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Review

Artificial Intelligence-Driven Innovations in Hydrogen Safety

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Abstract: This review explores recent advancements in hydrogen gas (H_2) safety through the lens of artificial intelligence (AI) techniques. As hydrogen gains prominence as a clean energy source, ensuring its safe handling becomes paramount. The paper critically evaluates the implementation of AI methodologies, including artificial neural networks (ANN), machine learning algorithms, computer vision (CV), and data fusion techniques, in enhancing hydrogen safety measures. By examining the integration of wireless sensor networks and AI for real-time monitoring and leveraging CV for interpreting visual indicators related to hydrogen leakage issues, this review highlights the transformative potential of AI in revolutionizing safety frameworks. Moreover, it addresses key challenges such as the scarcity of standardized datasets, the optimization of AI models for diverse environmental conditions, etc., while also identifying opportunities for further research and development. This review foresees faster response times, reduced false alarms, and overall improved safety for hydrogen-related applications. This paper serves as a valuable resource for researchers, engineers, and practitioners seeking to leverage state-of-the-art AI technologies for enhanced hydrogen safety systems.

Keywords: hydrogen safety; monitoring; artificial intelligence; computer vision; machine learning algorithms; wireless sensor networks; predictive modeling

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1. Introduction

Hydrogen has been used safely for more than a century in a variety of industries, primarily in oil refineries, ammonia production, fertilizers, metallurgical applications, food industry, and the space program. Despite being nontoxic and lighter than air properties, it is seen hazardous due to historical reasons like the Hindenburg disaster.

However, in the last few decades, in the drive to reduce carbon emissions, hydrogen gas (H_2) is potentially considered an important energy carrier for the industry and transport sector. Hydrogen and fuel cells will play a greater role in the energy sector, thus the safety related to the use of H_2 as a fuel is now essential. Safety considerations are a prerequisite to establishing the confidence of stakeholders and the public in accepting H_2 as a replacement for conventional fuels.

Traditional hydrogen production methods are based on fossil fuel processing and electrolysis of water. Hydrogen produced by electrolysis of water powered by renewable energy sources is now considered green H_2 and is preferred compared to steam reforming of fossil fuels. Like other gaseous fuels, the possibility of leakage and subsequent hazards are the main risks through the entire H_2 value chain, i.e., from production, storage to delivery, and end-use. Being a light molecule H_2 has to be stored under high pressure and due to its high diffusivity and permeation properties, the risk of leakage is high. In the event of leaks, it is undetectable to the human senses, and due to rapid diffusion, low ignition energy, and wide flammability range, the risk of leaks may be associated with ignition. Therefore, rigorous safety measures to mitigate these risks are critical.

The global drive toward hydrogen technologies for decarbonization, emphasized by Ocko and Hamburg [1], highlights H_2's pivotal role in mitigating climate change. However, their study also brings attention to hydrogen's short-term warming effects, challenging its perceived neutrality and emphasizing the need for emissions reduction and proactive safety measures. Recent investments aiming for the largest electrolyzer capacity by 2028 [2] underscore industry focus on decarbonization, demanding immediate safety standard development amidst rapid expansion.

Jahangiri et al. [3] highlighted the economic feasibility of hydrogen production via renewable energy systems like wind and solar power, with sensitivity analyses emphasizing emission penalties' influence on generation costs and the efficiency benefits of fuel cell integration. Fahd Amjad et al. [4] identified sites for large-scale green hydrogen production using solar energy, emphasizing proximity to national networks and water resources, with implications for energy storage and transportation sectors. Furthermore, ensuring hydrogen safety in these production and utilization processes remains paramount.

There are international standards for H_2 explosion protection IEC 60079 [5] and IEC 80079 [6], as well as specific standards (ISO 22734 [7] and ISO 19880 [8]) for H_2 facilities. Various sensors are commercially available, along with guidelines for selection installation and positioning, depending on the facility and the process. At the planning stage, engineers also obtain information on understanding the field of view and blind spots at the facilities for choosing the correct instrumentation, such as layered gas and flame detection sensors for specific potential hazards.

This paper undertakes a comprehensive exploration of recent advancements in hydrogen safety, particularly the application of AI methodologies in evaluating potential safety scenarios, and the design of safety measures is considered. Against this backdrop, the integration of AI methodologies emerges as a transformative paradigm in augmenting H_2 safety measures. The H_2 safety issues are leakage detection, explosion risk mitigation, material compatibility assessment, optimization of storage systems, infrastructure development planning, dispersion behavior prediction, combustion characteristic analysis, public perception management, emergency response planning, and environmental impact assessment, as shown in Figure 1.

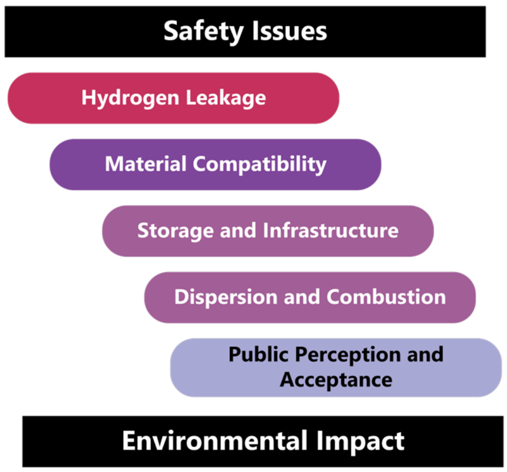

Figure 1. Hydrogen safety issues.

Leveraging ANNs, ML algorithms, CV, and data fusion techniques, as shown in Figure 2, AI promises to enhance detection capabilities, improve response times, and reduce false alarms across the H_2 value chain. These methods facilitate efficient data analysis, predictive modeling, risk assessment, and decision support. This review critically evaluates the efficacy of AI-driven approaches in real-time monitoring, hazard detection, and safety protocol optimization, offering insights into key challenges, opportunities, and future directions in the realm of hydrogen safety.

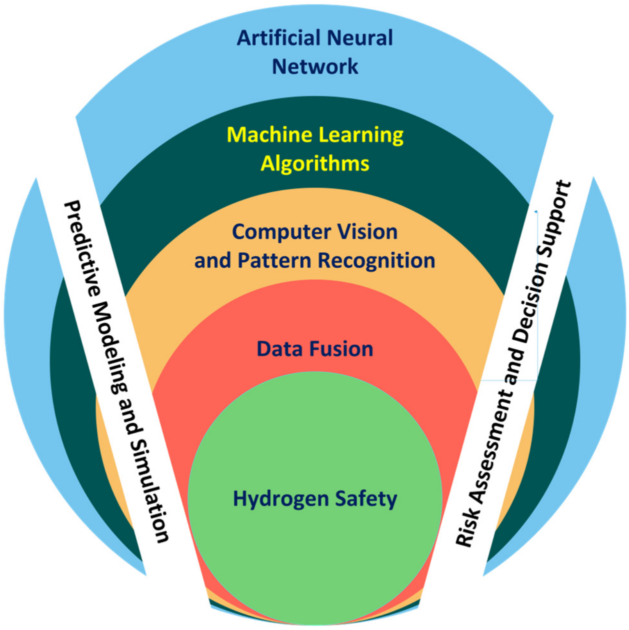

Figure 2. Digital techniques in hydrogen safety.

The need for a transition toward a sustainable hydrogen economy, the convergence of AI, and hydrogen safety represents a pivotal step toward realizing this vision. This fosters a safer, more resilient hydrogen ecosystem, paving the way for a cleaner, greener energy future. This work provides an understanding of the current landscape of hydrogen safety and identifies key opportunities and challenges for future research and development efforts in developing and implementing safety procedures in all areas of H_2 technology.

This paper is structured into six main sections. Section 1 introduces hydrogen energy and its associated safety concerns. Section 2 provides an in-depth review of state-of-the-art technologies in hydrogen safety, covering both conventional methods and advanced AI techniques such as ANN, ML, and CV. Section 3 presents various case studies and applications in hydrogen energy and safety. Section 4 offers a comparative analysis of these techniques for hydrogen safety research. Section 5 delves into safeguarding hydrogen through the integration of advances in materials, models, and storage techniques. Overall, Section 6 provides a discussion and conclusion, summarizing the key findings and outlining future research directions.

2. State-of-the-Art-Technologies in Hydrogen Safety

This section provides a comprehensive overview of the evolving landscape of hydrogen safety, encompassing both conventional methods and cutting-edge AI techniques. It delves into the traditional approaches like sensor-based detection systems, which have long been employed in hydrogen safety protocols. Additionally, it explores the integration of advanced AI methodologies, including ANNs, ML algorithms, and CV with pattern recognition, which offers the potential for real-time monitoring and proactive risk mitigation. By synthesizing insights from diverse sources, this section offers a holistic understanding of how traditional and innovative techniques converge to enhance safety measures in H_2-related applications. Despite promising progress, challenges persist in the field of hydrogen safety, emphasizing the necessity for ongoing research and development efforts. It sets a solid foundation for future research endeavors, providing valuable insights for stakeholders aiming to harness AI techniques for the advancement of H_2 leak detection systems, fostering a safer and more resilient energy landscape.

Figure 3 summarizes the distribution of research papers reviewed in this study by their publication year. It highlights the trend and growing interest in AI for hydrogen safety over time.

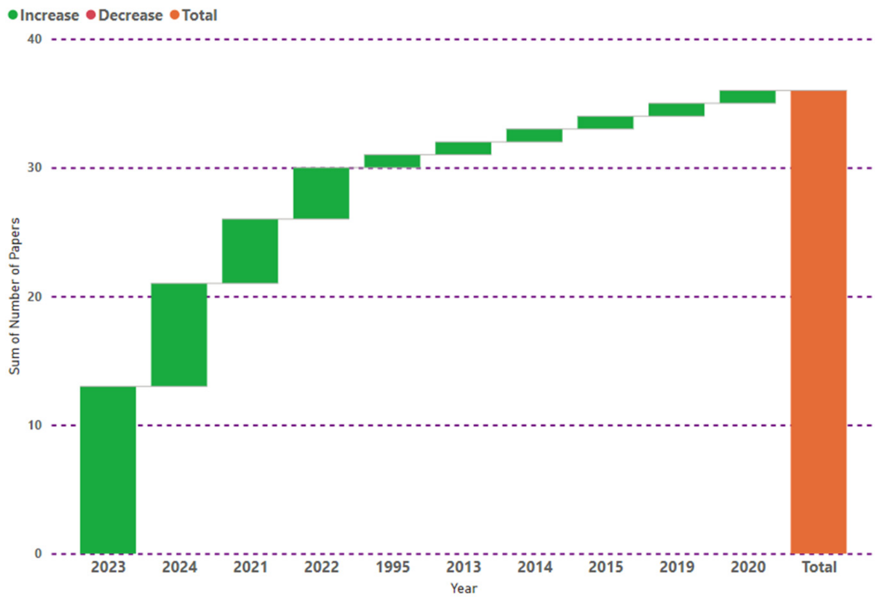

Figure 3. Articles considered over the year.

2.1. Conventional Techniques

In the realm of hydrogen safety, traditional experimental methods have long been employed to understand the complexities of H_2 leakage scenarios. Zhou et al. [9] conducted experimental research investigating the effects of ignition height on explosion characteristics within a 27 m^3 hydrogen/air cloud. Their study revealed a fascinating interplay of factors, demonstrating how variations in ignition height impact flame propagation velocity, oscillation frequency, and overpressure metrics. Additionally, a novel parameter, "t", was introduced to quantify buoyancy effects, shedding light on the intricate dynamics of gas explosions. This research underscores the significance of understanding ignition height dynamics in mitigating explosion risks, highlighting the importance of experimental approaches in comprehending hydrogen safety phenomena.

To gain a comprehensive understanding of hydrogen safety, it is crucial to explore the broader landscape of H_2 energy production and utilization. Tarhan and Çil [10] provided an insightful examination of H_2 energy as a sustainable solution amid mounting environmental concerns and energy demands. Their work elucidated various aspects of H_2 production, storage, and transportation, emphasizing its potential as a low-carbon energy source. Furthermore, the discussion extended to storage technologies like liquid organic hydrogen carriers (LOHCs) and solid-state systems, showcasing diverse applications in different sectors. By offering a comprehensive overview of H_2 energy, this study lays a robust foundation for understanding the critical role of leak detection in ensuring the safety and viability of hydrogen-based technologies.

In the domain of sensor technologies for H_2 leak detection, Baker [11] presented a hydrogen leak detection sensor database, offering technical specifications for various sensors, including the AppliedSensor Inc HLS-440. This resource provides essential details such as target gas concentration range, operating temperature, dimensions, and weight, facilitating informed decisions in sensor selection for hydrogen safety applications. Additionally, advancements in sensor technology have led to the development of innovative solutions like the H_2 IntelliSense Slim Hydrogen Sensor, employing solid-state electrochemical sensor technology for precise H_2 detection [12]. With features such as a broad sensing range, rapid response time, and versatile applications across industries, this sensor exemplifies the evolution of sensor technology in addressing hydrogen safety challenges.

Furthermore, addressing the challenging issue of pipeline leakage, Baroudi et al. [13] evaluated state-of-the-art leak detection systems (LDSs) and data fusion approaches to mitigate risks and protect the environment. Their comparative analysis underscored the importance of multiple LDSs for enhanced detection accuracy, emphasizing the need for rigorous data analysis and proper inputs. The study highlighted the role of historical data in predicting pipe deterioration, pointing towards future directions involving advanced technologies like ML and the Internet of Things (IoT) for improved pipeline safety. Additionally, Ramaiyan et al. [14] provided a comprehensive overview of recent developments in hydrogen sensor technology, emphasizing its crucial role in establishing a sustainable hydrogen economy. With a focus on applications such as leak detection and process monitoring throughout the supply chain, this review highlighted the significance of informed sensor selection for the effective implementation of H_2 energy solutions.

Table 1 summarizes relevant research investigating diverse techniques in hydrogen safety, displaying key findings and potential applications.

Table 1. Overview of Techniques and Applications.

Articles	Main Focus	Key Findings	Applications
Zhou et al. [9]	Impact of ignition height on explosion characteristics	Flame propagation velocity increases as ignition height decreases. Buoyancy effects intensify.	Understanding gas explosion dynamics
Tarhan and Çil [10]	Examination of H2 energy production and utilization	Emphasized hydrogen's potential as a low-carbon energy source. Explored storage technologies.	Energy production, transportation, storage
Baker [11]	H2 Leak Detection Sensor Database	Technical specifications of various sensors provided. Enhanced understanding of sensor selection.	Leak detection, safety monitoring
H2 IntelliSense Slim Hydrogen Sensor [12]	Innovative sensor technology for precise hydrogen detection	Broad sensing range, rapid response time, versatile applications across industries.	
Baroudi et al. [13]	Evaluation of leak detection systems for pipeline safety	Importance of multiple LDSs for enhanced detection accuracy. Future directions involving ML and IoT.	Pipeline safety, environmental protection
Ramaiyan et al. [14]	Overview of recent developments in hydrogen sensor technology	The crucial role of sensors in establishing a sustainable H2 economy.	Leak detection, process monitoring

2.2. Specific AI Techniques

2.2.1. Artificial Neural Networks (ANNs)

ANNs have emerged as a cornerstone in the realm of hydrogen safety, offering a versatile framework for detecting and mitigating potential risks associated with hydrogen leaks. These sophisticated computational models, inspired by the human brain's neural structure, have been extensively explored and refined to address various challenges in hydrogen safety. Hamdalla [15] delved into the realm of hydrogen detection using long-period fiber Bragg grating (LPFBG) coupled with ANNs, demonstrating their prowess in accurately predicting transmission power based on H_2 concentration. This innovative approach not only highlighted superior fitting to experimental data but also offered advantages in terms of computational time and flexibility, laying a solid foundation for rapid and effective hydrogen detection.

Furthermore, Kopbayev et al. [16] introduced a novel neural network model tailored for early detection and classification of natural gas leaks, highlighting remarkable accuracy without the need for fine-tuning. However, challenges persist, particularly in optimizing these models for shorter datasets and real-world scenarios. Bi et al. [17] proposed a hybrid CEEMDAN–CNN–LSTM model aimed at precise H_2 leakage localization in refueling stations. This cutting-edge approach, combining advanced algorithms with neural networks, yielded exceptional prediction performance, highlighting its potential for ensuring station safety. Zhao et al. [18] ventured into H_2 leak localization using ML techniques, demonstrating promising accuracy in predicting leak locations. Despite these advancements, further research is warranted to enhance accuracy and robustness, especially when applied to complex environments such as full-size garages. Additionally, Suzuki et al. [19] addressed the challenge of H_2 leakage from pipelines using unsupervised ML, highlighting its effectiveness in distinguishing between leakage and nonleakage conditions. Yang et al. [20] introduced a hybrid WD-KNN-CNN model for predicting hydrogen leakage in refueling stations (HRS), achieving 99.14% accuracy for leak location and 97.42% for intensity. Utilizing wavelet denoising and Bayesian optimization, it captures temporal data for fast, reliable predictions, suggesting a need for 14 monitoring points for effective management.

Moreover, He [21] introduced a physics-informed surrogate model for predicting hydrogen leak consequences, leveraging the power of neural networks to offer real-time risk warnings. Lastly, the development of an AI-enabled optical sensor for detecting low levels of H_2 by Swedish and Dutch researchers [22] marks a significant breakthrough, emphasizing the transformative potential of AI in ensuring safety across various sectors. These collective efforts, as shown in Table 2, underscore the pivotal role of ANNs in revolutionizing hydrogen safety, paving the way for a cleaner and safer energy future.

Table 2. Overview of Techniques and Applications.

Articles	Main Focus	Key Findings	Applications
Hamdalla [15]	H_2 detection using LPFBG and ANNs	Superior fitting to experimental data and efficient prediction of transmission power based on hydrogen concentration.	Rapid and effective H_2 detection
Alibek Kopbayev et al. [16]	Early detection and classification of gas leaks	High accuracy in predicting gas leakage and classifying its size using simulated concentration profiles.	Early detection and classification of natural gas leaks
Bi et al. [17]	Precise H_2 leakage localization	Proposed a hybrid CEEMDAN–CNN–LSTM model achieving exceptional prediction performance for H_2 leakage localization in refueling stations.	Ensuring station safety through precise H_2 leakage localization
Zhao et al. [18]	Hydrogen leak localization using ML	Promising accuracy in predicting leak locations, with potential applications in real scenarios and early warning systems for leaks in confined spaces.	Prediction of H_2 leak locations
Suzuki et al. [19]	Distinguishing between leakage and non-leakage	Distinguished between non leakage and leakage behaviors in hydrogen pipelines using unsupervised ML, contributing to sensor optimization during the process design stage.	Identification of leakage points in H_2 pipelines
He [21]	Predicting hydrogen leak consequences	Introduced a physics-informed ConvLSTM network for swift prediction of hydrogen concentration distribution following leakages, offering real-time risk warnings and improved computational efficiency.	Real-time prediction of H_2 leak consequences for risk management at hydrogen refueling stations
Swedish and Dutch researchers [22]	AI-enabled optical sensor for hydrogen detection	Developed an AI-enabled optical sensor capable of detecting low levels of H_2 with unprecedented sensitivity and enhanced safety in various sectors, including transportation and energy.	Detection of low levels of hydrogen for safety applications
WD-KNN-CNN Model [20]	Predicting hydrogen leakage location and intensity	Achieved high prediction accuracies of 99.14% for leak location and 97.42% for intensity level using wavelet denoising for data preprocessing and Bayesian optimization for hyperparameter optimization. Effectively captures temporal concentration information, enabling millisecond-level predictions, and addresses issues of delayed access to leak source information.	Provides a decision-making basis for on-site personnel to manage leakages in HRS.

2.2.2. Machine Learning Algorithms

ML algorithms emerge as a transformative tool, offering innovative solutions to mitigate risks associated with hydrogen leakage and optimize storage systems. El-Amin's research [23] delves into the complexities of H_2 dispersion prediction by employing ML algorithms on synthetic datasets, highlighting the effectiveness of random forest models in forecasting nanoparticle concentration. Building upon this foundation, El-Amin et al. [24] explore the turbulent flow of hydrogen buoyant jets, integrating ML techniques to predict H_2 concentration in the air. Their findings underscore the pivotal role of ML in understanding and predicting hydrogen leakage scenarios, with the random forest method demonstrating superior performance.

Davoodi et al. [25] extend the application of ML to optimize H_2 storage systems, displaying the efficacy of least squares support vector machines (LSSVM) in predicting hydrogen uptake by porous carbon media. Meanwhile, Shi et al. [26] focus on developing advanced sensing technologies for hydrogen leakage detection, leveraging ML models to estimate H_2 detection response for various nanocomposites. Their study emphasizes the reliability of ML-based mathematical models in automating hydrogen sensing processes.

The importance of ML in enhancing safety measures is further exemplified by research addressing real-world safety concerns. One such study [27] utilizes advanced analytics and ML models to predict physical phenomena during indoor H_2 releases, thereby improving safety protocols. Additionally, El-Amin et al. [28] employ a random forest ML approach to analyze turbulent buoyant jets and accurately predict hydrogen concentration distribution, contributing to safety enhancement efforts.

Furthermore, ML finds practical applications in real-time gas pipeline leak detection systems [29], quantitative risk assessment of liquid H_2 leaks from offshore platforms [30], and prediction of natural gas leakage levels in urban environments [31]. These studies underscore the versatility and efficacy of ML in addressing various safety challenges associated with hydrogen and natural gas handling. Overall, the integration of ML techniques represents a paradigm shift in hydrogen safety, offering unparalleled capabilities in predicting, detecting, and mitigating safety risks.

Table 3 provides a comprehensive overview of the ML techniques employed, along with key findings and their respective applications in enhancing safety and risk management in hydrogen-related scenarios.

Table 3. Various ML Techniques and Applications.

Articles	Machine Learning Techniques	Key Findings	Applications
El-Amin [23]	ANN, Random Forest, Gradient Boosting, Decision Trees	Random Forest outperforms in predicting H_2 dispersion. Dataset preparation and hyperparameter adjustments.	Mitigating safety risks associated with hydrogen leaks.
El-Amin et al. [24]	Linear Regression, ANN, SVM, k-NN, Random Forest	Random Forest excels in forecasting hydrogen concentration. Trained model helps in leak prediction.	Understanding and predicting hydrogen leakage scenarios.
Davoodi et al. [25]	GRNN (Recurrent Neural Network), LSSVM, ANFIS, ELM	LSSVM model demonstrates high accuracy in predicting PCM H_2-uptake. Pressure identified as influential variable.	Optimizing H_2 storage systems.
Shi et al. [26]	GEP, Support Vector Regression, ANN	MLPNN exhibits high accuracy in estimating HDR for SnO_2-based sensors. Mathematical models for HDR calculation.	Automating hydrogen sensing for nanocomposites.
Safety and Risk Management [27]	ML Models from HyTunnel project	Successful forecasting of physical phenomena during indoor H_2 releases. Analyzing large datasets for safety improvement.	Enhancing safety measures in H_2 handling.

Table 3. *Cont.*

Articles	Machine Learning Techniques	Key Findings	Applications
El-Amin et al. [28]	Random Forest	RF accurately predicts H_2 concentration distribution. Feature importance and hyperparameter tuning highlighted.	Analyzing turbulent buoyant jets for safety implications of hydrogen leakage.
Quy et al. [29]	k-NN	Real-time gas pipeline leak detection system demonstrates high classification accuracy. Feature exploration enhances performance.	Ensuring safety in real-world gas pipeline networks.
Kong et al. [30]	LSTM, Latin Hypercube Sampling, CFD	Quantitative risk assessment of liquid hydrogen leaks achieved using LSTM network. Proposed methodology meets ALARP criteria.	Predicting hazards during the filling process in offshore rocket launching platforms.
Dashdondov et al. [31]	XGBoost, KNN, DT, RF, NB, MLP	F-OE-XGBoost algorithm achieves high accuracy i.e., 95.14%, 95.75% F1-score, 0.028 MSE, and a 96.29% AUC) in predicting natural gas leakage levels. Success attributed to feature selection and clustering.	Early prediction of NG leakage levels and addressing concerns in urban NG distribution.

2.2.3. Computer Vision and Pattern Recognition

Computer vision plays a critical role in enhancing safety measures across various industrial domains, including hydrogen safety. These techniques leverage image analysis and processing algorithms, such as convolutional neural networks (CNNs) and region-based CNNs (R-CNNs), to interpret visual cues and patterns, enabling the detection of hazardous conditions such as gas leaks in real time. In the realm of hydrogen safety, CV techniques offer innovative solutions for early detection and monitoring, complementing traditional sensor-based approaches. This subsection delves into notable research endeavors harnessing computer vision and pattern recognition to mitigate risks associated with H_2 leaks and enhance safety protocols.

Jadin et al. [32] proposed a novel method utilizing infrared image analysis to detect gas leaks, offering a promising solution for identifying hazardous conditions in industrial environments. Their approach involves image filtering and segmentation to enhance and identify target regions of interest, contributing to the extraction and identification of leaky areas. Softweb Solutions' innovative approach [33] introduces an AI-powered leak detection system, leveraging CV techniques such as bidirectional CNNs, to enable real-time monitoring of pipeline integrity.

Additionally, Zhu et al. [34] addressed the challenges of subsea gas leak monitoring through a CV-based approach, demonstrating the potential for automatic and real-time detection of underwater gas leaks. Their study compares the performance of Faster R-CNN and YOLOv4 models with mathematical details supporting the efficacy of the faster R-CNN model in accurately classifying and locating gas plumes. Furthermore, Nooralishahi et al. [35] presented a drone-enabled gas leak detection technique, integrating video stabilization and optical flow analysis to enhance early detection capabilities. These research endeavors exemplify the diverse applications of computer vision and pattern recognition in augmenting hydrogen safety measures as given in Table 4, clearing the path for safer and more efficient hydrogen-related operations.

Table 4. Various CV Techniques and Applications.

Approach	Articles	Key Features	Applications
Infrared Image Analysis for Gas Leak Detection	Jadin et al. [32]	- Thermal imaging technology - Image filtering and segmentation - Classification of normal and abnormal conditions	- Industrial scenarios - Timely warnings for maintenance needs
AI-powered Leak Detection System	Softweb Solutions [33]	- Utilization of CV techniques - Integration of bidirectional CNNs - Data-driven approach for enhanced accuracy	- Real-time leak detection - Customization and remote access - Identification of small pipeline leaks
CV-Based Monitoring Approach	Zhu et al. [34]	- Adoption of faster R-CNN and YOLOv4 models with 1280×720 image size and no noise - Mathematical support for model performance	- Automatic and real-time detection of underwater leaks - Classification and location of gas plumes
Development of Gas Imaging Technologies	Nooralishahi et al. [35]	- Drone-enabled gas leak detection technique - Video stabilization and optical flow analysis	- Early detection of hazardous gas leaks - Gas flow visualization and detection

3. Case Studies and Applications

This section delves into practical applications of hydrogen safety technologies, showcasing their significance across diverse environments. These ensure safe hydrogen utilization across various domains such as industry, space, power, and transport sectors. Cutting-edge hydrogen leak detection systems offer rapid, multipoint monitoring and real-time leak data in order to safeguard critical environments.

Breakthroughs in low-cost distributed gas sensors offer cost-effective solutions for industrial settings and wireless sensor networks, spanning from fuel cells to environmental testing. Integrating gas leakage and fire detection into centralized networks enhances safety in buildings.

Advanced models utilizing CNNs enhance long-distance pipeline safety, while collaborative efforts enhance reliability and safety across hydrogen infrastructure. AI-based risk analysis optimizes transportation logistics, ensuring safety throughout the hydrogen value chain. With AI-enabled IoT solutions predicting the consequences of hazardous substance transportation and Arduino-based systems ensuring prompt mitigation of gas leaks, proactive measures are taken to safeguard lives and property in diverse environments. Table 5 gives the practical application details for hydrogen safety technologies.

Table 5. Real-world applications for hydrogen safety technologies.

Approach	Articles	Key Features	Applications
Hydrogen leak detection system for space shuttle	NASA Lewis Research Center, GenCorp Aerojet, Case Western Reserve University [36]	- Microfabricated hydrogen sensors developed for space shuttle applications	- Rapid, multipoint leak monitoring crucial for safety - Applications extend to diverse environments - Commercial system developed for the automotive industry detecting low hydrogen concentrations
Gencorp Aerojet automated hydrogen gas leak detection system	Gencorp Aerojet [37]	- Utilized palladium/Silver (PdAg) solid-state hydrogen sensors - Detects hydrogen concentrations from 1 to 4000 ppm - Allows operation of up to 128 sensors – Provides real-time data on leaks in pressurized systems	- Safety and quality control in industrial settings - Monitoring inert and combustible hydrogen mixtures - Adopted by Ford Motor Company for natural gas vehicle assembly lines

Table 5. *Cont.*

Approach	Articles	Key Features	Applications
Integration of gas leakage and fire detection systems	Salhi et al. [38]	- Integrates gas leakage and fire detection systems into a centralized Machine-to-Machine (M2M) network—Utilizes low-cost devices and ML for early prediction of risk incidents based on abnormal air state changes	- Enhancing safety in smart homes - Predicting danger levels in real-time
AI-based gas leak detection model for long-distance pipelines	Wang et al. [39]	- Utilizes CNNs for gas leak detection in long-distance pipelines - Effective detection without additional hardware requirements	- Detection of leaks in real transmission pipeline systems—Potential for applications in various industrial sectors
Collaborative efforts to enhance reliability and safety of hydrogen systems	Hartmann et al. [40]	- Quantitative data analysis of component leaks and failures using Prognosis and Health Management (PHM) and quantitative risk assessment (QRA) - Measurement of hydrogen leak rates with the leak rate quantification apparatus (LRQA)	- Improving system reliability and safety of hydrogen infrastructure - Supporting standards development for hydrogen technology
Breakthrough in hydrogen leak detection using low-cost distributed gas sensors	Element One, Inc. [41]	- Utilizes smart coatings with chemochromic materials for hydrogen leak detection - Offers cost-effective solutions for various applications - Provides current and historical leak information	- Industrial settings—Wireless sensor networks - Fuel cells, medical diagnostics, and environmental testing
AI-based risk analysis for hydrogen-fueled transportation	Aramix [42]	- Integrates traditional analysis methods with AI models for comprehensive risk analysis - Provides quantitative analysis and probabilistic information	- Ensuring safety throughout the hydrogen value chain in transportation - Optimizing planning and decision-making in logistics
Hydrogen leakage diagnosis methods for proton exchange membrane fuel cell (PEMFC) vehicles	Tian et al. [43]	- Recommends a combination of environmental hydrogen concentration, pressure decay, and model-based or data-driven methods for leakage diagnosis - Emphasizes the role of environmental hydrogen concentration and advanced diagnosis methods	- Diagnosis of hydrogen leakage in PEMFC vehicles - Ensuring safety in hydrogen-powered vehicles
CV approach for automating methane leak detection	Wang et al. [44]	- Introduces GasNet, a CNN-based CV approach for methane leak detection using Optical Gas Imaging (OGI) - Achieves high detection accuracy and excels at identifying large leaks in close proximity	- Automating methane leak detection - Environmental protection by addressing natural gas methane emissions
Chemochromic detector for H2 gas leaks during space shuttle fueling	Roberson et al. [45]	- Uses chemochromic pigments and polymer matrix for detecting and locating hydrogen leaks - Environmentally friendly and temperature-stable—Versatile applications in paint, tape, textiles, and Space Shuttle fueling	- Enhancing safety in hydrogen operations - Detection and localization of hydrogen leaks without power requirements

Table 5. *Cont.*

Approach	Articles	Key Features	Applications
Integration of gas sensor arrays (GSAs) with ML in electronic nose (E-nose) systems	Mahmood et al. [46]	- Reviews gas sensor arrays (GSAs) integrated with ML in electronic nose (E-nose) systems - Discusses fabrication technologies, operational frameworks, and signal preprocessing techniques - Addresses challenges and offers recommendations for future development	- Gas type determination and concentration estimation in various applications - Continuous real-time monitoring in medical, industrial, and environmental settings
AI-enabled IoT solution for disaster management in transporting hazardous substances	Dash et al. [47]	- Proposes an AI model for predicting consequences based on risk contours' diameter - Deploys at the edge of the IoT network for gas leakage detection during transportation - Prototype tested successfully at an LPG bottling plant	- Disaster management in transporting hazardous substances - Early detection and notification of gas leaks
Arduino-based system for gas leak detection	Parashar et al. [48]	- Utilizes an MQ6 gas sensor for detecting gas leaks in diverse settings - Automatically initiates precautionary measures upon detection - Enhanced with a Wi-Fi module for prompt user notification via SMS	- Preventing accidents and mitigating risks associated with gas leaks - Proactive measures for safety in various environments

4. Comparative Analysis

Table 6 presents a comprehensive analysis across different aspects of hydrogen safety research for leakage issues, providing insights into the research focus, approach, challenges, research gaps, and opportunities for further exploration and development in each area.

Table 6. Comprehensive analysis framework for hydrogen research.

Aspect	Approach	Challenges	Research Gaps	Opportunities for Further Research and Development
Conventional methods	Experimental methods, such as investigating ignition height dynamics, evaluating sensor technologies, and comparing leak detection systems.	- Limited scalability and applicability of experimental findings. - Difficulty in replicating real-world conditions in experiments. - Lack of standardization in experimental setups and methodologies.	- Standardization of experimental protocols and datasets. - Integration of experimental findings with computational models for comprehensive analysis.	- Development of advanced experimental setups to mimic real-world scenarios more accurately. - Collaboration between researchers and industry for standardized testing and validation.
Modeling with artificial neural networks	Deployment of ANNs for rapid and accurate H_2 detection, leak localization, risk analysis, and IoT solutions.	- Data scarcity and quality issues affecting model performance. - Complexity in optimizing models for diverse environmental conditions. - Interpretability and transparency of AI-driven decisions. - Overfitting and generalization challenges, especially for complex systems. - Computational complexity and resource requirements for training and inference.	- Development of standardized datasets and benchmarks for evaluating AI models. - Exploration of explainable AI techniques to enhance transparency and trust in AI-driven systems. - Exploration of transfer learning and semi-supervised techniques to mitigate data scarcity issues. - Development of lightweight ANN architectures for efficient deployment in resource-constrained environments.	- Integration of AI with sensor networks for real-time monitoring and response. - Investigation of federated learning approaches for collaborative model training without sharing sensitive data. - Investigation of hybrid models combining physics-based and data-driven approaches for improved accuracy and robustness. - Deployment of edge computing solutions for real-time ANN inference in IoT devices.

Table 6. *Cont.*

Aspect	Approach	Challenges	Research Gaps	Opportunities for Further Research and Development
Machine learning applications	Utilization of ML algorithms such as SVM, random forest, etc. for various applications in hydrogen safety, including dispersion prediction and leak detection.	- Model interpretability and explainability, especially for complex advanced ML models. - Bias and fairness concerns in dataset collection and model training. - Limited transferability of models across different environmental conditions.	- Development of interpretable ML models with transparent decision-making processes. - Exploration of adversarial robustness techniques to enhance model fairness and reliability.	- Investigation of multitasking and transfer learning approaches to improve model generalization across diverse environmental conditions. - Integration of human-in-the-loop methodologies for bias detection and mitigation.
Vision-based detection techniques	Application of CV techniques such as CNNs for automated leak detection and monitoring using image analysis.	- Limited availability of high-quality and annotated datasets for training leak detection models. - Challenges in adapting CV techniques to different lighting and environmental conditions. Real-time processing and inference constraints for embedded systems.	- Creation of large-scale annotated datasets specific to hydrogen leak detection scenarios. - Optimization of CV algorithms for real-time performance in resource-constrained environments.	- Development of novel sensor fusion techniques combining CV with other sensing modalities for improved leak detection accuracy. - Exploration of edge-based processing and inference solutions for real-time leak detection in IoT devices.
Real-world implementations	Demonstration of practical applications, including hydrogen leak detection systems, IoT solutions, and integration with fire detection systems for real-world safety.	- Integration and interoperability challenges when deploying safety systems in complex environments. - Scalability and cost considerations for widespread deployment. - User acceptance and adoption of AI-driven safety solutions.	- Development of interoperability standards and protocols for seamless integration of safety systems. - Cost reduction strategies for making safety technologies more accessible and affordable.	- Deployment of AI-driven safety systems in smart cities and industrial environments for comprehensive risk mitigation. - Collaboration with regulatory bodies and industry partners to establish safety standards and guidelines. - Continuous monitoring and evaluation of safety solutions for performance optimization

5. Safeguarding Hydrogen: Integrating Advances in Materials, Models, and Storage for Enhanced Safety

In the pursuit of hydrogen safety, a multidisciplinary approach is paramount, integrating advancements in materials, models, and storage methods to mitigate potential risks and ensure the safe utilization of this versatile energy carrier. Recent research efforts underscore the significance of comprehensive analyses in understanding hydrogen's role as a future fuel source.

Through meticulous examinations of hydrogen production methods, including the classification of hydrogen by color codes and evaluations based on cost, environmental impact, and technological maturity [49], researchers are delineating pathways toward safer and more sustainable hydrogen utilization. Additionally, the development of digital replicas (DRs) for proton exchange membrane electrolyzers (PEMELs) [50] represents a crucial advancement, enabling the simulation and validation of electrolysis processes, thereby enhancing efficiency and safety. Furthermore, the exploration of advanced materials in hydrogen production, as in [51], illuminates key considerations such as durability, stability, and scalability, essential for ensuring the integration of hydrogen into large-scale systems while mitigating potential hazards. As the hydrogen energy landscape continues to evolve, a proactive approach to safety, supported by innovative research and innovation, remains paramount for realizing its full potential as a sustainable energy solution.

6. Discussion and Conclusions

In conclusion, this comprehensive review underscores the transformative potential of integrating cutting-edge technologies into hydrogen safety measures for leakage issues. From traditional experimental methods to state-of-the-art AI techniques, the research landscape is vast and evolving, with each approach offering unique insights and solutions to address the complex challenges of hydrogen safety.

Through a thorough examination of literature, case studies, and real-world applications, this review has elucidated the critical role of artificial intelligence (AI), machine learning, computer vision, and sensor methodologies in enhancing leak detection, risk assessment, and safety protocols across diverse environments.

While significant progress has been made in leveraging these technologies, numerous challenges persist, including data scarcity, model optimization, and seamless integration into existing infrastructure. However, these challenges also present opportunities for further research and development, such as the creation of standardized datasets, advanced AI algorithms, and interdisciplinary collaborations. Also, current hydrogen leak detection technologies may have limitations in sensitivity, reliability, and response time, posing challenges in the timely identification and mitigation of leaks.

By synthesizing insights from various research domains, this review serves as a roadmap for researchers, engineers, and practitioners seeking to advance hydrogen safety technologies in leakage monitoring. It highlights the importance of continued innovation, collaboration, and investment in order to realize the vision of a cleaner, safer, and more sustainable hydrogen economy. Ultimately, by harnessing the power of technology and innovation, we can pave the way for a greener energy future while ensuring the safety and well-being of communities worldwide.

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Nomenclature

Terms	**Meaning**
AI	Artificial Intelligence
ANN	Artificial Neural Network
CNN	Convolutional Neural Network
RNN	Recurrent Neural Network
ML	Machine Learning
CV	Computer Vision
H2	Hydrogen gas
R&D	Research and Development
WSN	Wireless Sensor Network
IoT	Internet of Things
Leakage Detection	Identifying unintended releases of hydrogen
Explosion Risk Mitigation	Measures to reduce the potential for hydrogen explosions
Infrastructure Development Planning	Strategic planning for hydrogen infrastructure
Dispersion Behavior Prediction	Forecasting how hydrogen disperses in various environments
Combustion Characteristic Analysis	Studying how hydrogen burns under different conditions
Public Perception Management	Addressing public concerns and understanding about hydrogen safety
Emergency Response Planning	Preparing for and managing hydrogen-related emergencies
Environmental Impact Assessment	Evaluating the environmental effects of hydrogen use

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