

Review Article

# An Overview of Hazard Identification and Risk Assessment in Industrial Safety (2015–2025): A Narrative Review

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## ABSTRACT

**Background:** Hazard identification and risk assessment (HIRA) is a key element in occupational health and safety (OHS) and industrial safety systems, particularly in high-risk industrial sectors with complex processes and dynamic operations. Over the past decade, various methodological developments have been proposed, but their application remains scattered and not optimally integrated. **Objective:** This narrative review aims to synthesize and critically examine research findings related to the application of HIRA and risk assessment methods in the context of occupational and industrial safety and health. **Methods:** This study employed a narrative-review approach. A structured literature search was conducted through the ScienceDirect database for articles published between 2015 and 2025 via a combination of keywords related to hazard identification, risk assessment, occupational safety, and the industrial context. From the 2,093 publications obtained in the initial stage, a multistep screening process was conducted based on relevance, inclusion criteria, full-text evaluation, and conceptual assessment, ultimately yielding 15 core articles for the qualitative synthesis. **Results:** The synthesis results revealed that the methodological depth of HIRA implementation significantly impacts the quality of OHS decision-making support. Hybrid methods (e.g., fuzzy Bayesian networks integrated with HFACS) demonstrated 15–30% higher accuracy in hazard prioritization than standalone qualitative matrices did. The effectiveness of the method is highly dependent on the system complexity, hazard characteristics, and maturity level of the organization. **Conclusion:** This narrative review demonstrates a paradigm shift from HIRA as an administrative obligation to HIRA as a strategic, risk-based tool to support OHS decision-making. An adaptive, integrated, and decision-oriented risk assessment approach provides a stronger foundation for developing an effective and sustainable safety management system.

## KEYWORDS

Hazard identification;  
risk assessment;  
occupational health;  
industrial safety;  
public safety;  
Public health

## ARTICLE INFO

Received Jan 08, 2026

Revised Jan 22, 2026

Accepted Jan 23, 2026

Online Jan 27, 2026

## EDITOR

Dr. Budi Utomo, dr.,  
M.Kes.

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## CITE THIS ARTICLE

Aini N., Berliana R., and Badriyah L. (2025). An overview of hazard identification and risk assessment in industrial safety (2015–2025): A narrative review. *Svāsthya: Trends in General Medicine and Public Health*, 2(6): e154. <https://doi.org/10.70347/svsthy.v2i6.154>.



Supplemental data for this article can be accessed online at <https://doi.org/10.70347/svsthy.v2i6.154>

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## INTRODUCTION

Hazard identification and risk assessment (HIRA) is a fundamental element in occupational health and safety (OHS) and industrial safety systems, as it is directly related to worker health protection, public safety, and environmental sustainability [1,2]. In high-risk industries such as chemical, oil and gas, mining, manufacturing, energy generation, and construction, inaccuracies in hazard identification and risk assessment processes have been shown to play a significant role in workplace accidents, occupational diseases, large-scale industrial incidents, and the health impacts experienced by communities surrounding industrial areas [3–7].

Historically, HIRA implementation has relied heavily on qualitative and semiquantitative methods, including risk matrices, checklists, and job safety analysis [8,9]. These approaches were chosen because they are relatively easy to implement, easily understood by various stakeholders, and aligned with regulatory requirements and organizational policies. However, conventional risk assessment methods often face various limitations, such as high assessor subjectivity, limited accuracy, and inconsistencies in risk rankings, particularly when used by different assessors or in complex work environments [10,11]. Therefore, while traditional HIRA methods are still relevant in the initial stages of hazard identification and compliance, their ability to produce precise risk estimates and support comprehensive decision-making remains limited [12].

Furthermore, recent research indicates that conventional risk assessment practices do not fully capture the dynamic and sociotechnical nature of modern industrial systems [13,14]. A study Hunt et al. [15] revealed that workshop-based and focus group risk assessments are potentially influenced by cognitive biases, organizational pressures, and a tendency to reach consensus, which can ultimately lead to the neglect or normalization of important hazards. As industrial operations become more complex, involving human–technology interactions, the use of digital systems, and rapidly changing working conditions, these biases further reduce the effectiveness of traditional HIRA approaches in managing uncertainty, emerging risks, and hidden safety threats [16–18]. This underscores the need for a more systematic, transparent, and analytically robust risk assessment approach [19–21].

Over the past decade, studies in the fields of occupational safety, health, and industrial safety have shown an increasing use of sophisticated analytical methods and decision-support technologies [22–24]. Approaches such as Bayesian networks, fuzzy logic, multicriteria decision-making (MCDM), artificial intelligence, and data-driven analysis have been developed to improve predictive accuracy, minimize subjectivity, and integrate technical and human factors more comprehensively [25–29]. Three critical gaps persist: (1) the lack of cross-industry validation frameworks, (2) the limited integration of real-time operational data into HIRA systems, and (3) the absence of standardized metrics to evaluate HIRA effectiveness for long-term safety performance, resulting in limited application in occupational safety and public safety.

On the basis of these conditions, this study presents a narrative review of reputable scientific articles published between 2015 and 2025 to synthesize and integrate findings related to hazard identification and risk assessment in the context of occupational, health, and industrial safety. This review addresses the following questions: (1) What methodological advances have improved HIRA effectiveness? (2) How do hybrid approaches compare with traditional methods in complex systems? (3) What barriers limit the integration of HIRA into organizational decision-making? This review aims to identify key research themes, evaluate methodological trends, and highlight relevant research gaps as a basis for developing a more adaptive, systems-based, and safety-oriented HIRA approach.

## MATERIALS AND METHODS

### *Database and search strategy*

This narrative review was conducted via a structured and transparent approach to support clarity in the process of identifying, screening, and reporting the literature without eliminating the flexibility that is a key characteristic of narrative synthesis [30]. To maintain uniform indexing quality and publication standards, the literature search was conducted exclusively through the ScienceDirect database, which has extensive coverage of reputable journals in the fields of

occupational safety and health (OHS), industrial engineering and risk management. Although ScienceDirect ensures indexing consistency, this single-database approach may exclude relevant works in Scopus, Web of Science, or PubMed. To mitigate this, citation snowballing was performed on the 15 core articles to capture the missed studies.

The literature search strategy used a combination of keywords and Boolean operators as follows: (“hazard identification” OR “hazard analysis”) AND (“risk assessment” OR “risk management”) AND (“occupational safety” OR “industrial safety”) AND industry. The search was limited to English-language journal articles published between 2015 and 2025 and available in full text. Nonjournal publications, such as conference proceedings, editorials, and book chapters, were excluded to maintain the methodological rigor of the studies included.

### **Inclusion and exclusion criteria**

Studies were included if they (1) applied HIRA or risk assessment in industrial settings, (2) used empirical data or case studies, and (3) reported outcomes relevant to safety decision-making. Conceptual papers without applications, studies limited to safety culture surveys, and articles without clear methodology descriptions were excluded. Methodological quality was assessed via a modified CASP checklist focusing on (1) the clarity of the research objectives, (2) the appropriateness of the study design, (3) the transparency of the data analysis, and (4) the applicability of the findings to practice. Studies with scores less than 60% were excluded.

### **Screening and eligibility**

In a stepwise manner, the initial literature search yielded 2,093 publications, which, after screening on the basis of year of publication, article type, field of study, and availability of access, left 300 publications for title and abstract review; of these, 173 articles were excluded owing to irrelevance, resulting in 127 articles being evaluated through full-text review, with 7 articles excluded owing to low methodological quality and nonconformity to inclusion criteria, resulting in 122 studies for initial qualitative analysis, which were further narrowed down through further conceptual screening to 15 core articles as the basis for the final narrative synthesis.

All publications obtained from the initial search were subjected to a multistep screening process. In the first stage, duplicates were removed, and titles and abstracts were reviewed to assess their relevance to the study focus. Articles that did not address hazard identification, risk assessment, or safety management in an industrial or occupational safety context were excluded from the review. Articles that passed this stage were then evaluated through a full-text review, considering compliance with the inclusion criteria, clarity of the methodological approach, and contribution to OHS decision-making. Articles were excluded at this stage if they were of low methodological quality or did not align with the conceptual scope of this narrative review.

## **RESULTS**

### **Overview of the included studies**

The initial literature search yielded 2,093 publications, demonstrating the broad spectrum of research related to the topic. The literature selection process was conducted in a step-by-step and transparent manner. After the initial screening was based on the publication year (2015–2025), article category, field of study, and availability of full-text access, 300 publications were retained for the title and abstract screening stage. At this stage, 173 publications were excluded because of their inadequate relevance to the study focus, either in terms of context, variables studied, or research objectives. The 127 articles that passed the screening stage were evaluated through a full-text review. This evaluation focused on the methodological suitability and conceptual relevance of the objectives of the narrative review. The evaluation resulted in 7 articles being excluded: 5 with low methodological quality and 2 that did not meet the inclusion criteria. A total of 122 studies were included in the initial qualitative analysis.

To ensure a thorough and coherent synthesis, further conceptual screening of the studies was conducted. At this stage, 107 articles were excluded because of overlapping focuses, limited conceptual contributions, or solely descriptive findings without strong theoretical or practical

implications. This process resulted in 15 core articles deemed the most representative and relevant for the final narrative synthesis. The final 15 articles represented all three thematic clusters (HIRA applications, methodological comparisons, and integrated frameworks) and covered major industrial sectors (chemical, oil and gas, mining, and manufacturing), achieving thematic saturation, where additional articles yielded no new conceptual insights.

Geographically, the majority of the analyzed studies originated from Asia ( $n = 8$ ), followed by Europe ( $n=5$ ) and other regions, such as the Americas and transnational regions ( $n = 2$ ). This pattern demonstrates the dominance of research contributions from regions with high levels of industrial activity and occupational safety system development while also reflecting the increasing attention given to safety and risk assessment issues in both developing and developed countries. On the basis of the focus of the safety approach, the synthesized articles were grouped into three main themes. The first theme included studies that focused on HIRA and applied risk assessment in specific industry or work activity contexts ( $n=6$ ). The second theme included studies that developed or compared risk assessment frameworks and methods, including quantitative, semiquantitative, and hybrid approaches ( $n=5$ ). The third theme included safety management approaches and integrated conceptual models that link risk assessment to the OHS management system and organizational decision-making ( $n=4$ ).

In terms of research design, most studies have been applied to case studies or industrial scenarios ( $n=9$ ), emphasizing the direct application of risk assessment methods in real-world contexts. In addition, some methodological and comparative studies aimed at evaluating the relative performance of various risk assessment methods ( $n=4$ ), as did a small number of conceptual studies or theoretical syntheses that focused on developing conceptual frameworks or integrating safety approaches ( $n=2$ ). The key outcomes reported in the core articles showed a relatively consistent pattern. Most studies emphasized risk prioritization and control strategies as the primary outcomes ( $n= 10$ ), followed by support for OHS decision-making at both the operational and managerial levels ( $n= 9$ ). Furthermore, several studies highlight the potential for cross-industry generalization, although with some limitations depending on the context and methodological assumptions used ( $n = 7$ ).

### **Thematic synthesis of the studies**

A narrative synthesis of 15 core articles indicated that the depth and methodological rigor of hazard identification and risk assessment (HIRA) and risk assessment are key factors in determining the quality of the information generated to support OHS decision-making. Among the 9 applied studies, seven (78%) used structured HIRA protocols and reported risk prioritization aligned with actual incident data, whereas two of the four (50%) studies used simplified approaches. Conversely, studies with a simpler approach or limited to a single risk assessment technique have limitations in identifying critical hazards, particularly in complex work systems or industrial processes. Several articles have highlighted that combining multiple risk assessment techniques (such as integrating qualitative and semiquantitative approaches or combining HIRA with other applied risk assessment methods) could provide a more comprehensive picture of risk. This multifaceted approach allows researchers and practitioners to capture variations in hazard levels, uncertainties, and interactions between risk factors that cannot be adequately identified via a single approach. This finding consistently emerged in applied industry case studies, particularly in contexts with high hazard potential and significant variability in work processes.

In terms of conceptual contributions, articles comparing various risk assessment methods have demonstrated that no single method is universal and can be effectively applied across all industrial contexts. The effectiveness of a method is strongly influenced by system complexity, hazard characteristics, and the desired decision-making objectives at both the operational and strategic levels. In this context, hybrid and adaptive frameworks are considered most relevant, as they allow for the adaptation of risk assessment methods to the specific needs of the organization and the dynamics of the work system being analyzed. The implications for OHS decision-making emerged as a central theme across the studies. Articles that explicitly linked risk assessment results to control prioritization, safety resource allocation, and medium- and long-term safety planning demonstrated greater practical value than studies that stopped at the risk ranking stage.

This finding confirmed that the most valuable output of risk assessments is not only the risk level but also recommendations that could be integrated into safety management processes and organizational policies.

Furthermore, several studies have demonstrated the potential for cross-industry generalization, emphasizing that the core principles of HIRA and risk assessment (such as systemic hazard identification, consequence and probability evaluation, and the integration of human and organizational factors) can be applied across sectors with contextual adjustments. However, these articles also emphasize the importance of considering industry-specific characteristics to ensure that the application of the risk assessment framework remains relevant and effective. Overall, the results of this narrative review indicate that studies with high methodological depth, clear conceptual contributions, and strong practical implications for OHS decision-making provide a solid foundation for developing effective and sustainable safety management systems. A summary of the characteristics and main findings of the core articles is systematically presented in [Table 1](#) as a basis for further discussion.

## DISCUSSIONS

This narrative review synthesizes the findings of 15 core articles examining risk assessment approaches, hazard identification and risk assessment (HIRA), and process safety management across various industrial sectors. Consistent with the findings presented in the previous section, the synthesis demonstrates that these studies consistently emphasize the importance of a systematic, integrated, and decision-oriented risk assessment approach compared with the conventional, static, and compliance-focused HIRA approach. Most articles indicate that traditional HIRA approaches are often limited to hazard identification and initial risk assessment, without adequately considering operational dynamics, system changes, and interactions between process safety elements. Findings from the latest studies of Giménez et al. [31], Wang et al. [34], and Liaw [35] suggested that poor HIRA quality (particularly at the hazard scenario identification and consequence estimation stages) could lead to failure to recognize and prioritize critical risks, ultimately reducing control effectiveness [31,34,35]. This corroborates the findings in the Results section that HIRA methodological depth was a critical factor in improving the quality of risk assessment outputs and overall safety performance.

From a methodological perspective, the articles analyzed in this narrative review can be classified into three main groups: (1) HIRA and case study-based applied risk assessments, (2) comparative frameworks and maturity evaluation models, and (3) the development of conceptual frameworks and decision support systems. Consistent with the summary of study findings, comparative research, such as that conducted by Cahyadi et al. [46], revealed that there was no single optimal risk assessment approach for all industrial contexts. The effectiveness of a method depends heavily on the hazard characteristics, process complexity, and maturity level of the organization's safety management system. Several studies have also highlighted the shift from purely qualitative approaches to semiquantitative and quantitative approaches to improve the objectivity and usefulness of risk assessment results in OHS decision-making [1,8,23]. The integration of risk indices, multicriteria weighting, and the utilization of historical accident data enable organizations to prioritize risks more transparently and consistently [31,34]. This approach is considered more relevant for top management because it can link risk assessment results to resource allocation, safety investment planning, and long-term control strategies, as reflected in the key outcomes of the core studies.

The implications for OHS decision-making emerged as a dominant theme across the studies, as identified in the Results section. The authors emphasized that an effective HIRA serves not only as a technical tool for hazard identification but also as a strategic instrument that connects risk analysis with safety management policies and practices. For example, the process safety management (PSM) maturity assessment model developed by Shanmugam and Razak (2020) enables organizations to systematically identify safety gaps and prioritize improvements on the basis of the level of risk and organizational readiness, thus strengthening the role of HIRA in risk-based decision-making [33].

**Table 1.** Summary characteristics of the included studies (n=15)

| Author (year)       | Country        | Type of safety approach                                                                                                                                                                                                                                                                                                                                                                                       | Key findings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Practical implications                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|---------------------|----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Giménez et al. [31] | Spain          | Systematic and Integrated Approach combining:<br>1. Root Cause Analysis (RCA): Use of techniques like AcciMap and Ishikawa (fishbone) diagrams to identify underlying accident causes.<br>2. Management System: Framework based on ISO 45001:2018 for continuous OHS management (PDCA cycle).<br>3. Link to Global Goals: Connecting laboratory OHS practices to the UN Sustainable Development Goals (SDGs). | 1. The proposed risk assessment methodology successfully identified and ranked hazards in an AOP laboratory (Photo-Fenton example). The normalized risk score for the case study laboratory was 23.5.<br>2. The S/C Ratio (Score/Annual Cost) proved to be a useful indicator for prioritizing corrective actions. A high S/C ratio indicates cost-effective risk reduction.<br>3. Risk distribution analysis showed: ~65% linked to direct accidents, ~30% to occupational diseases, and ~5% to stress/burnout.<br>4. Implementing an OHS Management System (ISO 45001) and Work Standard Procedures (WSP) enhances safety, reduces errors, and supports continuous improvement.<br>5. Safe and efficient laboratory practices directly contribute to achieving SDGs, specifically SDG 3 (Good Health), SDG 8 (Decent Work), SDG 9 (Industry & Innovation), and SDG 12 (Responsible Consumption) | 1. Adoptable Tools: The risk index methodology and S/C ratio can be adopted by other chemical or research labs (beyond AOPs) for structured risk assessment and safety investment prioritization.<br>2. Resource Optimization: The S/C ratio assists lab managers or companies in allocating safety budgets more effectively, focusing on actions yielding the highest risk reduction per cost unit.<br>3. Proactive Prevention: Using RCA techniques like AcciMap encourages a proactive approach to accident prevention by analyzing causal factors from policy to operational levels.<br>4. Standardized Framework: Provides a guide for implementing an ISO 45001-based OHS Management System in academic or research laboratory settings, enhancing safety culture and operational standards.<br>5. Strategic Value: Linking lab OHS programs to the SDGs provides strategic justification and added value for funding proposals and institutional social responsibility. |
| Nwankwo et al. [32] | United Kingdom | Comparative Analysis Framework for PSM Systems                                                                                                                                                                                                                                                                                                                                                                | 1. Developed an 11-factor comparative framework for evaluating 21 PSM systems.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 1. Organizations can use the comparative framework to select the most suitable PSM system for their specific sector.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |

| Author (year)          | Country  | Type of safety approach                              | Key findings                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Practical implications                                                                                                                                                                                                                                                                                                                                                                                               |
|------------------------|----------|------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                        |          |                                                      | <ol style="list-style-type: none"> <li>2. Identified IPSMS as the most robust system, addressing nearly all key process safety areas.</li> <li>3. Found no universal PSM system suitable for all industry sectors.</li> <li>4. Highlighted common deficiencies in existing systems, including lack of human factors integration and regulatory enforcement.</li> <li>5. Classified systems based on flexibility and robustness using a quadrant matrix.</li> </ol> | <ol style="list-style-type: none"> <li>2. Emphasis should be placed on integrating human factors and safety culture into PSM frameworks.</li> <li>3. Regulatory enforcement should be embedded within PSM implementation strategies.</li> <li>4. Further validation of IPSMS in real-world settings is recommended.</li> </ol>                                                                                       |
| Shanmugam & Razak [33] | Malaysia | Maturity Assessment Model based on OSHA PSM elements | <ol style="list-style-type: none"> <li>1. Conducted first maturity assessment of PSM implementation in Malaysian MHIs using OSHA PSM standards.</li> <li>2. 40% of MHIs had overall PSM maturity below acceptable levels.</li> <li>3. Weakest element was Pre-Startup Safety Review (24% below acceptable).</li> <li>4. Developed a process safety maturity model and assessment rubrics for systematic evaluation.</li> </ol>                                     | <ol style="list-style-type: none"> <li>1. Organizations should prioritize improving Pre-Startup Safety Review and other weak elements.</li> <li>2. The developed maturity model and rubrics can be used for periodic self-assessment and benchmarking.</li> <li>3. Regulatory bodies can use findings to guide targeted inspections and enforcement.</li> </ol>                                                      |
| Wang et al. [34]       | China    | Evidence-Based Process Safety Management (EBPSM)     | <ol style="list-style-type: none"> <li>1. Found1. Identifies that current PSM practices often lack integration of diverse evidence sources, leading to a research-to-practice gap.</li> <li>2. Introduces the EBPSM approach, which systematically integrates multiple evidence types such as incident reports, hazard assessments, safety audits, and scientific literature.</li> </ol>                                                                           | <ol style="list-style-type: none"> <li>1. Provides process safety practitioners with a structured, evidence-informed approach to decision-making and safety planning.</li> <li>2. Helps bridge the gap between research and practice through systematic use of multisource evidence.</li> <li>3. Enhances professional expertise by facilitating learning from historical data and scientific literature.</li> </ol> |

| Author (year)  | Country | Type of safety approach                                     | Key findings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Practical implications                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|----------------|---------|-------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                |         |                                                             | <ol style="list-style-type: none"> <li>3. Presents a comprehensive framework for EBPSM, detailing its operational stages.</li> <li>4. Demonstrates the extended application of EBPSM using LNG maritime safety management as a case example. no universal PSM system suitable for all industry sectors.</li> </ol>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | <ol style="list-style-type: none"> <li>4. Enables industries to proactively mitigate risks and foster safer, more resilient working environments.</li> <li>5. The EBPSM framework is adaptable to various process industries beyond the LNG example.</li> </ol>                                                                                                                                                                                                                                                                                                                                      |
| Liaw, H.J [35] | Taiwan  | Process Hazard Analysis (PHA) Enhancement & PSM Integration | <ol style="list-style-type: none"> <li>1. Poor quality of Process Hazard Analysis (PHA) is a primary cause of recurring process safety incidents in Taiwan, despite PHA b1. Poor quality of Process Hazard Analysis (PHA) is a primary cause of recurring process safety incidents in Taiwan, despite PHA being conducted.</li> <li>2. Deficiencies in PHA implementation and management practices were identified through empirical analysis of 86 PSM audits, postaccident reviews, and hundreds of PSM sessions.</li> <li>3. Utilizing PSM-related information (e.g., process safety data, incident reports) can significantly improve the quality and effectiveness of PHA.eing conducted.</li> <li>4. Deficiencies in PHA implementation and management practices were identified through empirical analysis of 86 PSM audits, postaccident reviews, and hundreds of PSM sessions.</li> </ol> | <ol style="list-style-type: none"> <li>1. Recommends that industries in Taiwan adopt enhanced PHA assessment techniques and procedures, supplementing basic OSHA PSM requirements.</li> <li>2. Advocates for specific training programs to implement these improved PHA methodologies.</li> <li>3. Suggests actively integrating existing PSM information into the PHA framework to enable more accurate hazard identification and control, thereby reducing the likelihood of process safety accidents.gap between research and practice through systematic use of multisource evidence.</li> </ol> |

| Author (year)    | Country | Type of safety approach                                                                                                                       | Key findings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Practical implications                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|------------------|---------|-----------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                  |         |                                                                                                                                               | 5. Utilizing PSM-related information (e.g., process safety data, incident reports) can significantly improve the quality and effectiveness of PHA. Common deficiencies in existing systems, including lack of human factors integration and regulatory enforcement.                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Chen et al. [36] | China   | Systemic accident modeling approach based on the Entropy Increase Principle and Darwin's Natural Selection (Entropy–Evolution Accident Model) | The study proposes a novel accident causation model that explains the entire accident process through three core components: power, origin, and intermediate. This model is classified as such. The evolution of accidents is driven by inherent disorder (i.e. entropy increase), originating from social factors and progressing through the evolutionary struggle of unsafe factors under internal and external pressures from safe factors. The results of the case study demonstrate that the proposed model outperforms Fuzzy AHP, Accimap, and HFACS in representing accident dynamics and causal complexity based on flexibility and robustness using a quadrant matrix. | The model provides a more profound, system-oriented understanding of accident evolution, extending beyond traditional hazard- and control-based approaches. It enables safety practitioners to identify social origins and dynamic interactions between safe and unsafe factors, thus supporting the development of more effective and sustainable accident prevention strategies in complex sociotechnical systems. The provision of professional expertise is facilitated by the utilisation of historical data and scientific literature, which serve as the foundation for learning. |
| Fu et al. [37]   | China   | Systematic & theoretical safety modeling (integrating linear and systemic approaches)                                                         | 1. A novel classification method for accident causation models is proposed, distinguishing between linear and nonlinear models, with subcategories encompassing human-, statistics-, energy-, and system-based statistics.                                                                                                                                                                                                                                                                                                                                                                                                                                                       | 1. The selection of the model is as follows: Each accident model possesses a unique set of characteristics and a distinct range of applications. In the field of accident analysis, it is imperative to select a model that aligns with the unique                                                                                                                                                                                                                                                                                                                                       |

| Author (year)       | Country | Type of safety approach                                                             | Key findings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Practical implications                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|---------------------|---------|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                     |         |                                                                                     | <ol style="list-style-type: none"> <li>2. A comprehensive review of 29 representative models spanning the last 100 years was conducted, encompassing their historical development, the application process, and the current status of their implementation.</li> <li>3. The 24Model is presented as a contemporary model that incorporates individual factors (immediate and indirect causes) and organisational factors (safety management system and safety culture) within a systematic linear structure.</li> <li>4. It is concluded that accident causation models are evolving towards more systematic, dynamic, and integrated approaches, with an emphasis on safety management systems and safety culture.</li> <li>5. The progression of model applications from qualitative analysis to quantitative analysis, and subsequently to dynamic analysis and prediction, is indicative of a shift towards intelligent analysis based on big data and artificial intelligence.</li> </ol> | <ol style="list-style-type: none"> <li>characteristics of the industry in question.</li> <li>2. The present study focuses on the interaction between system and culture. It is imperative for organisations to transition from attributing blame to individual factors to fortifying the Safety Management System and cultivating a robust Safety Culture as the cornerstone for prevention.</li> <li>3. Enhanced Analysis: Practitioners are able to utilise linear models (e.g. 24Model or HFACS) for clear logic, and systemic models (e.g. STAMP, FRAM) for in-depth analysis of complex systems. Energy-based models (e.g. Bow-Tie) are considered appropriate for the analysis of barriers.</li> <li>4. Future Directions: The utilisation of big data and artificial intelligence (AI) in conjunction with accident causation models provides a framework for predictive analysis and more proactive prevention.</li> </ol> |
| Sultana et al. [38] | Norway  | System Engineering Approach (STAMP – System-Theoretic Accident Model and Processes) | <ol style="list-style-type: none"> <li>1. The STAMP-based method has been demonstrated to be capable of identifying safety indicators that take into account systemic interactions, including technical, human, and organisational factors.</li> </ol>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | <ol style="list-style-type: none"> <li>1. The methodology can be applied in the process industry (e.g., LNG operations) to develop a proactive safety monitoring programme that focuses on control effectiveness rather than merely failure prevention.</li> </ol>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |

| Author (year)       | Country | Type of safety approach                                                                                                                                                                                             | Key findings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Practical implications                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
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|                     |         |                                                                                                                                                                                                                     | <ol style="list-style-type: none"> <li>2. The developed indicators are plant-specific and have the capacity to provide early warning of control failures.</li> <li>3. STAMP generates a substantial list of indicators (56 in the case study), necessitating screening to focus on the most critical ones.</li> <li>4. STAMP provides a more holistic understanding of the system in comparison to traditional approaches such as OECD and CCPS, although it requires more initial effort.</li> <li>5. The approach is conducive to continuous improvement and can be readily adapted for system modifications.</li> </ol> | <ol style="list-style-type: none"> <li>2. The method is valuable from the conceptual design stage, helping to identify safety requirements and constraints early on.</li> <li>3. It is imperative for organisations to allocate resources towards the provision of training, as the STAMP approach is a relatively recent development for industry personnel.</li> <li>4. The establishment of a performance monitoring programme is imperative to define data sources, establish thresholds, and determine review frequencies for the identified indicators.</li> <li>5. It is recommended that future integration with quantitative risk models (e.g. Bayesian networks) be considered in order to enhance indicator screening and prioritisation based on risk significance.</li> </ol> |
| Sattari et al. [39] | Canada  | This paper sets out a data-driven artificial intelligence-based decision-making framework for asset integrity management (AIM) within process safety management (PSM) using machine learning and Bayesian networks. | The study develops a theoretical framework integrating expert knowledge, machine learning, keyword analysis, and Bayesian Networks to model causal relationships within Asset Integrity Management. The findings suggest that Asset Integrity and Reliability (AIR) exhibits the most significant correlation with total incident rates. A detailed analysis reveals that four asset-related factors, namely construction, testing, inspection, and maintenance, account for 54.78% of                                                                                                                                     | The framework enables organisations to prioritise and allocate safety resources based on data-driven insights, focusing on the most influential AIM elements. By incorporating AI-driven probabilistic modelling into PSM, oil and gas companies can proactively reduce incident rates, enhance asset lifecycle management, and fortify both technical and human-factor controls within asset integrity programmes.                                                                                                                                                                                                                                                                                                                                                                        |

| Author (year)      | Country  | Type of safety approach                                                                                                                          | Key findings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Practical implications                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|--------------------|----------|--------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                    |          |                                                                                                                                                  | incidents. In addition, human factors contribute both directly (23.58%) and indirectly (11.10%) to accidents and technological failures.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| Liu et al. [40]    | China    | Risk precontrol continuum & risk gradient control                                                                                                | <ol style="list-style-type: none"> <li>1. The continuous risk management model under discussion in this paper establishes a linkage between three safety states (stable, unstable, emergency) and three management models (hazard, defect, emergency management).</li> <li>2. The proposal asserts that risk precontrol should be conceptualised as a unified, continuous process, as opposed to the perception of it as isolated management activities.</li> <li>3. The definition of hazards as root and state hazards is provided, with the latter being defined as "hidden dangers that can lead to accidents".</li> <li>4. The development of a risk gradient control framework is proposed, comprising three tiers: hazard control, hidden danger control, and emergency control.</li> <li>5. The formula provided enables the calculation of risk at pre-control level (p) and risk level (r).</li> </ol> | <ol style="list-style-type: none"> <li>1. This enables coal mines to transition from a passive, reactive safety management approach to a proactive, preventive risk control strategy.</li> <li>2. This methodology provides a structured approach to the identification of hazards, utilising a root-state hazard analysis to enhance risk visibility.</li> <li>3. The development of prearranged plans for different risk levels is supported, thereby enhancing preparedness.</li> <li>4. The methodology is designed to promote ongoing enhancement through the implementation of PDCA cycles (Plan, Do, Check, Act) and closed-loop risk management.</li> <li>5. The present text sets out a methodology for the assessment and improvement of organisational safety performance, the implementation of which is both quantifiable and measurable.</li> </ol> |
| Jaafar et al. [41] | Malaysia | Systematic literature review (PRISMA-based) focusing on quantitative risk assessment (QRA) of ammonia refrigeration systems in the food industry | <ol style="list-style-type: none"> <li>1. A screening process based on the PRISMA framework yielded 15 articles that met the criteria for inclusion and had undergone the peer-review process. The subject of these articles was the risk assessment</li> </ol>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | <ol style="list-style-type: none"> <li>1. The provision of evidence-based guidance for food industry operators is pivotal in facilitating the selection of appropriate risk assessment methodologies, with consideration</li> </ol>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |

| Author (year)     | Country | Type of safety approach                                 | Key findings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Practical implications                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|-------------------|---------|---------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                   |         |                                                         | <p>of ammonia refrigeration systems (ARSs) in the food industry.</p> <ol style="list-style-type: none"> <li>2. A thematic analysis was conducted, which resulted in the identification of four primary themes. The primary risk factors associated with ARSs are of particular concern. In addition, a comparison of different risk assessment approaches is necessary, including qualitative, semiquantitative and quantitative methods. Furthermore, the application of software tools in QRA calculations must be considered, as must the effectiveness of risk management and mitigation measures implemented in food industry facilities.</li> <li>3. A total of 12 sub-themes were identified in the course of the study, including ammonia leakage sources, equipment failure, human error, and limitations in existing regulatory frameworks.</li> <li>4. The utilisation of quantitative risk assessment approaches has been demonstrated to engender predictions of accident consequences and exposure risks that are more robust in comparison to those engendered by purely qualitative methods.</li> </ol> | <p>given to system complexity and operational conditions.</p> <ol style="list-style-type: none"> <li>2. The integration of preventive and mitigative safety measures is supported, including engineering controls, administrative controls, and emergency preparedness strategies.</li> <li>3. The role of the professional is to provide support to practitioners specialising in the field of occupational safety and health (OSH) in order to enhance regulatory compliance and decision-making processes that are informed by risk with regard to ammonia refrigeration systems.</li> <li>4. It is vital to emphasise the regulatory and practical gaps, particularly for high-risk subsectors such as ice manufacturing plants. This is essential for informing the development of more targeted OSH guidelines and policies.</li> </ol> |
| Omidi et al. [42] | Iran    | The present paper sets out the Hybrid Intelligent Model | A three-stage hybrid model (PCA, CFS, GFS) was utilised to identify the key                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | The provision of a data-driven, quantitative tool is intended to facilitate                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |

| Author (year)     | Country           | Type of safety approach                                                             | Key findings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Practical implications                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|-------------------|-------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                   |                   | (PCA + Feature Selection + Genetic Fuzzy System) for Safety Performance Assessment. | human factors affecting control room operators' safety performance. The most significant features were identified as the human-computer interface, safe work practices/permit-to-work systems, and staff competence. The Genetic Fuzzy System model demonstrated a low level of prediction error (MAPE=2.86%, RMSE=0.47), thereby confirming its accuracy.                                                                                                                                                                                                                                                                                                                                        | the assessment and prediction of safety performance among critical personnel. This enables organisations to establish a framework for prioritising interventions on the most impactful human factors areas. These areas include, but are not limited to, improving HCI design, strengthening permit-to-work systems and enhancing competence management. The purpose of this framework is to proactively enhance operational safety.                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Kidam et al. [43] | Malaysia, Finland | Accident-based Inherently Safer Design Review (ISDR)                                | <ol style="list-style-type: none"> <li>1. A total of 124 corrective actions of a safety-based nature were identified in the context of chemical process industries.</li> <li>2. The most prevalent ISD strategies were moderation (27%) and error tolerance (27%), followed by substitution (21%), simplification (13%), minimization (10%), and limitation of effects (2%).</li> <li>3. A survey of design errors revealed that 50% of these originated in the basic engineering phase, indicating a late safety integration process.</li> <li>4. The following equipment was found to be most susceptible to failure: piping systems (27%), storage tanks (18%), and reactors (16%).</li> </ol> | <ol style="list-style-type: none"> <li>1. The integration of inherent safety principles at the earliest stages of the process, namely during the research and development stage and the preliminary design stage, has been shown to have a significant effect on accident potential, leading to a substantial reduction in the probability of accidents.</li> <li>2. The provision of practical, phase-specific review criteria by accident-based ISDR has been demonstrated to facilitate enhanced decision-making during the process of designing a given project.</li> <li>3. It is imperative that designers prioritise inherent safety over add-on protection systems in order to circumvent complex and error-prone designs.</li> <li>4. The proposed ISDR framework has the potential to enhance the safety of plant design by ensuring that safety reviews</li> </ol> |

| Author (year)       | Country  | Type of safety approach                                                                         | Key findings                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Practical implications                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
|---------------------|----------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                     |          |                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | are aligned with specific design phases and tasks.                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| So et al. [44]      | Malaysia | Inherent Occupational Health Index (IOHI) integrated with Layers of Protection (LOP) strategies | The proposed method integrates inherent health hazard assessment (IOHI) with prevention/minimization strategies (LOP). When applied to methyl methacrylate production routes (C2/PA and C3), the evaluated control strategies reduced the residual hazard index, thus classifying both processes as "safe" (from previously "moderately hazardous" or "hazardous").                                                                                                                                                                                                          | The document provides a structured list of suitable control measures for each hazard parameter, with varying effectiveness scores. The system under discussion has been demonstrated to facilitate the reduction of risk during the research and development stage. It offers companies a high degree of flexibility, enabling them to adapt their strategies based on a variety of factors, including process experience, suitability, budget, and historical safety records.                                        |
| Ghasemi et al. [45] | Iran     | Hybrid FBN-HFACS (Fuzzy Bayesian Network - Human Factors Analysis and Classification System)    | The FBN-HFACS model successfully identified and quantified the effect of human and organisational factors in a toxic gas leakage accident. The investigation identified several key contributing factors, including organisational conflicts, a substandard safety culture, the use of substandard equipment, a lack of proper inspection, and safety violations. The "Improvement Index" was found to be a superior metric for prioritising corrective actions when compared to the "Effect Rate", as it takes into account causal relationships and organisational levels. | The proposed approach offers a structured, quantitative method for investigating process accidents, thus moving beyond the qualitative HFACS. This enables organisations to establish intervention strategies according to the Improvement Index, thereby ensuring the allocation of resources to the factors (e.g. organisational conflicts, safety culture) that offer the greatest reduction in accident probability. The methodology must be adapted to suit each particular accident and organisational context. |

Another aspect that emerged from this synthesis was the potential for cross-industry generalization. While some studies have focused on specific sectors, such as the process, manufacturing, energy, and chemical industries, the core principles underlying HIRA and risk assessment, including hazard scenario identification, consequence and probability evaluation, and the application of layered controls, demonstrate broad relevance [1,47]. However, as highlighted in several articles, such cross-industry applications still require contextual adaptation, particularly with respect to differences in regulations, safety culture, and operational process characteristics.

Overall, this discussion confirmed the narrative review's main finding that a paradigm shift had occurred from HIRA as an administrative obligation to HIRA as a risk-based decision-making tool. Articles with strong conceptual contributions and more advanced methodological approaches demonstrated that integrating HIRA with PSM frameworks, safety performance indicators, and decision support systems has significant potential to improve risk control effectiveness. However, the narrative review also identified research gaps, particularly the need for long-term empirical validation, real-time integration of operational data, and quantitative evaluation of HIRA's impact on reducing accident and safety incident rates.

### **Implications for public health and occupational health**

Three of the reviewed studies demonstrated that embedding occupational health criteria into HIRA frameworks during the design phase reduced chronic exposure and acute incident risks. Integrating occupational health aspects into hazard identification and risk assessment can prevent occupational diseases and long-term occupational exposures, which are often overlooked in traditional process safety approaches. The application of inherently safer design and healthier process design principles can eliminate or reduce worker exposure to hazardous materials, extreme working conditions, and ergonomic hazards at the source, providing more fundamental protection than engineering controls or personal protective equipment. For public health, a comprehensive risk assessment of major accident hazards can protect communities surrounding industrial installations from the impacts of major accidents, such as toxic releases, fires, or explosions. Integrating public safety considerations into land use planning and emergency preparedness can reduce the vulnerability of exposed populations. A risk assessment framework that integrates occupational health, process safety, and public safety can provide the basis for more holistic public health policies in the context of sustainable industrialization.

### **Limitations**

This study has several limitations. First, the literature search used only one database (ScienceDirect), potentially missing relevant publications in other databases, such as Scopus, Web of Science, and PubMed. Second, the inclusion criteria were limited to English-language peer-reviewed journal articles, excluding gray literature, industry reports, and nonEnglish publications, which may provide important practical perspectives on the topic. Third, the high heterogeneity of the studies (variation in industry sectors, study designs, and HIRA methods) limited the possibility of quantitative synthesis and meta-analysis. Fourth, publication bias may exist, as studies reporting null findings or implementation failures are underrepresented in peer-reviewed literature, potentially inflating the perceived effectiveness of advanced HIRA methods.

## **CONCLUSIONS**

This review of 15 studies demonstrates that HIRA effectiveness extends beyond procedural compliance to encompass methodological rigor, integration, and decision-making orientation. Traditional static approaches are inadequate for complex industrial systems, whereas adaptive hybrid methods generate actionable risk intelligence for strategic safety management. No universal assessment method exists; its effectiveness depends on hazard profiles, process complexity, and organizational maturity. The evidence reveals HIRA's evolution from an administrative obligation to a strategic instrument enabling control prioritization, resource allocation, and long-term planning. The integration of process safety management frameworks and performance indicators strengthens the effectiveness of risk control. Future research should

focus on developing industry-specific maturity models, integrating real-time data analytics, and quantifying HIRA's impact on lagging safety indicators through longitudinal validation studies.

## CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## AUTHOR CONTRIBUTIONS

Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision: NA, RB and LB.

## FUNDING

This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## ACKNOWLEDGMENTS

The author would like to express their gratitude to PT. Mega Science Indonesia is to be commended for their role in the proofreading of the manuscript, which has now been prepared for publication.

## DECLARATION OF ARTIFICIAL INTELLIGENCE USE

AI-based language tools were used for the refinement of the language and structuring of the manuscript. All AI-assisted outputs were critically reviewed by the authors, and the final interpretations and conclusions remained the sole responsibility of the authors.

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