gases and smoke, whereas MQ-6 is commonly selected for LPG and propane. This makes MQ sensors attractive for educational prototypes and household warning devices. Nevertheless, the international MOS-sensor literature clarifies that high response does not equal high selectivity or calibrated accuracy [9-17].

The most important limitations are cross-sensitivity to multiple reducing gases, heater-driven power consumption, baseline drift, aging, dependency on ambient humidity and temperature, and the need for calibration under known gas concentration. Some prototype papers report threshold values or alarm activation without describing calibration gas, exposure chamber, ventilation condition, warm-up time, sensor placement, or repeated trials. Such reporting prevents meaningful comparison of sensor accuracy, sensitivity, detection range, and false-alarm rate (**Fig. 2**).

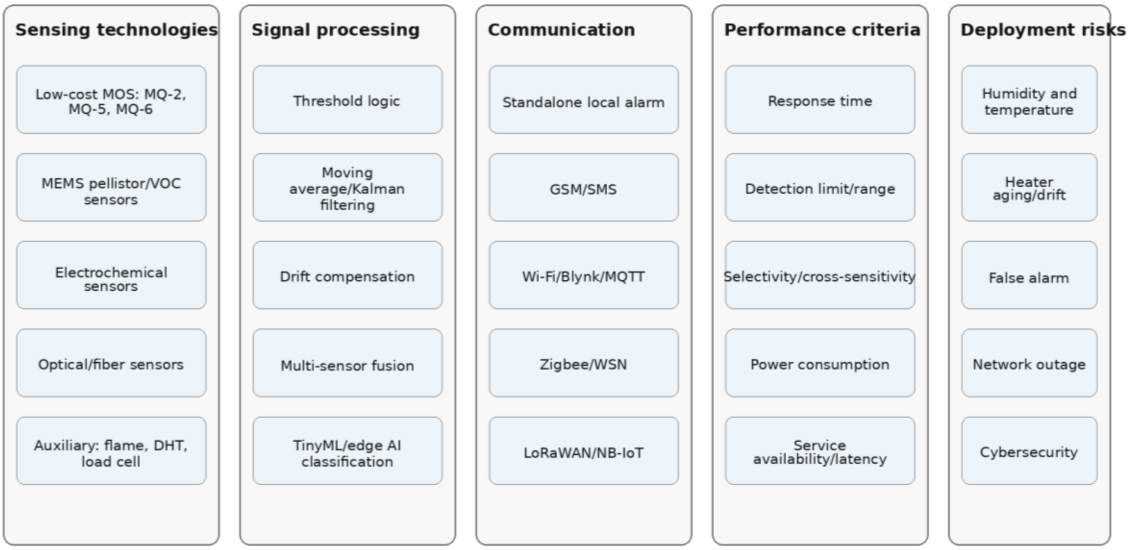

Figure 2. Taxonomy for LPG leak-detection technology selection [8-17], [21-25], [39], [46]

Alternative technologies such as MEMS gas sensors, optical/fiber sensors, conducting polymer sensors, and sensor arrays provide possible improvements in size, power, selectivity, or signal richness [17], [43-54]. However, these alternatives also introduce trade-offs in cost, calibration complexity, packaging, and availability. For low-cost LPG detection, the most realistic improvement is not necessarily replacing MQ sensors immediately, but using MQ sensors with better calibration, environmental compensation, multi-sensor fusion, and transparent performance reporting.

3.3. Embedded and IoT system architectures

A typical low-cost LPG leak detector follows an input-processing-output architecture. The sensor node measures gas concentration or sensor voltage, the controller compares the signal with a threshold or algorithmic output, and the system activates local and remote warnings. Arduino Uno remains common for simple prototypes, while ESP8266, ESP32, NodeMCU, and Raspberry Pi support Wi-Fi, web dashboards, or more advanced processing. Local warnings include buzzer, LED, and LCD. Active mitigation includes exhaust fan, water pump, and in more advanced systems, a solenoid shut-off valve. The architecture of an IoT-based LPG leak detection system as shown in **Fig. 3**.

Communication design strongly affects practical performance. Local alarms have the shortest path because the sensor and actuator are directly connected. GSM/SMS systems support users without internet dashboards, but delay depends on cellular coverage, credit, gateway status, and module stability. Wi-Fi/cloud applications such as Blynk may provide fast notification under good connectivity, but they depend on router availability, internet service, cloud uptime, and mobile application permissions. LPWAN and WSN approaches such as LoRa, Zigbee, and NB-IoT are more relevant for larger buildings, industrial monitoring, or distributed sensor deployment [21-25], [42], [43].

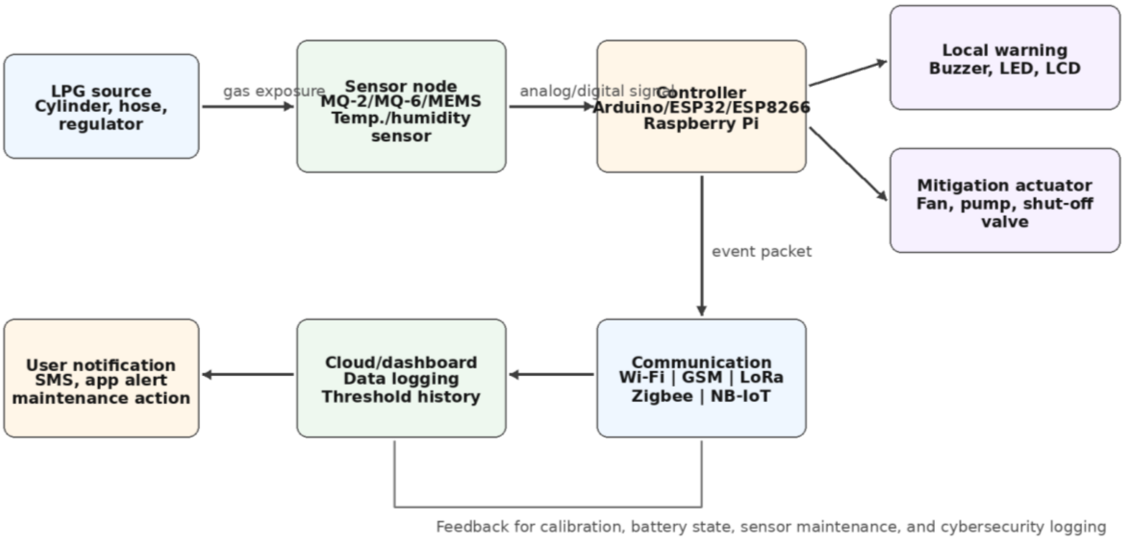

Figure 3. Architecture of an IoT-based LPG leak detection system [8], [42]-[44]

3.4. Comparative technical analysis

The reviewed studies cannot be benchmarked directly because they use different gases, thresholds, distances, enclosures, ventilation conditions, communication channels, and performance indicators. A system reporting a sub-second application notification is not directly comparable to an SMS-based system reporting a 4-6 s delay, because the measured delay includes different communication paths. Similarly, a threshold of 300 ppm cannot be generalized unless sensor calibration, reference gas, and environmental conditions are reported.

For this reason, the revised comparison condenses systems into technical categories rather than repeating long descriptive rows. This format better highlights what each category can and cannot prove. Table 2 summarizes the comparative implications for future prototype reporting.

Table 2. Condensed comparative technical analysis of LPG gas leak detection systems

System category	Typical sensor/control configuration	Strength	Main limitation	Recommended reporting metric
Stand-alone Arduino alarm	MQ-2/MQ-6 + Arduino + buzzer/LED/LCD	Fast local warning, low cost, easy maintenance	No remote monitoring; threshold often uncalibrated	Warm-up time, response/recovery time, threshold basis, false alarm rate
Arduino + GSM/SMS	MQ sensor + Arduino + SIM800L/SIM900A	Works without Wi-Fi; useful for remote user notification	SMS latency and delivery depend on network, credit,	End-to-end alert delay, delivery success rate, signal strength, power draw

System category	Typical sensor/control configuration	Strength	Main limitation	Recommended reporting metric
			and module stability	
ESP8266/ESP32 + cloud app	MQ sensor + Wi-Fi microcontroller + Blynk/MQTT/web dashboard	Fast dashboard update; enables logging and remote visualization	Depends on router, internet, cloud service, app notification permissions	Local delay vs cloud delay, uptime, packet loss, reconnection time
WSN/LPWAN system	Sensor array + Zigbee/LoRa/NB-IoT node	Suitable for distributed monitoring and larger areas	More complex deployment, gateway cost, duty-cycle and payload limitations	Range, packet delivery ratio, battery life, gateway reliability
AI/TinyML or sensor-array system	Multi-sensor data + edge ML or BP neural network	Improves classification and may reduce false alarms	Needs validated datasets, drift handling, and explainability	Accuracy, precision/recall, drift robustness, dataset transparency
Hybrid safety actuator system	Gas + flame + temperature sensor with fan/pump/valve	Links detection with mitigation action	Actuator failure may create false sense of safety	Actuator response time, fail-safe behavior, power backup, maintenance interval

3.5. Data processing, AI, and sensor drift

Basic threshold logic is simple and appropriate for low-cost alarms. However, it is vulnerable to sensor noise, drift, and environmental fluctuations. Filtering techniques such as moving average or Kalman filtering can smooth sensor readings and reduce short-term fluctuations. Nevertheless, filtering does not, by itself, address selectivity or calibration. A filtered wrong baseline remains wrong if the sensor has drifted or if an interferent gas causes a similar response.

The international machine olfaction literature emphasizes that gas sensor arrays often require feature extraction, pattern recognition, drift compensation, and robust validation over time [18-20]. Recent TinyML and WSN-based combustible gas studies show a shift from simple threshold devices toward edge intelligence and multi-sensor classification [43], [44]. For LPG safety devices, this means machine learning should be introduced only with transparent datasets, defined gas concentrations, environmental variation, repeated trials, and field evaluation.

3.6. IoT reliability and cybersecurity

IoT connectivity improves remote awareness, but it also creates new failure modes. A gas detector must still provide a local alarm when Wi-Fi, cellular signal, cloud service, or smartphone notification is unavailable. Therefore, remote notification should be treated as an additional layer rather than the only safety mechanism. Reliability-oriented studies of IoT gas detection emphasize service availability, long-term node robustness, and realistic operating conditions [42].

Cybersecurity is also relevant because compromised IoT gas detectors could leak occupancy or household information, suppress alerts, send false alarms, or alter threshold settings. The IoT security literature highlights device identity, authentication, secure configuration, software updates, access control, encryption, and device-state monitoring as core requirements [26-31]. Future LPG detection prototypes should therefore report not only detection results but also the network architecture, access control, firmware update strategy, and behavior during communication failures.

3.7. Ergonomic and practical deployment

Gas leak detectors operate in spaces where users may be non-technical. Practical design therefore, requires clear installation instructions, an audible alarm at an appropriate volume, visible indicators, an easy reset, a safe power supply, enclosure ventilation, splash and heat protection, and access for sensor replacement. Placement is also critical: the detector must be positioned based on LPG's physical behavior and the likely leak source, while avoiding locations that could trigger nuisance alarms or expose the detector to water, oil, or excessive heat.

Ergonomic design should not be limited to enclosure size. A deployable LPG safety device should consider user comprehension of warning states, alarm fatigue, maintenance reminders, and MSME workflows. In restaurants or small production kitchens, the alarm must be loud enough to be heard. However, the interface must also tell users what action to take: turn off the regulator, open ventilation, avoid ignition sources, evacuate, or inspect the installation.

4. Review Limitations

This review still has limitations. First, it is a focused review and not a formal systematic review with exhaustive Scopus record counting. Second, the reviewed LPG prototype studies use heterogeneous test conditions, so quantitative meta-analysis is inappropriate. Third, many low-cost prototype papers do not report calibration gas, measurement uncertainty, humidity, temperature, distance, ventilation, repeated trials, power consumption, or long-term stability. Fourth, the term Scopus-indexed should be verified against the latest Scopus Source List before final editorial submission because journal indexing status can change over time. The revised manuscript addresses the reviewers' concerns by expanding the international literature base, adding redrawn figures from the published literature, separating the review methodology from the hardware design, and including an analytical discussion of limitations, reliability, cybersecurity, and future research directions.

5. Future Research Directions

Future LPG detection studies should move from demonstration toward validated safety engineering. The priority is standardized testing using known LPG or propane concentration, defined leakage rate, controlled distance, ventilation state, ambient temperature, humidity, and repeated measurements. Reports should distinguish sensor response time, controller processing time, actuator activation time, local alarm delay, cloud transmission delay, and smartphone notification delay.

The second priority is calibration and uncertainty reporting. Researchers should report sensor warm-up time, baseline stabilization, calibration procedure, detection range, recovery time, repeatability, cross-sensitivity, and long-term drift. For MQ-based systems, environmental compensation and periodic recalibration should be discussed explicitly.

The third priority is reliability-aware IoT design. Prototypes should include fail-safe local alarms, power backup or low-battery indication, offline behavior, reconnection strategy, secure access control, and firmware update mechanisms. IoT dashboards should not be considered sufficient without local warning and mitigation. The fourth priority is user-centered deployment, including ergonomic enclosure design, installation guidelines, maintenance instructions, alarm audibility, and field validation in household, restaurant, MSME, and industrial environments.

6. Conclusion

Arduino- and IoT-based LPG gas leak detection systems remain attractive because they can provide low-cost local alarms and remote notifications. The expanded review, however, shows that practical safety performance cannot be inferred from simple alarm activation alone. Reliable LPG detection depends on sensor calibration, selectivity, environmental robustness, signal processing, communication reliability, fail-safe local actuation, and user-centered installation. MQ-series sensors are suitable for low-cost early-warning prototypes. However, they should be treated as semi-quantitative sensors unless calibration and environmental compensation are performed. IoT connectivity adds value through remote monitoring and logging, yet it also introduces latency, outage, and cybersecurity risks. The strongest direction for future systems is therefore a hybrid approach: calibrated sensing, local fail-safe alarms, multi-sensor fusion, edge intelligence where justified, secure communication, and standardized performance reporting.

Conflict of interest

The authors declare no conflict of interest.

References

[1] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," Computer Networks, vol. 54, no. 15, pp. 2787-2805, 2010, doi: 10.1016/j.comnet.2010.05.010.

[2] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions," Future Generation Computer Systems, vol. 29, no. 7, pp. 1645-1660, 2013, doi: 10.1016/j.future.2013.01.010.

[3] D. Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, "Internet of Things: Vision, applications and research challenges," Ad Hoc Networks, vol. 10, no. 7, pp. 1497-1516, 2012, doi: 10.1016/j.adhoc.2012.02.016.

[4] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," IEEE Communications Surveys & Tutorials, vol. 17, no. 4, pp. 2347-2376, 2015, doi: 10.1109/COMST.2015.2444095.

[5] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for smart cities," IEEE Internet of Things Journal, vol. 1, no. 1, pp. 22-32, 2014, doi: 10.1109/JIOT.2014.2306328.

[6] C. Perera, A. Zaslavsky, P. Christen, and D. Georgakopoulos, "Context aware computing for the Internet of Things: A survey," IEEE Communications Surveys & Tutorials, vol. 16, no. 1, pp. 414-454, 2014, doi: 10.1109/SURV.2013.042313.00197.

[7] E. Borgia, "The Internet of Things vision: Key features, applications and open issues," Computer Communications, vol. 54, pp. 1-31, 2014, doi: 10.1016/j.comcom.2014.09.008.

[8] J. B. A. Gomes, J. J. P. C. Rodrigues, R. A. L. Rabelo, N. Kumar, and S. Kozlov, "IoT-enabled gas sensors: Technologies, applications, and opportunities," Journal of Sensor and Actuator Networks, vol. 8, no. 4, p. 57, 2019, doi: 10.3390/jsan8040057.

[9] N. Yamazoe, "Toward innovations of gas sensor technology," Sensors and Actuators B: Chemical, vol. 108, no. 1-2, pp. 2-14, 2005, doi: 10.1016/j.snb.2004.12.075.

[10] N. Barsan, D. Koziej, and U. Weimar, "Metal oxide-based gas sensor research: How to?," Sensors and Actuators B: Chemical, vol. 121, no. 1, pp. 18-35, 2007, doi: 10.1016/j.snb.2006.09.047.

[11] G. Korotcenkov, "Metal oxides for solid-state gas sensors: What determines our choice?," Materials Science and Engineering B, vol. 139, no. 1, pp. 1-23, 2007, doi: 10.1016/j.mseb.2007.01.044.

[12] A. Dey, "Semiconductor metal oxide gas sensors: A review," Materials Science and Engineering B, vol. 229, pp. 206-217, 2018, doi: 10.1016/j.mseb.2017.12.036.

[13] K. Wetchakun et al., "Semiconducting metal oxides as sensors for environmentally hazardous gases," Sensors and Actuators B: Chemical, vol. 160, no. 1, pp. 580-591, 2011, doi: 10.1016/j.snb.2011.08.032.

[14] X. Liu et al., "A survey on gas sensing technology," Sensors, vol. 12, no. 7, pp. 9635-9665, 2012, doi: 10.3390/s120709635.

[15] G. F. Fine, L. M. Cavanagh, A. Afonja, and R. Binions, "Metal oxide semiconductor gas sensors in environmental monitoring," Sensors, vol. 10, no. 6, pp. 5469-5502, 2010, doi: 10.3390/s100605469.

[16] C. Wang, L. Yin, L. Zhang, D. Xiang, and R. Gao, "Metal oxide gas sensors: Sensitivity and influencing factors," Sensors, vol. 10, no. 3, pp. 2088-2106, 2010, doi: 10.3390/s100302088.

[17] H. Bai and G. Shi, "Gas sensors based on conducting polymers," Sensors, vol. 7, no. 3, pp. 267-307, 2007, doi: 10.3390/s7030267.

[18] A.-C. Romain and J. Nicolas, "Long term stability of metal oxide-based gas sensors for e-nose environmental applications: An overview," Sensors and Actuators B: Chemical, vol. 146, no. 2, pp. 502-506, 2010, doi: 10.1016/j.snb.2009.12.027.

[19] S. Marco and A. Gutierrez-Galvez, "Signal and data processing for machine olfaction and chemical sensing: A review," IEEE Sensors Journal, vol. 12, no. 11, pp. 3189-3214, 2012, doi: 10.1109/JSEN.2012.2192920.

[20] A. Vergara et al., "Chemical gas sensor drift compensation using classifier ensembles," Sensors and Actuators B: Chemical, vol. 166-167, pp. 320-329, 2012, doi: 10.1016/j.snb.2012.01.074.

[21] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of LPWAN technologies for large-scale IoT deployment," ICT Express, vol. 5, no. 1, pp. 1-7, 2019, doi: 10.1016/j.icte.2017.12.005.

[22] R. S. Sinha, Y. Wei, and S.-H. Hwang, "A survey on LPWA technology: LoRa and NB-IoT," ICT Express, vol. 3, no. 1, pp. 14-21, 2017, doi: 10.1016/j.icte.2017.03.004.

[23] A. Augustin, J. Yi, T. Clausen, and W. M. Townsley, "A study of LoRa: Long range and low power networks for the Internet of Things," Sensors, vol. 16, no. 9, p. 1466, 2016, doi: 10.3390/s16091466.

[24] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios," IEEE Wireless Communications, vol. 23, no. 5, pp. 60-67, 2016, doi: 10.1109/MWC.2016.7721743.

[25] F. Adelantado et al., "Understanding the limits of LoRaWAN," IEEE Communications Magazine, vol. 55, no. 9, pp. 34-40, 2017, doi: 10.1109/MCOM.2017.1600613.

[26] S. Sicari, A. Rizzardi, L. A. Grieco, and A. Coen-Porisini, "Security, privacy and trust in Internet of Things: The road ahead," Computer Networks, vol. 76, pp. 146-164, 2015, doi: 10.1016/j.comnet.2014.11.008.

[27] R. Roman, P. Najera, and J. Lopez, "Securing the Internet of Things," Computer, vol. 44, no. 9, pp. 51-58, 2011, doi: 10.1109/MC.2011.291.

[28] F. A. Alaba, M. Othman, I. A. T. Hashem, and F. Alotaibi, "Internet of Things security: A survey," Journal of Network and Computer Applications, vol. 88, pp. 10-28, 2017, doi: 10.1016/j.jnca.2017.04.002.

[29] Y. Yang, L. Wu, G. Yin, L. Li, and H. Zhao, "A survey on security and privacy issues in Internet-of-Things," IEEE Internet of Things Journal, vol. 4, no. 5, pp. 1250-1258, 2017, doi: 10.1109/JIOT.2017.2694844.

[30] D. E. Kouicem, A. Bouabdallah, and H. Lakhlef, "Internet of Things security: A top-down survey," Computer Networks, vol. 141, pp. 199-221, 2018, doi: 10.1016/j.comnet.2018.03.012.

[31] M. A. Al-Garadi et al., "A survey of machine and deep learning methods for Internet of Things security," IEEE Communications Surveys & Tutorials, vol. 22, no. 3, pp. 1646-1685, 2020, doi: 10.1109/COMST.2020.2988293.

[32] H.-J. Kim and J.-H. Lee, "Highly sensitive and selective gas sensors using p-type oxide semiconductors: Overview," Sensors and Actuators B: Chemical, vol. 192, pp. 607-627, 2014, doi: 10.1016/j.snb.2013.11.005.

[33] Z. Li et al., "Quasi-one-dimensional metal oxide-based heterostructural gas-sensing materials: A review," Sensors and Actuators B: Chemical, vol. 221, pp. 1570-1585, 2015, doi: 10.1016/j.snb.2015.08.003.

[34] A. Mirzaei, S. G. Leonardi, and G. Neri, "Detection of hazardous volatile organic compounds by metal oxide nanostructures-based gas sensors: A review," Ceramics International, vol. 42, no. 14, pp. 15119-15141, 2016, doi: 10.1016/j.ceramint.2016.06.145.

[35] G. Korotcenkov and B. K. Cho, "Metal oxide composites in conductometric gas sensors: Achievements and challenges," Sensors and Actuators B: Chemical, vol. 244, pp. 182-210, 2017, doi: 10.1016/j.snb.2016.12.117.

[36] E. Espid and F. Taghipour, "UV-LED photo-activated chemical gas sensors: A review," Critical Reviews in Solid State and Materials Sciences, vol. 42, no. 5, pp. 416-432, 2017, doi: 10.1080/10408436.2016.1226161.

[37] N. Kaur, M. Singh, and E. Comini, "One-dimensional nanostructured oxide chemoresistive sensors," Langmuir, vol. 36, no. 23, pp. 6326-6344, 2020, doi: 10.1021/acs.langmuir.0c00701.

[38] G. W. Hunter et al., "Editors' choice - Critical review - A critical review of solid state gas sensors," Journal of The Electrochemical Society, vol. 167, no. 3, p. 037570, 2020, doi: 10.1149/1945-7111/ab729c.

[39] T. Dutta et al., "Road map of semiconductor metal-oxide-based sensors," Sensors, vol. 23, no. 15, p. 6849, 2023, doi: 10.3390/s23156849.

[40] H. Chai et al., "Stability of metal oxide semiconductor gas sensors: A review," IEEE Sensors Journal, vol. 22, no. 6, pp. 5470-5481, 2022, doi: 10.1109/JSEN.2022.3148264.

[41] M. J. Page et al., "The PRISMA 2020 statement: An updated guideline for reporting systematic reviews," BMJ, vol. 372, p. n71, 2021, doi: 10.1136/bmj.n71.

[42] E. Landi et al., "Reliability and performance evaluation of IoT-based gas detection sensor node," Electronics, vol. 14, no. 19, p. 3798, 2025, doi: 10.3390/electronics14193798.

[43] M. Zhou, S. Wang, J. Li, Z. Wei, and L. Shui, "A wireless sensor network-based combustible gas detection system using PSO-DBO-optimized BP neural network," Sensors, vol. 25, no. 10, p. 3151, 2025, doi: 10.3390/s25103151.

[44] M. El Barkani, N. Benamar, H. Talei, and M. Bagaa, "Gas leakage detection using Tiny Machine Learning," Electronics, vol. 13, no. 23, p. 4768, 2024, doi: 10.3390/electronics13234768.

[45] B. Renganathan et al., "Investigating the performance of SnO2-functionalized fiber optic sensors for LPG gas detection at varying ambient conditions," Fuel, vol. 413, p. 138205, 2026, doi: 10.1016/j.fuel.2025.138205.

[46] Y. Wu et al., "Research progress of MEMS gas sensors," Sensors, vol. 24, no. 24, p. 8125, 2024, doi: 10.3390/s24248125.

[47] J. Wei et al., "Intelligent gas sensors: From mechanism to applications," Sensors, vol. 25, no. 20, p. 6321, 2025, doi: 10.3390/s25206321.

[48] A. A. S. AlQahtani et al., "A comprehensive review and bibliometric analysis of IoT-enabled fire safety systems," Safety, vol. 11, no. 2, p. 41, 2025, doi: 10.3390/safety11020041.

[49] F. Schedin et al., "Detection of individual gas molecules adsorbed on graphene," Nature Materials, vol. 6, pp. 652-655, 2007, doi: 10.1038/nmat1967.

[50] M. G. Chung et al., "Highly sensitive NO2 gas sensor based on ozone treated graphene," Sensors and Actuators B: Chemical, vol. 166-167, pp. 172-176, 2012, doi: 10.1016/j.snb.2012.02.036.

[51] T. Hubbert, L. Boon-Brett, G. Black, and U. Banach, "Hydrogen sensors - A review," Sensors and Actuators B: Chemical, vol. 157, no. 2, pp. 329-352, 2011, doi: 10.1016/j.snb.2011.04.070.

[52] H. Yoon, "Current trends in sensors based on conducting polymer nanomaterials," Nanomaterials, vol. 3, no. 3, pp. 524-549, 2013, doi: 10.3390/nano3030524.

[53] E. Comini, "Metal oxide nano-crystals for gas sensing," Analytica Chimica Acta, vol. 568, no. 1-2, pp. 28-40, 2006, doi: 10.1016/j.aca.2005.10.069.

[54] E. Comini, "Metal oxide nanowire chemical sensors: Innovation and quality of life," Materials Today, vol. 19, no. 10, pp. 559-567, 2016, doi: 10.1016/j.mattod.2016.05.016.

[55] N. Hidayat, S. Hidayat, N. A. Pramono, and U. Nadirah, "Sistem deteksi kebocoran gas sederhana berbasis Arduino Uno," REKAYASA, vol. 13, no. 2, pp. 181-186, 2020.

[56] A. Sumaedi, F. R. Rosman, and F. Fiqri, "Perancangan sistem keamanan pendeteksi gas dalam ruangan menggunakan sensor gas MQ-2 berbasis mikrokontroler Arduino Uno R3," Jurnal Sistem Komputer dan Kecerdasan Buatan, vol. VII, no. 3, pp. 198-207, 2024.

[57] D. Nurnaningsih, "Pendeteksi kebocoran tabung LPG melalui SMS gateway menggunakan sensor MQ-2 berbasis Arduino UNO," Jurnal Teknik Informatika, vol. 11, no. 2, pp. 121-126, 2018.

[58] R. H. Pramana, "Embedded system of LPG leakage detection using Arduino microcontroller and Kalman Filter algorithm," IT Journal Research and Development, vol. 10, no. 1, pp. 11-20, 2025.

[59] S. Laitera, W. A. Dewa, and S. Arifin, "Application of Arduino Uno-based alarm system to detect LPG gas leakage," Jurnal Janitra Informatika dan Sistem Informasi, vol. 2, no. 2, pp. 96-106, 2022, doi: 10.25008/janitra.v2i2.159.

[60] Y. Mauluddin and S. Hamidah, "Perancangan alat pendeteksi kebocoran gas LPG berbasis

Arduino dengan pendekatan ergonomi," Jurnal Algoritma, vol. 22, no. 2, pp. 1364-1372, 2025, doi: 10.33364/algoritma/v.22-2.2167.
[61] K. Chan, "Sistem pendeteksi kebocoran gas berbasis Arduino menggunakan NodeMCU dan Blynk," Jurnal Sains Informatika Terapan, vol. 04, no. 03, pp. 568-573, 2025.
[62] S. I. Allkadri and Y. Chandra, "Rancang bangun sistem pendeteksi kebocoran gas berbasis Internet of Things (IoT)," ENTRIES, vol. 02, no. 02, pp. 1-6, 2023, doi: 10.58466/entries.
[63] Nurhapsari, S. Paembonan, R. Suppa, Dasril, H. Abduh, and Hasnahwati, "Rancang bangun sistem pendeteksi kebocoran gas berbasis IoT," JITET, vol. 13, no. 1, pp. 326-338, 2025.
[64] M. M. Effendi, A. T. Zy, and Sanudin, "Implementing Internet of Things (IoT) technology for real-time detection and monitoring of LPG gas leaks," Info Sains, vol. 14, no. 03, pp. 246-256, 2024, doi: 10.54209/infosains.v14i03.
[65] D. D. Hutagalung, "Rancang bangun alat pendeteksi kebocoran gas dan api dengan menggunakan sensor MQ2 dan flame detector," Jurnal Rekayasa Informasi, vol. 7, no. 2, pp. 43-53, 2018.