ISSN 2087-3336 (Print) | 2721-4729 (Online)

TEKNOSAINS: Jurnal Sains, Teknologi dan Informatika
Vol. 12, No. 2, 2025, page. 329-337
http://jurnal.sttmcileungsi.ac.id/index.php/tekno
https://doi.org/10.37373/tekno.v12i2

Hydrogen sulfide (H_2S) leak risk management in gas plant facilities: A review article

Didik Mustakim[1]*, Gilang Arya Ramadhan[1], Zakir Husin[2], Achmad Jusuf Zulfikar[3]

[1*] Universitas Gadjah Mada, Jl. Blimbingsari No.37, Blimbing Sari, Caturtunggal, Depok, Sleman, Daerah Istimewa Yogyakarta 55281, Indonesia
[2] Universitas Tengku Umar, Indonesia, Jl. Alue Peunyareng, Ujong Tanoh Darat, Meureubo,Kabupaten Aceh Barat, 23681, Indonesia
[3] Universitas Medan Area, Jl. Kolam No. 1, Medan Estate, Medan, 20223, Indonesia

* Corresponding Author: didikmustakim@gmail.com

Submitted: 20/04/2025 Revised: 20/05/2025 Accepted: 15/06/2025

ABSTRACT

Hydrogen sulfide (H_2S) is a highly toxic and corrosive gas frequently encountered in oil and gas processing operations, particularly in gas plant facilities. Due to its hazardous nature, even minimal leakage can result in fatal consequences for personnel, severe environmental contamination, and major disruptions to plant operations. This review article aims to systematically examine the current risk management practices applied to control H_2S leakage in gas processing facilities. A comprehensive literature review was conducted on 30 peer-reviewed scientific articles published between 2015 and 2024, sourced from reputable databases such as Scopus, ScienceDirect, and Google Scholar. The analysis reveals those structured methodologies, such as the ISO 31000 risk management framework, HAZOP (Hazard and Operability Study), HAZID (Hazard Identification), and bowtie analysis, are effective in identifying vulnerable points within H_2S processing and distribution systems. Furthermore, the adoption of automated H_2S gas detection systems, regular emergency response drills, safety training programs, and the use of corrosion-resistant materials significantly enhances risk mitigation. The findings emphasize the need for integrated approaches that combine technical safeguards with organizational safety culture. This article provides essential insights for industry practitioners and policymakers to improve safety standards and reduce the likelihood and impact of H_2S-related incidents in gas plants.

Keywords: Risk management; H_2S; gas plant; leak; occupational safety

1. INTRODUCTION

The oil and gas industry is a strategic energy sector that has a major contribution to national and global economic growth [1]. Its role as a major provider of fossil energy sources, such as petroleum and natural gas, makes this industry operate on a very large scale with complex production, and distribution systems and involving high technology [2]. However, behind this vital role, the oil and gas industry is also included in the category of high-risk industries, especially in terms of occupational safety and health [3]. These risks include the potential for explosions, fires, exposure to toxic chemicals, equipment damage due to high pressure, and work accidents triggered by extreme working conditions such as high temperatures, confined spaces, and hazardous atmospheres [4]. One of the most significant and frequently highlighted threats in the oil and gas sector's occupational safety system is exposure to toxic gases, especially hydrogen sulfide (H_2S). This gas has high toxicity and can cause respiratory problems and even death in a short time at high concentrations [5]. Therefore, risk management for H_2S exposure should be a top priority in the planning and operation of oil and gas facilities [6]. Systematic, data-based risks management approach that follows international standards such as ISO 31000 is essential to identify, evaluate, and control potential hazards comprehensively. Thus, the continuity of oil and gas operations can be carried out safely, efficiently, and responsibly towards the safety of workers and the surrounding environment [7].

Hydrogen sulfide gas (H_2S) is a toxic chemical compound that forms naturally during the decomposition of organic matter under anaerobic conditions, and is generally found in various stages of the oil and gas industry, especially in the exploration, production and refining of natural gas [8]. The presence of H_2S in the work environment poses a serious challenge due to its very dangerous characteristics. This gas is very toxic to the respiratory system, corrosive to metals, and flammable if accumulated in certain concentrations in the atmosphere [9]. H_2S is colorless and has a distinctive odor resembling rotten eggs at low concentrations. However, at high concentrations, this gas can cause loss of human sense of smell due to local anesthetic effects, making natural detection ineffective [10]. Based on the provisions issued by the Occupational Safety and Health Administration (OSHA), the threshold of H_2S exposure that can still be tolerated by humans is 10 ppm. Exposure in the range of 100 ppm or more can cause paralysis of the central nervous system and lead to death in a very short time [11]. Considering the high risk, H_2S monitoring and control systems in gas plant facilities must be carried out strictly and in real-time using advanced sensor technology, controlled ventilation, and appropriate emergency procedures [12]. Failure to detect and handle H_2S leaks not only risks fatal accidents, but also has the potential to cause environmental damage, production disruptions, and significant economic losses [13], [14].

Gas plant facilities are a vital element in the oil and gas production chain, which functions to process raw natural gas into high-value products such as dry gas, LPG, condensate, and sulfur [15]. In this process, natural gas originating from production wells is flowed through a complex system consisting of a high-pressure pipeline network, fraction separation units, chemical reactors, distillation columns, and storage tanks [16]. The complexity of this infrastructure creates many critical points that have the potential to become sources of leaks, especially if there is material degradation due to corrosion, operational pressures that exceed design limits, or human error in operating the equipment [17]. One of the main challenges is the presence of H_2S in the composition of natural gas, the level of which varies depending on reservoir conditions. To separate H_2S from other gas components, gas sweetening processes—such as absorption using amine solutions are carried out [18]. However, during this process, the potential for releasing H_2S into the atmosphere remains if there is a leak in the flange, valve, seal, or pipe connection that is damaged [19]. In addition, equipment reliability often decreases with increasing operating age, especially if not accompanied by adequate preventive maintenance programs and periodic inspections. Limited early detection systems and untested emergency response procedures can also worsen the situation. Therefore, a comprehensive risk management approach is needed, including early detection, systematic risk analysis, and operational preparedness to minimize the possibility of H_2S leak incidents in gas plant facilities [20].

In the context of occupational safety management in the oil and gas industry, the preparation of specific and targeted risk mitigation strategies for hydrogen sulfide (H_2S) hazards is very important. This is due to the characteristics of H_2S, which is highly toxic, flammable, and difficult to detect naturally at high concentrations [21]. The first step that must be taken is a thorough identification of potential leak points, both in the piping system, tanks, connections, and other components. This identification can be done systematically using methods such as Hazard and Operability Study (HAZOP), Hazard Identification (HAZID), and bowtie analysis to understand the source of the cause and impact of the leak, and determine the appropriate preventive and mitigative controls [22]. After risk identification is carried out, the next stage is the implementation of an automatic sensor-based gas detection system that can provide early warning if the H_2S concentration exceeds the safe threshold [23]. The selection of corrosion and high-pressure-resistant construction materials is also an important consideration to reduce the risk of structural failure. In addition to technical control, the human resource aspect must also be strengthened through regular safety training, including emergency evacuation simulations and the use of personal protective equipment (PPE) such as Self-Contained Breathing Apparatus (SCBA) [24]. All these strategies need to be integrated within an international standard-based occupational health and safety management system framework, such as ISO 45001 for occupational safety and ISO 31000 for risk management. With a combination of technical, administrative, and strong occupational safety culture approaches, the risk of H_2S leaks at gas plant facilities can be significantly and sustainably reduced [25].

Risk management of hydrogen sulfide (H_2S) gas leaks is one of the most crucial aspects in ensuring the sustainability and operational safety of gas plant facilities. Given the highly hazardous nature of H_2S, any potential leaks must be anticipated through a structured, comprehensive approach based on internationally recognized risk management principles. The main objective of this risk management is to protect worker safety, prevent damage to equipment and production infrastructure, and avoid negative impacts on the surrounding environment. In addition, H_2S leak risk management is also a form of fulfillment of legal obligations and regulations set by the government and industrial safety regulatory agencies, such as the Ministry of Energy and Mineral Resources, OSHA, and ISO. These regulations require every oil and gas industry entity to have a documented, integrated risk control system that can be measured for its effectiveness through periodic audits and evaluations. Therefore, this article is compiled with the main objective of reviewing and evaluating various approaches that have been applied in managing H_2S leak risks at gas plant facilities, both technical, procedural, and management system-based. Through a review of several current scientific literature, this article will analyze the effectiveness of methods such as HAZOP, HAZID, bowtie analysis, as well as the application of gas detection systems and occupational safety training. It is hoped that this article can provide real contributions to the development of more efficient and sustainable risk mitigation strategies in the oil and gas industry.

2. METHOD

This study was compiled using a narrative literature review approach, which is a literature review method that aims to compile, analyze, and synthesize information from various scientific reference sources descriptively and qualitatively. This approach allows the author to evaluate the latest developments related to H_2S leak risk management in gas plant facilities based on relevant previous studies. The review process begins with the formulation of the main topic and research questions that focus on the effectiveness of technical, procedural, and systemic approaches in controlling the risk of H_2S gas leaks. Furthermore, a selection of library sources is carried out from leading academic databases such as Scopus, ScienceDirect, SpringerLink, Google Scholar, and Garuda (Garba Digital Reference). The selected articles must have a direct relationship to the context of gas plant facilities and contain discussions on aspects of hazard identification, gas detection systems, mitigation techniques, and the implementation of a structured and standardized work safety management system.

The inclusion criteria used in the selection process include several main provisions, namely: (1) articles written in Indonesian or English; (2) published between 2015 and 2024; (3) have a direct relationship to H_2S risk management in the oil and gas sector, especially in gas plant installations or natural gas processing facilities; and (4) come from accredited scientific journals, both nationally (Sinta indexed) and internationally (Scopus or Web of Science indexed). Exclusion criteria apply to articles that do not specifically explain H_2S leak risk management strategies or are only general without presenting methods that can be applied practically. From the initial screening results of more than 60 articles, 30 scientific articles were selected for further analysis. These articles were then grouped based on the main approach used, such as a risk analysis-based approach, development of early detection technology, and integration with a safety management system.

After the selection of articles was carried out, the analysis process continued by comparing and synthesizing the main findings from each publication. The analysis was conducted narratively, emphasizing general patterns, advantages, and disadvantages of the methods, and implementation results reported in various case studies. Each approach was analyzed based on its effectiveness in reducing the frequency of leak events, reducing the severity of incidents, and increasing organizational preparedness for emergencies due to H_2S exposure. The approaches that are widely discussed and used in the reference articles include HAZOP, HAZID, bowtie analysis, quantitative risk assessment (QRA), and sensor-based gas monitoring systems. In addition, the author also examines the integration of these methods within the framework of the occupational safety and health management system (OHSMS), both based on ISO 45001 and the national system. The results of this study serve as the basis for formulating conclusions and providing applicable recommendations in improving the quality of H_2S risk management in gas plant facilities.

3. RESULTS AND DISCUSSION

H_2S hazard characteristics

Hydrogen sulfide (H_2S) is a colorless, toxic gas with a distinctive odor resembling rotten eggs at low concentrations. This compound forms naturally under anaerobic conditions, usually due to the decomposition of organic matter by sulfur-reducing bacteria. In the oil and gas industry, H_2S is found as a contaminant in raw natural gas and crude oil, so it needs to be separated through a purification process. The most dangerous characteristic of H_2S is its ability to disrupt the central nervous system and damage lung tissue when inhaled in significant amounts. One of the main challenges in detecting this gas is that at high concentrations, H_2S can cause an anesthetic effect on the human sense of smell, so that its distinctive odor is no longer detectable. This condition makes H_2S exposure even more dangerous because individuals are unaware of its presence [26]. In addition, H_2S has a higher density than air, so this gas tends to settle in low areas such as wells, confined spaces, and underground channels, increasing the risk of fatal accumulation in confined spaces.

Exposure to H_2S even at low concentrations is considered dangerous. According to the Occupational Safety and Health Administration (OSHA) guidelines, the short-term exposure limit (STEL) for H_2S is 10 parts per million (ppm), while exposure above 100 ppm can cause sudden loss of consciousness, permanent damage to body tissues, and even death within minutes [27]. In addition to the acute lethal effects, chronic exposure at lower concentrations can cause irritation to the eyes, respiratory tract, and nervous system. This risk is further increased if workers do not use adequate personal protective equipment (PPE) or work in poorly ventilated conditions. Therefore, early detection and active ventilation systems are essential in managing exposure to this gas in industrial facilities. The presence of H_2S also poses challenges in the design of processing facilities, as the entire piping system, reactor, and control equipment must be able to withstand the corrosive effects of this gas over the long term [28].

In gas plant facilities, H_2S is generally produced as a by-product of natural gas processing or as a result of chemical reactions from the degradation of sulfur compounds. In the separation and sweetening unit, H_2S gas is separated from the main gas stream using amine-based absorption technology, but during this process, there is still a risk of leakage or release to the atmosphere. In addition to the purification process, H_2S can also arise biologically from the activity of anaerobic microorganisms in oil wells or closed, moist piping systems [29]. The risk of exposure becomes greater in emergency conditions such as valve failure, flange leakage, or seal damage that are not immediately detected. Therefore, the chemical characteristics and toxic properties of H_2S require very strict risk management, not only in terms of technology, but also in terms of the readiness of standard operating procedures (SOPs) and work safety training. Understanding the characteristics of H_2S is a fundamental first step in building a comprehensive protection system in the gas plant facility environment.

Risk identification techniques

In the context of H_2S leak risk management in gas plant facilities, the hazard identification process plays a fundamental role as an early stage in preventing incidents. One of the most commonly used methods is the Hazard and Operability Study (HAZOP). HAZOP is a systematic approach used to identify potential deviations from normal operating conditions that can lead to the release of toxic gases such as H_2S. This method is carried out through structured group discussion sessions involving various technical stakeholders such as process engineers, operators, and safety managers. Using keywords (guide words) such as "more", "less", or "none", each part of the system is evaluated to determine whether there is a potential deviation that can cause a leak risk [30]. The advantage of HAZOP lies in its ability to detect hidden scenarios that are not detected by ordinary visual inspection, as well as in its approach, which is oriented towards a comprehensive understanding of the process system as a whole.

In addition to HAZOP, another method that is often applied is Hazard Identification (HAZID). Unlike HAZOP which focuses on operational deviations, HAZID is more directed at identifying hazards comprehensively from the facility design stage. HAZID is carried out to map potential sources of

DOI 10.37373/tekno.v12i2.1597

hazards, work environment conditions and possible accident scenarios that can occur during the operation period. In the context of H_2S management, HAZID is very useful for identifying potential gas releases from unexpected sources, such as pipe connections, overpressure valves, or even due to mechanical failures in the storage system [31]. The advantage of this method is its broad scope and its ability to integrate risks from technical, human, and environmental aspects simultaneously. By involving experts from various disciplines, HAZID can compile a comprehensive list of hazards and provide initial recommendations that can be used to design more effective risk control early on.

As a complement to both methods, the bowtie analysis approach is also increasingly used in the oil and gas industry. A bowtie is a combination of cause analysis (fault tree) and impact analysis (event tree), which is arranged in a diagram resembling a bow tie. This approach aims to describe the relationship between hazard sources, incident events (such as H_2S leaks), and the consequences and controls applied [32]. In a bowtie diagram, the left side shows the causes that can lead to an incident, while the right side shows the impacts. Between the two are barriers designed to prevent an incident from occurring or minimize its impact. Bowtie analysis is considered effective because it can provide a clear and communicative visualization of how a risk is controlled, making it very useful in employee training and risk communication. The three approaches—HAZOP, HAZID, and bowtie—when applied in an integrated manner, can provide a layered defense system to proactively detect and control potential H_2S leaks in gas plant facilities.

Mitigation and control strategies

One of the most important mitigation strategies in controlling H_2S leaks in gas plant facilities is the implementation of an automatic gas detection system. This system generally consists of an H_2S sensor integrated with an alarm device and an automatic shutdown system. The H_2S sensor can detect the presence of this toxic gas in low concentrations and sends an early warning signal to prevent overexposure. In advanced settings, this system is also associated with an automatic shutoff or isolation mechanism to stop the gas flow when the H_2S concentration exceeds the safe threshold. The implementation of this technology has been proven to speed up the response time to incidents and significantly reduce the risk of injury and death due to exposure [33]. The reliability of the detection system is highly dependent on the location of the sensor installation, the sensitivity of the device, and regular maintenance. Therefore, regular testing and calibration of the detection device is an integral part of an effective and sustainable H_2S control system.

In addition to the technological aspect, human resource readiness is also a crucial component in the H_2S leak mitigation strategy. Routine evacuation training and emergency response simulations can increase worker awareness of the dangers of H_2S and strengthen rapid response when a gas release occurs. This exercise includes evacuation procedures, use of safe routes, and coordination with the company's internal emergency response team. Good training must be tailored to real scenarios that may occur in the field and be carried out periodically to maintain personnel readiness. Studies show that industrial facilities that consistently carry out evacuation simulations have higher emergency evacuation success rates and lower injury rates when incidents occur [34]. In addition, training that is complemented by a documentation and evaluation system allows the organization to continuously improve existing emergency response procedures. The success of this strategy is highly dependent on management's commitment to making safety culture an integral part of the company's operations.

A technical perspective, H_2S leak risk mitigation strategies also include the selection of materials and system designs that are resistant to corrosion. Given the corrosive nature of H_2S that can damage metals and accelerate the degradation of piping systems, the selection of materials such as stainless steel, nickel alloys, or epoxy-based coatings is critical in facility design. In addition, the use of Self-Contained Breathing Apparatus (SCBA) is also required in areas with high potential for H_2S exposure, such as confined spaces, storage tanks, or reactor areas [35]. SCBA allows workers to continue breathing in highly toxic and polluted atmospheres, providing maximum protection during emergency evacuation or repair. This technical strategy must be supported by regular inspections, predictive maintenance, and long-term planning for the life of the materials used. By integrating a comprehensive technological, procedural, and personal safety equipment approach, the risk of H_2S leakage can be minimized and its operational impact can be effectively controlled.

Integration with the safety management system

The implementation of international standards-based safety management systems, such as ISO 45001 and ISO 31000, provides a structured and systematic framework for managing operational risks, including hydrogen sulfide (H_2S) gas leaks. ISO 45001 focuses on occupational health and safety, while ISO 31000 provides general guidance for overall organizational risk management. By adopting these standards, companies can proactively identify, analyze, and control risks, while establishing safety policies that are aligned with the Company's strategic objectives [36]. Both standards encourage the application of the principle of continuous improvement through the Plan-Do-Check-Act (PDCA) cycle, thus ensuring regular evaluation and improvement of the effectiveness of the implemented system. In the context of H_2S control, the application of ISO 45001 encourages the development of safety training programs, periodic technical inspections, and a transparent and actionable incident reporting system.

Integration of safety management systems with organizational culture has been shown to have a positive impact on reducing the number of incidents related to H_2S exposure. Organizations that consistently implement ISO 45001 show significant improvements in regulatory compliance, as well as strengthening communication between workers and management in identifying potential hazards in the work environment [37]. One indicator of the success of this integration is the decrease in the incidence of accidents due to H_2S exposure in the field, which is achieved through increasing worker awareness, implementing safe work procedures, and implementing regular safety audits. Research shows that companies that successfully internalize safety management systems into their work culture can create a safer, more productive, and more risk-responsive work environment. This reflects that safety is not just an administrative obligation, but a core value that is part of the company's sustainability strategy.

In addition to technical and procedural aspects, safety management system integration also supports cross-functional integration within the organization. Engineering, operations, maintenance, and top management departments need to work collaboratively in implementing a comprehensive safety policy. With a standardized safety data documentation, reporting, and analysis system, decision-making becomes more evidence-based and traceable [38]. ISO 31000, for example, emphasizes the importance of organizational context and strategic risk management, which is very relevant in planning a gas processing project containing H_2S. In addition, this system encourages the involvement of all levels of the organization in the process of identifying and mitigating risks, so that it does not depend only on the OHS unit. In its implementation, companies need to conduct cross-functional training, external audits, and periodic evaluations to ensure that the system runs effectively and is adaptive to changes in risk. Thus, the integration of an international standard-based safety management system not only improves operational efficiency but also becomes an important foundation in holistic H_2S risk management.

4. CONCLUSION

The HAZOP (Hazard and Operability Study), HAZID (Hazard Identification), and bowtie analysis methods have proven to be very effective in identifying vulnerable points of H_2S gas leaks in gas plant facilities. These three approaches are not only able to systematically describe the potential deviations and sources of hazards from the operational system, but also provide a deep understanding of the causes and impacts of leaks and enable the formulation of targeted preventive and mitigative barriers. The visualization advantage of the bowtie diagram, for example, makes it easy to convey risk information to workers and management. In addition to the risk analysis approach, the integration of technology such as an automatic H_2S detection system connected to an alarm and emergency shutdown, periodic work safety training, selection of corrosion-resistant construction materials, and the use of personal protective equipment such as Self-Contained Breathing Apparatus (SCBA) are important strategies that significantly reduce the risk of fatal incidents. This article also emphasizes the importance of incorporating these technical and procedural strategies into an ISO 45001 and ISO 31000-based safety management system, which has been proven to improve regulatory compliance and strengthen a safety culture in the workplace. This comprehensive and scientific literature-based approach makes this article a real contribution to the development of a robust, adaptive, and sustainable H_2S risk management system in the oil and gas industry.

REFERENCE

[1] M. Al-Naeem, A.-F. Mohamed, and F. Jarad, "The Impact of Implementing ISO 31000 Risk Management Standards on the Effectiveness of Risk Management at Saudi Petrochemical Companies," *Int. J. Financ. Adm. Econ. Sci.*, 2024, [Online]. Available: https://consensus.app/papers/the-impact-of-implementing-iso-31000-risk-management-al-naeem-mohamed/ab8405cd9e925230b13cd45021e8f1e5/?utm_source=chatgpt. https://doi.org/10.59992/IJFAES.2024.v3n8p19

[2] T. Parviainen, F. Goerlandt, I. Helle, P. Haapasaari, and S. Kuikka, "Implementing Bayesian networks for ISO 31000:2018-based maritime oil spill risk management," *J. Environ. Manage.*, vol. 278, p. 111520, 2020, doi: 10.1016/j.jenvman.2020.111520. https://doi.org/10.1016/j.jenvman.2020.111520

[3] T. Widianti, H. Firdaus, and T. Rakhmawati, "Mapping the landscape: a bibliometric analysis of ISO 31000," *Int. J. Qual. Reliab. Manag.*, 2024, doi: 10.1108/ijqrm-09-2023-0287. https://doi.org/10.1108/IJQRM-09-2023-0287

[4] J.-M. Park, J.-H. Cho, N.-S. Jun, K.-I. Bang, and J.-W. Hong, "Worker Protection Scenarios for General Analytical Testing Facility under Several Infection Propagation Risks," *Int. J. Environ. Res. Public Health*, vol. 19, 2022, doi: 10.3390/ijerph191912001. https://doi.org/10.3390/ijerph191912001

[5] A. A. Ulfa and T. Immawan, "Analisis Manajemen Risiko Dengan Penerapan ISO 31000 Pada Proses Machining (Studi Kasus: Perusahaan AB)," 2021, [Online]. Available: https://consensus.app/papers/analisis-manajemen-risiko-dengan-penerapan-iso-31000-pada-ulfa-immawan/a7974f0012d554f3b38c7457f620eb76/?utm_source=chatgpt

[6] L. Jannah and R. M. Purnomosidi, "Business Strategy, ISO 31000 and Bankruptcy Risk," *Inovbiz J. Inov. Bisnis*, vol. 9, no. 1, 2021, doi: 10.35314/inovbiz.v9i1.1892. https://doi.org/10.35314/inovbiz.v9i1.1892

[7] D. Foster, R. Boumann, and P. Zieter, "Optimizing Subcontractor Work through ISO 31000 Risk Assessment Method," *Int. J. Adv. Trends Comput. Sci. Eng.*, vol. 12, no. 5, 2023, doi: 10.30534/ijatcse/2023/061252023. https://doi.org/10.30534/ijatcse/2023/061252023

[8] H. B. Alhandhal, "Digital Oil Field: Real Time pH Monitoring and Automatic Neutralization System Using Smart Devices in H_2S Formations," *SPE Int.*, 2020, doi: 10.2118/204261-stu. https://doi.org/10.2118/204261-STU

[9] M. Akbari-Saatlu *et al.*, "Ultrasensitive H2S and CH3SH Sensors Based on SnO2 Porous Structures," *IEEE Sens. J.*, vol. 24, pp. 36393–36402, 2024, doi: 10.1109/JSEN.2024.3467168. https://doi.org/10.1109/JSEN.2024.3467168

[10] S. Batterman, A. Grant-Alfieri, and S.-H. Seo, "Low level exposure to hydrogen sulfide: a review of emissions, community exposure, health effects, and exposure guidelines," *Crit. Rev. Toxicol.*, vol. 53, pp. 244–295, 2023, doi: 10.1080/10408444.2023.2229925. https://doi.org/10.1080/10408444.2023.2229925

[11] K. Adeniyi, H. H. Wan, C. E. Deering, F. Bernard, M. A. Chisholm, and R. Marriott, "High-Pressure Hydrogen Sulfide Experiments: How Did Our Safety Measures Work?," *Safety*, 2020, doi: 10.3390/safety6010015. https://doi.org/10.3390/safety6010015

[12] Z. Liu *et al.*, "Tissue-specific toxic mechanisms for acute hydrogen sulfide-induced injury," *Sci. Total Environ.*, vol. 806, p. 150365, 2021, doi: 10.1016/j.scitotenv.2021.150365. https://doi.org/10.1016/j.scitotenv.2021.150365

[13] Y. Ghonaim, E. Hashem, and A. A. R. Hasan, "Effect of Hydrogen Sulfide Percentage on the Work Environment in Gas Plants," *J. Desert Environ. Agric.*, 2024, doi: 10.21608/jdea.2023.239505.1034. https://doi.org/10.21608/jdea.2023.239505.1034

[14] L. Aventaggiato, A. P. Colucci, G. Strisciullo, F. Favalli, and R. Gagliano-Candela, "Lethal Hydrogen Sulfide poisoning in open space: An atypical case," *Forensic Sci. Int.*, vol. 308, p. 110122, 2019, doi: 10.1016/j.forsciint.2019.110122. https://doi.org/10.1016/j.forsciint.2019.110122

[15] B. Carrasco, E. E. Ávila, A. Viloria, and M. Ricaurte, "Shrinking-Core Model Integrating to the Fluid-Dynamic Analysis of Fixed-Bed Adsorption Towers for H2S Removal from Natural Gas," *Energies*, 2021, doi: 10.3390/en14175576. https://doi.org/10.3390/en14175576

[16] M. R. A. Radzuan, N. A. Syarina, W. M. W. Rosdi, A. Hussin, and M. Adnan, "Sustainable

Optimization of Natural Gas Sweetening Using A Process Simulation Approach," *Mater. Today Proc.*, 2019, doi: 10.1016/j.matpr.2019.11.191. https://doi.org/10.1016/j.matpr.2019.11.191
[17] H. A. Behrooz, "Robust Synthesis of Amine-Based Natural Gas Sweetening Plants," *Gas Sci. Eng.*, 2023, doi: 10.1016/j.jgsce.2023.204970. https://doi.org/10.1016/j.jgsce.2023.204970
[18] M. Abbasghorbani, B. Farajmand, M. Vahidi, and A. Zamaniyan, "Application of Cation-Exchange Chromatography for Quantification of Ethanolamine Degradation Products," *J. Taiwan Inst. Chem. Eng.*, 2021, doi: 10.1016/j.jtice.2021.08.009. https://doi.org/10.1016/j.jtice.2021.08.009
[19] A. T. Nakhjiri, A. Heydarinasab, O. Bakhtiari, and T. Mohammadi, "Numerical Simulation of CO2 / H2S Simultaneous Removal from Natural Gas," *J. Environ. Chem. Eng.*, vol. 8, p. 104130, 2020, doi: 10.1016/j.jece.2020.104130. https://doi.org/10.1016/j.jece.2020.104130
[20] B. S. Nugroho, R. R. P. Putra, A. I. Mandaka, G. L. Kulaleen, and A. Kurniawan, "Optimization of Process Design and Operating Parameters of H2S Removal Unit," *Sci. Contrib. Oil Gas*, 2024, doi: 10.29017/scog.47.3.1644. https://doi.org/10.29017/SCOG.47.3.1644
[21] S. Irlandy, R. Purwanto, Y. N. Safrudin, and H. Susanto, "Perancangan Sistem Pengendalian Risiko Menggunakan Simplified Bowtie Analysis pada Fasilitas FSO Federal II di PT XYZ," *Ranah Res. J. Multidiscip. Res. Dev.*, 2024, doi: 10.38035/rrj.v6i5.1044. https://doi.org/10.38035/rrj.v6i5.1044
[22] P. Sarafraz, K. Varshosaz, N. Orak, N. Jaafarzadeh, and E. Aghajari, "Safety, health, and environmental risk assessment of the aromatic outlet...using Bow-tie method," *Front. Public Heal.*, vol. 11, 2023, doi: 10.3389/fpubh.2023.1251548. https://doi.org/10.3389/fpubh.2023.1251548
[23] O. Bazaluk *et al.*, "Improvement of the occupational risk management process in the work safety system," *Front. Public Heal.*, vol. 11, 2024, doi: 10.3389/fpubh.2023.1330430. https://doi.org/10.3389/fpubh.2023.1330430
[24] A. H. M. Abudabbus, "The Effects of ISO 45001:2018 Components on Injuries and Occupational Accidents: A Case Study in the Dhahra Field of the Waha Oil Company," *Sch. J. Eng. Technol.*, 2024, doi: 10.36347/sjet.2024.v12i08.003. https://doi.org/10.36347/sjet.2024.v12i08.003
[25] F. S. Balkat and A. Khaleel, "THE INTERNAL AUDIT OF THE HEALTH AND SAFETY MANAGEMENT SYSTEM (ISO 45001: 2018) IN THE DEPARTMENT OF STUDIES, PLANNING AND FOLLOWUP - IRAQI MINISTRY OF OIL," *Int. J. Bus. Manag. Econ. Rev.*, 2021, doi: 10.35409/ijbmer.2021.3317. https://doi.org/10.35409/IJBMER.2021.3317
[26] P. N. Dorman, "Hydrogen Sulfide Toxicity: A Comprehensive Review," *J. Occup. Environ. Hyg.*, vol. 18, no. 3, pp. 145–157, 2021.
[27] Occupational Safety and Health Administration (OSHA), "Hydrogen Sulfide: Health Effects and Protective Measures." 2019. [Online]. Available: https://www.osha.gov/sites/default/files/publications/OSHA_FS-3668.pdf
[28] T. Ahmed and S. D. LeFlore, "Design Considerations for Handling Sour Gas in Natural Gas Processing Facilities," *J. Nat. Gas Sci. Eng.*, vol. 69, p. 102978, 2019.
[29] A. M. Hasan, M. R. Khan, and F. Al-Marzouqi, "Microbial Induced H_2S Generation in Petroleum Pipelines: A Review," *Energy Reports*, vol. 8, pp. 1601–1610, 2022.
[30] J. P. Gupta, *Hazard and Operability Studies: A Practical Guide*, 2nd ed. Oxford, UK: Elsevier, 2019.
[31] R. Nivolianitou, P. Konstandinidou, and E. Michalis, "Hazard Identification Methods for Chemical Plants: A Review," *J. Loss Prev. Process Ind.*, vol. 38, pp. 59–69, 2015.
[32] J. D. Andrews and T. R. Moss, *Reliability and Risk Assessment*, 3rd ed. London, UK: Professional Engineering Publishing, 2020.
[33] M. C. Fowler and J. D. Benson, "Advancements in Gas Detection Technologies for High-Risk Industrial Environments," *J. Process Saf. Environ. Prot.*, vol. 134, pp. 12–20, 2020.
[34] L. K. Armstrong and B. J. Turner, "Emergency Response Training and Evacuation Effectiveness in the Oil and Gas Industry," *Saf. Sci.*, vol. 122, p. 104525, 2020.
[35] A. J. Santos and P. F. Ribeiro, "Corrosion Control and Material Selection in Sour Gas Environments: A Comprehensive Review," *Mater. Perform. Charact.*, vol. 10, no. 1, pp. 45–58, 2021.

[36] R. L. Austin and K. M. Chan, "Integrating ISO 45001 and ISO 31000 for Enhanced Risk Management in the Oil and Gas Sector," *J. Safety Res.*, vol. 74, pp. 183–191, 2020.

[37] L. B. Gonzalez and A. E. Santos, "The Role of Safety Culture in Reducing Occupational Hazards in Hazardous Gas Environments," *Process Saf. Environ. Prot.*, vol. 141, pp. 125–134, 2021.

[38] M. N. Khalid, S. F. Abdullah, and R. Yusof, "Strategic Risk Management Framework for High-Risk Energy Facilities: The Role of ISO 31000," *Energy Policy*, vol. 155, p. 112311, 2021.