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Worker Safety and Health in the Green Hydrogen Supply Chain: Impacts and Challenges in H_2V

Luiz Sérgio Nocrato Vidal[1] https://orcid.org/0009-0004-4499-3419; Josy Fonteles Ribeiro da Silva[2] https://orcid.org/0009-0001-2569-2619; Rickardo Léo Ramos Gomes[3] https://orcid.org/0000-0001-6101-9571;

[1] *Postgraduate in MBA in Renewable Energy Management (IEL/FBUNI);*
[2] *Postgraduate in MBA in Renewable Energy Management (IEL/FBUNI);*
[3]*Doctorate in Biological Sciences - FICL; Master's in Phytotechnics - Federal University of Ceará;*
Corresponding Author: Rickardo Léo Ramos Gomes

ABSTRACT
Green hydrogen (H2V) emerges as a promising alternative in the global energy transition scenario, standing out for its ability to reduce carbon emissions and promote sustainability. However, the H2V production chain, encompassing the stages of generation, transportation, storage, distribution, and utilization, presents significant challenges related to worker safety and health. These aspects are crucial to ensuring the feasibility and sustainability of operations in this expanding sector. This study adopted a qualitative approach to understand the impacts and challenges associated with worker safety and health in the green hydrogen (H2V) production chain. The overarching objective of this scientific article is to present the impacts of worker safety and health across the green hydrogen chain, including generation, transportation, storage, distribution, and utilization. Based on the data analyzed, it was possible to propose control measures, including risk mitigation strategies, continuous worker training, and the adoption of advanced technologies to improve occupational safety and health in the H2V chain. These measures aim not only to protect workers but also to ensure the sustainability of operations related to the production and utilization of green hydrogen.

***Keywords**: Green hydrogen; Control measures; Safety impacts; Worker health.*

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I. INTRODUCTION

The topic of green hydrogen has been gaining attention and prominence in the current global energy transition, as it represents a clean alternative for energy generation across electricity, industry, heating, and transportation sectors, replacing carbon-based fuels and contributing to sustainable development (Ribeiro et al., 2024).

In 2022, global hydrogen production reached approximately 90 million tons, marking a 3% increase compared to 2021. Of this total, around 62% was produced from natural gas through the steam methane reforming (SMR) process without carbon capture, 21% from coal gasification—predominantly in China—16% as by-products, and only 1% through water electrolysis (IEA, 2023).

Despite its modest share in global production, the International Energy Agency (IEA) highlights that the installed capacity and the number of announced projects for hydrogen production via water electrolysis have grown rapidly in recent years, reflecting a 30% increase compared to its 2022 report (IEA, 2023).

Green hydrogen, as a promising clean energy vector, demands a balance between its benefits and the risks associated with its production, storage, and transportation. Hydrogen is highly flammable and explosive, requiring specialized care to ensure safety and reliability in all related operations. Proper risk management is crucial to prevent accidents, given the inherent hazards of this gas. This underscores the need for a comprehensive, research-based approach to implement safe practices and mitigate risks posed by physical, chemical, mechanical, or ergonomic factors.

An examination of the available research reveals effective strategies and emerging technologies aimed at accident prevention in the green hydrogen sector, particularly regarding the control measures necessary to ensure safety throughout the entire process chain, including transportation, storage, and utilization of this clean energy source.

Addressing these aspects ensures that producers and transporters of green hydrogen prioritize the safety of workers involved in the process and the general public. Continuous development of safety technologies and practices is essential for fostering the safe acceptance and expansion of green hydrogen as an energy source.

Green hydrogen emerges as a promising alternative within the global energy matrix. However, its production, transportation, storage, distribution, and use present significant challenges in terms of worker safety and health.

This article is justified by the relevance of the topic and the necessity to examine the occupational risk impacts from both social and environmental perspectives across all stages of the green hydrogen process chain. The general objective of this scientific article is: To present the impacts on worker safety and health in the green hydrogen chain, encompassing generation, transportation, storage, distribution, and utilization. The specific objectives are as follows: - To examine the general aspects of green hydrogen production and provide an overview of worker safety and health impacts in the green hydrogen production chain (H_2V). - To evaluate occupational risks associated with the generation, transportation, storage, distribution, and use of green hydrogen. - To analyze accidents related to hydrogen use and compile data on accidents in activities correlated with H_2V risks. - To identify best practices and gaps in accident and disease prevention measures across the green hydrogen chain. - To describe safety and health control measures for workers and the general community, aiming for a favorable, safe, and healthy working environment.

This article is structured into four main sections. The Introduction presents the topic, the research's relevance, and its central objectives. The Methodology section details the qualitative approach adopted, as well as the bibliographic and documentary research procedures utilized. The Theoretical Framework discusses key concepts and studies related to worker safety and health in the green hydrogen chain, emphasizing the impacts and challenges identified in the scientific literature. Finally, the Conclusion synthesizes the study's main findings, highlights the importance of its conclusions, and outlines directions for future research on the topic.

II. MATERIAL AND METHODS

This study adopted a qualitative approach to understand the impacts and challenges related to worker safety and health in the green hydrogen (H_2V) chain. The research procedures involved bibliographic and documentary analysis, aimed at gathering and examining information from reliable and relevant sources on the subject. A total of 27 scientific works were selected, chosen based on the quality of the publications and the credibility of their authors, all of which specifically address the topic under discussion.

The bibliographic research encompassed scientific articles, books, and book chapters, while the documentary research included technical reports, regulations, and other institutional documents related to safety and health within the context of the H_2V chain.

The analysis of the selected works sought to identify the main aspects related to occupational safety and the challenges faced by workers involved in the green hydrogen production chain. The goal was to contribute to the development of safer and more sustainable practices in the sector.

III. THEORETICAL FRAMEWORK

This theoretical framework was organized into four subtopics, focusing on worker protection. The first subtopic addressed the general aspects of H_2V production, exploring how operations in the green hydrogen chain influence worker safety and health. The second subtopic examined the risk factors associated with the operations carried out in the H_2V production chain. The third subtopic focused on accidents involving hydrogen, presenting a survey of incidents related to high-risk activities similar to those in the H_2V sector. Finally, the fourth subtopic discussed how such impacts can be mitigated to foster a favorable, safe, and healthy working environment.

This section highlighted the importance of continuous worker training and the adoption of control measures to ensure workplace and process safety. Additionally, it showcased examples of international best practices that can be adapted to the Brazilian context, emphasizing the potential for reducing accidents and improving operational efficiency.

3.1 General Aspects of Green Hydrogen and the Influence of Operations in the H2V Production Chain on Worker Safety and Health

The role of green hydrogen within the European Commission's strategy to reduce greenhouse gas (GHG) emissions and decarbonize the economy will be decisive. The objective of all stakeholders in the green hydrogen industry (operators, users, regulators, insurers) is to achieve the highest safety standards, both in terms of design and engineering as well as operations and maintenance, ensuring that accidents in facilities are minimized and, consequently, operational and business continuity is maintained (Delgado, Remesal, González, 2024).

By its nature, hydrogen, like other fuels, poses risks to workers' health. This is primarily because the gas is odorless, colorless, and tasteless, making leaks undetectable by human senses. Safety is one of the primary concerns when handling hydrogen (Blog Itaipu Parquetec, 2024).

Hydrogen is a very small molecule with low viscosity, making it prone to leaks. It has a low density, being approximately 14 times lighter than air and about 8 times lighter than natural gas. This characteristic enables rapid dispersion in open spaces, where hydrogen tends to rise quickly and dissipate into the air. Conversely, in enclosed spaces, gas accumulation can easily reach flammable concentrations, ranging from 4% to 75% in air, a much wider range than that of natural gas, which spans from 5% to 15%. This makes hydrogen highly flammable and renders combustion control more challenging (Hydrogen Tools, 2022).

The explosion potential of hydrogen is significantly higher than that of methane, as at higher concentrations in air (above 20%), the flame speed of hydrogen is considerably faster than that of methane. Furthermore, hydrogen-air mixtures can lead to detonation, a phenomenon not observed with methane (DNV, 2022).

The entire hydrogen value chain, from production to end-use, requires robust infrastructure due to its physical properties, such as low energy density, high flammability, and the potential for material embrittlement. This necessitates the development of technologies that combine cost reduction and increased energy efficiency with safe infrastructure.

According to Fonseca (2023), an important aspect to consider in projects involving hydrogen is the structural integrity of equipment and the potential effects and reactions that may occur. Liquid or gaseous hydrogen in contact with metals, such as in pipelines or storage tanks, can react and cause material degradation. The main issues include hydrogen embrittlement, hydrogen-induced cracking, and high-temperature hydrogen attack (Li et al., 2022).

Given the dangers and risks associated with hydrogen, tools and software are employed to simplify and standardize the methodologies used in quantitative risk analysis (QRA) across the hydrogen value chain (Marchi et al., 2017). It can be observed and concluded that the application of these tools to identify, assess, and manage risks in green hydrogen facilities enables the design of intrinsically safe installations and the identification and evaluation of risks (there is no zero-risk scenario) (Delgado, Remesal, González, 2024).

Therefore, worker safety in the H2V production chain is a fundamental pillar for the success and sustainability of this sector. The rigorous implementation of safety standards, investment in adequate training, and the adoption of effective process safety systems are indispensable measures to ensure a safe and healthy work environment, minimizing risks and promoting the well-being of the professionals involved.

3.2 Risk Factors Associated with Operations in the H2V Production Chain

The starting point for ensuring a safe working environment is identifying the risk factors present. These can include: - Physical factors, such as intense noise, vibrations, extreme temperatures, and radiation. - Chemical factors, like exposure to toxic or corrosive substances. - Biological factors, such as contact with pathogenic agents. - Ergonomic factors, related to improper postures and repetitive movements. - Safety factors, including explosions, fires, unguarded machinery, defective electrical installations, and inadequate working conditions. Recognizing these hazards allows the implementation of preventive measures to minimize risks and protect the health and physical integrity of workers. For a deeper understanding, it is essential to define the term 'risk.' According to the ABNT ISO 31000 standard, risk is the effect of uncertainty on objectives. In other words, it is the possibility that a future event may hinder goal achievement, whether in financial, safety, environmental, or other contexts (ABNT, 2023).

Risk can be characterized by two interconnected dimensions:

- Probability of occurrence: The likelihood of an adverse event happening. This probability can be estimated based on historical data, statistical analyses, and contextual knowledge (ABNT, 2023). - Severity or magnitude: The extent of the damage or losses that could result from the event, considering its financial, environmental, social, and safety impacts (ABNT, 2023).

In summary, risk is a combination of the probability of an event occurring and the magnitude of its consequences. By quantifying these two dimensions, it is possible to evaluate the level of risk associated with each threat and take appropriate mitigation measures. It is also crucial to understand the definitions of accident, incident, and near miss.

According to ANP Resolution No. 882/2022 (Brazil, 2022), three key terms are defined in the field of operational safety:

- Accident: An event causing concrete damages, such as pollution, injuries, material losses, or operational disruptions (Brazil, 2022).
- Near miss: An event that could have caused harm but, for some reason, did not result in severe consequences (Brazil, 2022).
- Incident A broader term encompassing both accidents and near misses. Any occurrence that causes or could cause harm is considered an incident (Brazil, 2022).

In summary: - Accident: Actual damage. - Near miss: Potential for damage. - Incident: Covers both actual and potential damage (Brazil, 2022).

Classifying an event as an accident, near miss, or incident is important for:

- Risk analysis: Identifying and assessing risks in operations (Brazil, 2022).

- Cause investigation: Understanding the underlying factors that led to the event and implementing preventive measures (Brazil, 2022).

- Continuous improvement Supporting the adoption of measures to prevent future occurrences (Brazil, 2022).

By clearly defining these terms, ANP Resolution No. 882/2022 aims to promote a stronger safety culture within the regulated sector (Brazil, 2022). The Ministry of Labor and Employment's Ordinance No. 3,214/1978 classifies occupational risks into five major groups, based on the nature of the causal agent:

Table 1 – Occupational Risks

Type of Risk	Description	Examples	Possible Consequences
Physical	Related to physical agents present in the workplace.	Noise, vibration, extreme temperature, radiation, humidity.	Hearing loss, respiratory diseases, burns, cancer.
Chemical	Resulting from exposure to chemical substances.	Dust, gases, vapors, fumes, mists.	Respiratory diseases, dermatitis, intoxication.
Biological	Associated with exposure to biological agents.	Bacteria, venomous animals, viruses, fungi, parasites.	Infectious diseases, allergies.
Ergonomic	Related to poor adaptation of tasks to workers' psychophysiological characteristics.	Inadequate postures, repetitive movements, weight lifting.	Musculoskeletal disorders, RSI/WMSD, stress.
Accidents	Resulting from unsafe workplace conditions or process safety systems.	Explosions, falls, collisions, fires, cuts, electrical shocks.	Injuries, fractures, burns, amputations, deaths.

Source: Researchers' Data from Ordinance No. 3,214/1978 (Brazil, 2022).

Hydrogen, with its potential as a clean energy source, has gained prominence in discussions about energy transition. However, the handling of this gas requires special precautions due to the inherent risks. Classifying these risks is essential to ensure safety in operations involving hydrogen. A widely used tool to classify chemicals based on their risks is the Hommel diagram, developed by the National Fire Protection Association (NFPA).

This diagram assigns numerical values to health risks, flammability, reactivity, and special risks. In the case of hydrogen, the original classification by the NFPA significantly underestimated the hazards associated with this gas.

Recent studies, such as those by Soriano et al. (2024), have shown that hydrogen presents higher health risks than initially classified. Additionally, the corrosive nature of hydrogen, which can weaken materials, was not accounted for in the original classification. In light of these new findings, the authors proposed a more accurate reclassification of hydrogen to reflect its true level of hazard.

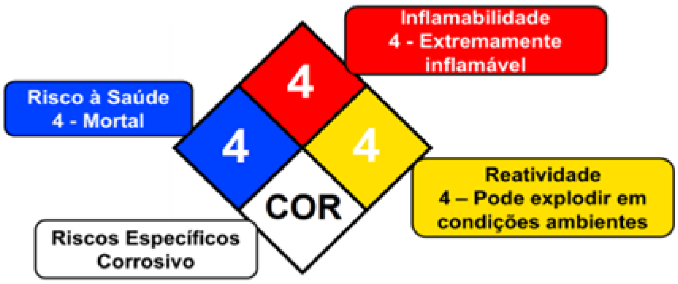
The National Fire Protection Association (NFPA)—an international organization dedicated to reducing injuries, fatalities, and material and economic losses due to fires—describes the risks of hydrogen using the Hommel color-coded diamond, where the risks are classified from 0 (minimal risk) to 4 (maximum risk). The colors in the diagram represent: flammability (red), health risks (blue), reactivity (yellow), and special information (white). See Figure 1.

Figure 1: Risk diagram for hydrogen

Source: NFPA (2023)

The new classification, presented in Figure 2, assigns higher values to the health and reactivity risks of hydrogen, in addition to including a specific risk related to its corrosivity. This reclassification is crucial to ensure that the safety measures implemented in hydrogen operations are adequate to the actual risks.

Figure 2: Hommel diagram for hydrogen.



Source: Soriano et al. (2024)

The new classification of hydrogen in the Hommel diagram, proposed by Soriano et al. (2024), is as follows:

- Blue (Health): Level 4, indicating lethal risk upon short exposure. Hydrogen can cause asphyxiation by displacing oxygen (CRRQ, 2023).

- Red (Flammability): Level 4, indicating high and extreme flammability. Hydrogen forms explosive mixtures with air (CRRQ, 2023).

- Yellow (Reactivity): Level 4, indicating high and extreme reactivity. Mixtures of hydrogen with air can detonate (CRRQ, 2023).

- White (Special Risks): COR symbol, indicating corrosivity (CRRQ, 2023).

Hydrogen weakens metals, especially at high temperatures and pressures. This extreme classification reflects the dangers associated with hydrogen and the need for special precautions in its handling and storage. It is important to emphasize that risk classification is an essential tool for safety management in any activity involving chemical substances.

In the case of hydrogen, the reclassification proposed by Soriano et al. (2024) represents a significant advancement toward a more accurate assessment of the risks associated with this gas and contributes to the development of safer practices in its handling and storage. Within the production stage and as part of the H_2V (green hydrogen) value chain, we have Proton Exchange Membrane (PEM) electrolysis, a variant of water electrolysis that uses a proton exchange membrane as a separator between the electrodes to produce hydrogen. This technology is especially valued for its efficiency under moderate temperature and pressure conditions, contributing to safer and more controllable operation compared to other electrolysis methods (Lange, 2024).

It is essential that the production of green hydrogen through PEM electrolysis be conducted with meticulous planning and constant monitoring, aiming to maximize environmental benefits and minimize operational risks. In process safety, within a dynamic industrial environment, accident and incident prevention is crucial. The implementation of effective safety measures, involving the identification and control of risks in production processes, is essential to protect the health and physical integrity of workers, as well as to avoid financial losses and damage to the company's reputation (Bolanho; Gotti, 2019).

3.3 Accidents Involving Hydrogen Use

Over time, the use of hydrogen has been marked by several incidents that have highlighted the imperative need for robust safety protocols in all stages of its use, from production to final application. One of the most tragic episodes associated with hydrogen in aviation history is the explosion of the Hindenburg airship in 1937. The combination of factors such as a hydrogen leak, adverse weather conditions that generated static electricity, and the high flammability of the gas resulted in a catastrophic fire during the attempted landing in New Jersey. The rapid spread of flames, fueled by the airship's outer structure, caused the death of dozens of people, marking a turning point in the history of air transportation (Aeroflap, 2022).

A more recent occurrence involved an explosion at a hydrogen fueling station in Norway, which led to the temporary suspension of hydrogen-powered vehicle sales by Toyota and Hyundai in the country. The incident, which took place at an Uno-X network station, left two people injured and caused the shutdown of the hydrogen fueling network. The causes of the explosion are still under investigation.

In response, Toyota and Hyundai halted the sales of their fuel cell models, offering loaner vehicles to customers while the situation was being addressed. Despite the incident, the companies assert that they remain confident in hydrogen technology and that hydrogen-powered vehicles are safe. However, the explosion reignited the debate about the safety and viability of hydrogen vehicles as an alternative to battery-electric vehicles. The incident raises questions about the safety of hydrogen fueling infrastructure and consumer trust in this technology (Lambert, 2019).

3.4 Control Measures to Mitigate Impacts and Promote a Favorable, Safe, and Healthy Work Environment in Green Hydrogen (H_2V) Production

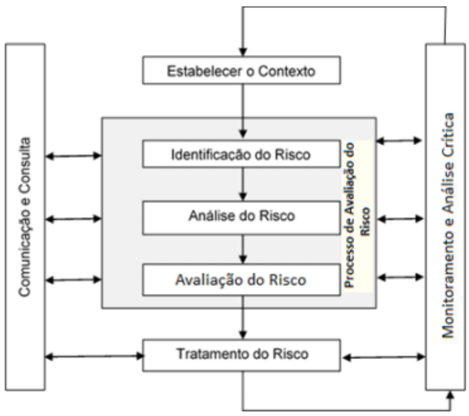
Risk management, as outlined by the PMBOK, aims to identify, analyze, and proactively respond to factors that may affect the success of a project. "By quantifying and qualifying risks, it is possible to maximize opportunities and minimize threats, ensuring the delivery of the project within the defined timeline, budget, and scope" (PMBOK, 2019, p. 319).

Occupational risk management is essential to prevent accidents, illnesses, and financial losses within organizations. By identifying and controlling hazards in the workplace, companies ensure the health and safety of their employees, optimize their processes, and strengthen their reputation. Risk analysis is a proactive process that aims to identify and assess hazards before adverse events occur. By mapping potential risk scenarios, organizations can develop contingency plans and implement safety measures to mitigate negative impacts. This approach allows companies to operate more safely and efficiently, reducing exposure to risks and increasing the reliability of their processes (CCPS, 2017).

The Regulatory Standard NR1 emphasizes the importance of Preliminary Risk Analysis (APR) as a tool for identifying and controlling risks in workplace environments. The APR, typically conducted at the start of a project, uses techniques such as checklist analysis and risk matrix development to assess the likelihood and severity of adverse events. This proactive approach contributes to the prevention of accidents and occupational diseases (Sherique, 2015).

ISO 31.000 (2018) advocates for the integration of the Risk Management Process (PGR) at all levels of the organization, from strategy to project execution. This integration is crucial for effective business management as it enables more assertive decision-making aligned with strategic objectives. As illustrated in Figure 3, the PGR involves an iterative cycle of five stages, which are continuously and adaptively applied to the organizational context (ABNT, 2023).

Figure 3: Risk management process diagram from ISO 31000 standard.



Source: ABNT (2023)

Another tool that has a significant impact on risk investigation and mitigation is HAZOP. Developed from the critical examination of processes, HAZOP (Hazard and Operability Study) is a robust tool for risk analysis in industrial processes.
This methodology, widely used in sectors such as petrochemicals and oil and gas, aims to identify potential deviations from design intentions that may compromise the safety and operability of a facility (Andrade, 2018).

By applying HAZOP, organizations can take preventive measures to minimize risks and ensure the integrity of processes. In a relevant study, "Green Hydrogen and Power-to-X Market: Demand for Professional Capacitation," developed by the National Service for Industrial Learning (SENAI), it is highlighted that Brazil has enormous potential to stand out as one of the world's leading producers and exporters of green hydrogen (H_2V). However, to operate in this global market, it is essential that professionals in this emerging industry possess comprehensive knowledge of the overall energy sector structure, its market and regulatory framework, computational tools, and data analytics capabilities. Furthermore, it is crucial that professionals acquire specific skills and competencies, such as knowledge of H_2 electrolysis and combustion technologies, operational safety, and management of H_2 infrastructure projects (Castro; Leal; Bruno, 2023).

To prevent and mitigate risks, the following additional suggestions are offered to complement the previous measures, covering everything from process control to administrative aspects. These measures aim to ensure the safe operation of a green hydrogen production plant:

1. Change Management: - Safe Work Procedures (PTS): Develop detailed PTS for each task, including specific safety measures. - Work Permits: Implement a work permit system for high-risk activities. - Job Safety Analysis (JSA): Conduct JSAs to identify hazards and associated controls for each task (Ringdahl, 2001).

2. Training and Awareness: - Simulations: Regularly conduct emergency simulations to train the team in incident response procedures. - Safety Training: Provide specific training on hydrogen risks and safety measures to be adopted. - Communication: Establish effective communication channels to inform and engage all employees in safety programs.

3. Monitoring and Evaluation: - Performance Indicators: Define performance indicators to monitor the effectiveness of safety measures. - Audits: Conduct regular audits to verify compliance with safety norms and procedures. - Root Cause Analysis: Investigate incidents and accidents to identify root causes and implement corrective measures.

4. Safety Culture (Lima; Silva, 2004): - Leadership: Promote a strong safety culture with involvement from top management. - Incentives: Implement recognition and incentive programs for safe behaviors. - Innovation: Encourage employee participation in identifying new ideas to improve safety.

5. Remote Monitoring: Use remote monitoring systems to track equipment performance and detect anomalies in real-time.

6. Artificial Intelligence: Employ AI algorithms to analyze data and identify patterns that may indicate potential risks.

7. Virtual Reality: Use virtual reality to simulate emergency situations and train employees more effectively.

8. Robotics: Employ robots to perform hazardous tasks or operate in hard-to-reach environments. By implementing these additional measures, the green hydrogen production chain can achieve an even higher level of safety and reliability.

It is important to emphasize that the selection of the most appropriate measures will depend on the specific characteristics of each facility and the risks involved. Therefore, it is recommended that safety measures be reviewed and updated periodically to ensure they remain effective.

IV. DISCUSSION AND CONCLUSION

This study aimed to present the impacts of worker safety and health in the green hydrogen (H_2V) value chain, covering the stages of generation, transportation, storage, distribution, and utilization. To achieve this objective, general aspects of green hydrogen production, occupational risks associated with its operations, accidents involving hydrogen use, as well as best practices and gaps related to accident and disease prevention measures in the H_2V production chain were investigated.

The research revealed that operations involved in the green hydrogen value chain present several risk factors that can directly impact the safety and health of workers. Among the challenges identified, the chemical and physical risks inherent to the activities stand out, in addition to the need for increased awareness and training to mitigate incidents.

Accidents in related activities were analyzed, and gaps in preventive policies and practices were identified, emphasizing the importance of proper control measures to promote a safe and healthy work environment. Based on the analyzed data, control measures were proposed, including risk mitigation strategies, continuous worker training, and the adoption of advanced technologies to enhance occupational safety and health in the H_2V value chain. These measures aim not only to protect workers but also to ensure the sustainability of operations related to the production and use of green hydrogen.

It is concluded that the study fully achieved its proposed objectives, contributing to the discussion on the impacts of safety and health in the green hydrogen value chain and providing insights for the development of safer practices in this strategic sector.

As a recommendation for future research, it is suggested to explore technological advancements and innovations in safety systems, as well as investigate public policies and specific regulations for green hydrogen, aiming to strengthen the safety culture and occupational health in this promising segment.

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