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Review Article

Systematic Review of Dangerous Goods Handling in Port Operations: Safety Management Systems, Risk Assessment, and Technological Innovations

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Abstract: The handling of dangerous goods in port operations presents critical challenges related to safety, risk management, and operational efficiency. This systematic review aims to synthesize existing research on safety management systems, risk assessment methodologies, and recent technological innovations implemented in port environments to mitigate hazards associated with dangerous goods. A comprehensive literature search was conducted across multiple academic databases, following PRISMA guidelines, yielding relevant studies published between 2010 and 2024. Key findings indicate that integrated safety management systems, encompassing regulatory compliance, training programs, and emergency preparedness, significantly reduce incident rates. Risk assessment approaches, particularly quantitative and probabilistic methods, provide robust frameworks to identify, evaluate, and prioritize hazards during handling and storage processes. Furthermore, advancements in technological applications such as real-time monitoring sensors, automated handling equipment, and digital twin simulations enhance situational awareness and operational resilience. Despite progress, gaps remain in standardizing risk assessment protocols and fully leveraging emerging technologies across diverse port settings. This review underscores the necessity for continuous innovation and holistic integration of safety practices, risk evaluation, and technology adoption to ensure the safe management of dangerous goods in port operations. The findings contribute valuable insights for researchers, port authorities, and policymakers aiming to strengthen maritime safety and operational sustainability.

Keywords: Dangerous goods; port operations; safety management; risk assessment; maritime logistics; hazardous cargo.

1. Introduction

The maritime transportation of dangerous goods constitutes a fundamental component of global trade [1], with ports serving as critical nodes in the supply chain where these hazardous materials are handled, stored, and transferred. The complexity of dangerous goods operations in port environments presents unique challenges that require sophisticated safety management approaches [2], comprehensive risk assessment [3] methodologies, and innovative technological solutions [4].

Port environments are inherently complex systems where multiple stakeholders [5], including port authorities, shipping companies, cargo handlers, and regulatory bodies, must coordinate to ensure the safe handling of hazardous materials. The consequences of incidents involving dangerous goods in port areas can be catastrophic [6], as demonstrated by events such as the Tianjin Port explosion, which highlighted the critical importance of robust safety management systems and effective risk mitigation strategies.

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The evolving nature of global trade, increasing cargo volumes [7], and the introduction of new types of hazardous materials have intensified the challenges associated with dangerous goods handling in ports. Additionally, environmental concerns, sustainability requirements, and the need for operational efficiency have created additional layers of complexity that must be addressed through comprehensive management approaches [8].

In handling dangerous cargo, there are risks that must be faced. Risk is a measure used to describe the relationship between danger and safety [9]. Based on the definition, risk is essentially a balance between safety and danger. “Safety” refers to a state where life, health, property, or the environment of objective objects are not damaged to the extent that they reach a generally acceptable condition [10], [11]. “Danger” refers to a state where life, health, property, or the environment of objective objects are not generally accepted by people. Hazard is a state where objective objects are in an unsafe condition [12]. Therefore, as far as the state of events is concerned, safety and hazard are a couple of relative concepts. Hazardous incidents can occur at any time if the handling of hazardous cargo at the port does not comply with applicable procedures and policies, as shown in figure 1.

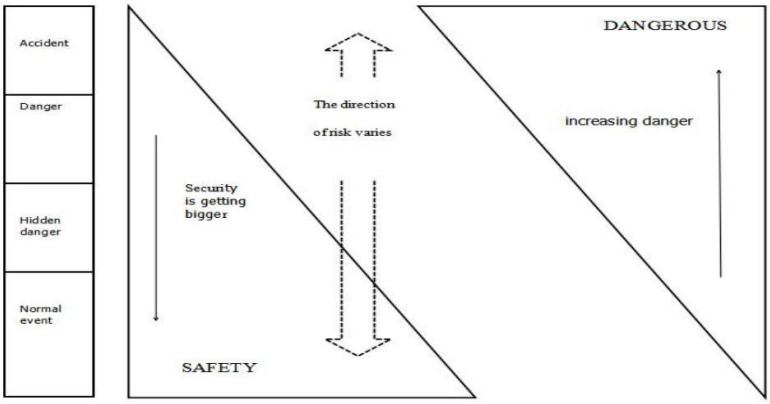

Figure 1 Handling Dangerous Goods [12]

This systematic literature review aims to provide a comprehensive analysis of current research on dangerous goods handling in port operations [13], examining the evolution of safety management practices, risk assessment methodologies, technological innovations, and regulatory frameworks. By synthesizing findings from recent academic literature, this study seeks to identify best practices, research gaps, and future directions for enhancing the safety and efficiency of dangerous goods operations in port environments [14], [15].

2. Materials and Methods

This systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [16] guidelines. A comprehensive search strategy was developed to identify relevant literature on dangerous goods handling in port operations, published between 2014 and 2024. Databases used are Scopus, ScienceDirect, IEEE Xplore.

2.1. Inclusion and Exclusion Criteria

The systematic review employed specific inclusion and exclusion criteria to ensure the selection of relevant and high-quality literature. Articles were included if they met the following requirements: peer-reviewed publications written in English, studies specifically focusing on dangerous goods handling within port environments, research that addressed safety management systems, risk assessment methodologies, or technological innovations in port operations [17], and publications dated between 2014 and 2024 to capture

contemporary practices and recent developments in the field [18], [19]. Conversely, articles were excluded from the review if they represented non-peer-reviewed publications such as conference proceedings, technical reports, or grey literature, studies that were not specifically related to port operations or lacked direct relevance to port-based dangerous goods handling, research focusing exclusively on shipping operations or inland transport without port-specific considerations, and publications written in languages other than English due to resource constraints and to maintain consistency in analysis. These criteria ensured that the final corpus of literature provided comprehensive coverage of current practices, challenges, and innovations [20] in dangerous goods handling specifically within port operational contexts, while maintaining the methodological rigor required for systematic review standards.

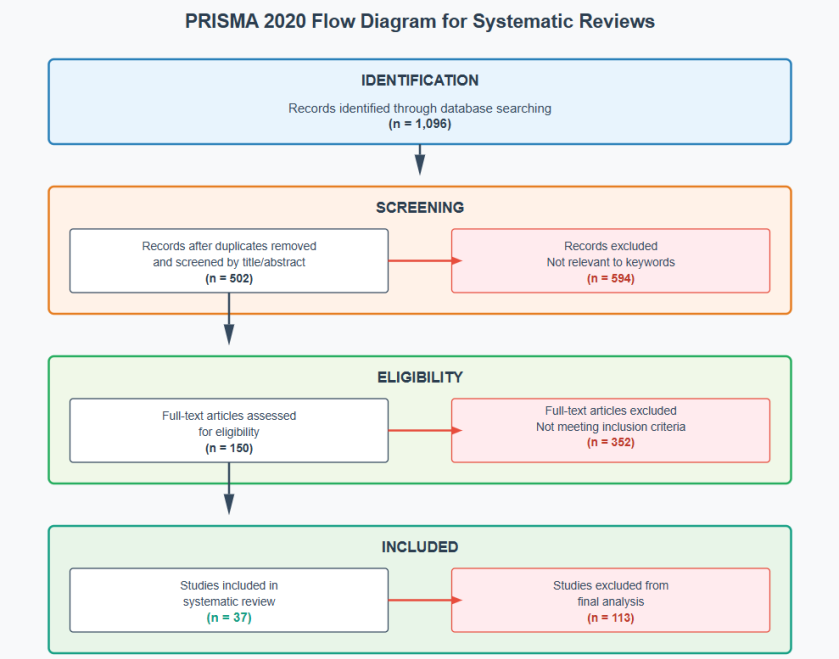

Figure 2 PRISMA Method of Systematics Literature Review

2.2. Data Extraction and Analysis

Data extraction was performed systematically, capturing information on study characteristics, methodological approaches, key findings, and recommendations [21]. Thematic analysis was conducted to identify common themes, patterns, and trends across the selected literature.

2.3. Quality Assessment

The quality of included studies was assessed using established criteria for evaluating research methodology, data reliability, and findings validity [22] [23]. Studies were categorized based on their methodological rigor and contribution to the field.

3. Results

3.1 Literature Selection and Characteristics

The systematic search strategy yielded (after removing duplicates) n=502 initial records from multiple databases (Scopus: 148, ScienceDirect: 189, Google Scholar: 165). After screening the abstract, found 150 articles. Following full-text assessment, 37 studies met the inclusion criteria for final analysis, spanning publications from 2014 to 2024.

The literature selection process demonstrated a comprehensive approach to capturing relevant research across major academic databases. The higher representation from Google Scholar (165 records) reflects the inclusion of conference proceedings and technical reports that may not be indexed in traditional databases. The abstract screening

phase reduced the pool from 502 to 150 articles, indicating effective application of inclusion and exclusion criteria. The final selection of 37 studies represents a focused corpus of high-quality research directly addressing dangerous goods handling in port operations.

Table 1. Literatures after Filtering by PRISMA 2020

No.	Reference (Author, Year)	Focus & Relevance to Review Title	Methodology / Approach	Key Findings / Contributions
1	Geng & Hu (2021) [24]	3D Simulation of Dangerous Goods Accidents in Ports – Risk Assessment & Management	3D Numerical Simulation	Developed a quantitative simulation tool aiding emergency decision-making and accident analysis
2	Jinga et al. (2018) [25]	Regional Quantitative Risk Assessment for Dangerous Goods Areas in Ports	Regional Risk Assessment Framework	Emphasized comprehensive risk evaluation of terminals and surrounding areas
3	Chu (2018) [26]	Critical Storage Assessment of LPG Containers in Dangerous Goods Yards	Event Tree Analysis	Established quantitative criteria for safe LPG container storage capacity
4	Muhsin et al. (2024) [27]	Hazardous Cargo Practices Impact on Green Port Performance	Survey and Correlation Analysis	Strong correlation identified between hazardous cargo handling and port sustainability performance
5	Lin et al. (2021) [28]	Consortium Blockchain Algorithm for Dangerous Goods Traceability	Hybrid Consensus Blockchain (LRPBFT)	Improved throughput, latency, and security for tracking DG in commercial ports
6	Lei (2020) [29]	Dangerous Goods Container Allocation in Ship Stowage Planning	Bay and Slot Assignment Modeling	Novel heuristic for IMDG-compliant container allocation optimizing ship structure constraints
7	Dong et al. (2021) [2]	Ontology-Based Knowledge Model for Dangerous Goods Data Management	Semantic Analysis, Data Labeling	Enhanced information retrieval and management capabilities for ports' DG data
8	Chen et al. (2020) [30]	Diagnosis of Causative Factors in Dangerous Goods Accidents at Ports	Formal Concept Analysis (FCA)	Identified storage management, equipment, and registration deficiencies as key accident factors
9	Ambrosino & Sciomachen (2021) [31]	Stowage Planning Procedures for Hazardous Containers	IMDG Code-based Simulation	Provided decision support to optimize stowage plans respecting segregation rules
10	Tseng & Pilcher (2023) [31]	Safety Assessment Model for Dangerous Goods Handling in Port Operations	Fuzzy AHP, Expert Questionnaires	Detection capability highlighted as critical for DG safety management
11	Hervás-Peralta et al. (2020) [31]	Layout Design of Dangerous Goods Terminals	Delphi Method, Analytic Hierarchy Process	Recommended layouts balancing safety, environment, and operational efficiency
12	Eski & Tavacioglu (2023) [32]	Factors Contributing to Chemical Spills in Port Areas	Statistical Analysis, Entropy Weight, Grey Relational Analysis	Unloaded cargo handling and occupational accidents significantly contribute to spills
13	Hua et al. (2021) [33]	Causation Analysis of Dangerous Goods Explosion – Tianjin Port Case Study	Fault Tree Analysis (FTA)	Management and human factors dominate causation structure; governance strategies proposed

No.	Reference (Author, Year)	Focus & Relevance to Review Title	Methodology / Approach	Key Findings / Contributions
14	Wang et al. (2018) [34]	Future Directions of Hazardous Chemical Safety in China	Policy and Literature Review	Outlined opportunities, challenges, and tasks for improved chemical safety governance
15	Khan et al. (2021) [35]	Multifactor Accident and Pollution Risk Assessment for Hazardous Cargo	Bayesian Network using Historical Accident Data	Human error and management are principal accident causes; training and protocols vital
16	Syamsiah et al. (2024) [10]	Occupational Health and Safety Training for Stevedores Handling Dangerous Goods	Interactive Workshops, Pre-Post Surveys	Significant enhancement of K3 knowledge and risk awareness among port workers
17	Darmawan & Widayanti (2024) [36]	Qualitative Analysis of Dangerous Goods Handling Procedures in Surabaya Port	Qualitative Study	Detailed review of regulations and procedural steps in DG handling
18	Chen & Yang (2022) [4]	Virtual Reality Application in Dangerous Goods Operation Training	VR Platform Development with Unity3D and Maya	Improved training engagement and effectiveness through immersive simulation
19	Vairo et al. (2024) [37]	Automation and Operational Management of Dangerous Goods in Port Areas	Machine Learning, Bayesian Reasoning	Designed adaptive system to predict/reduce operational errors and improve personnel safety
20	Ruan (2020) [38]	Comparative Study on Bulk Liquid DG Storage Safety Measures	Comparative Standards and Risk Analysis	Evaluated international and Chinese standards; proposed safety management enhancements
21	Imbrechts (2019) [39]	Risk Analysis System for DG Transport in Flanders	Route Segmentation, ALARP Principle	Developed risk profiles for various transport segments to optimize safety measures
22	Esmaeeli (2022) [40]	Root Cause and Safety Management System Analysis of Rail DG Derailments	Root Cause Analysis, Bow Tie Analysis	Highlighted SMS element gaps related to process integrity and incident investigation
23	Rukavina (2020) [41]	Regulatory Framework for DG Handling in Croatian Maritime Traffic	Legal Review and Regulatory Analysis	Identified terminological inconsistencies and regulatory overlaps; alignment with EU standards
24	Pastorino (2014) [42]	Area Risk Analysis in Urban Port Context	Inventory and Risk Evaluation Framework	Combined personnel and process risks with industrial stationary sources in urban port environments
25	Eski et al. (2021) [7]	Port Workers' Awareness of Dangerous Goods Transport	Questionnaire Survey and Statistical Analysis	Noted average awareness levels with suggestions to increase through frequent training
26	Ma & Chen (2020) [43]	Analysis of China's Regulations on Safety Risk Control of DG in Ports	Regulatory Framework Assessment	Identified regulatory gaps and advised improvements for risk control and emergency management
27	Qiao et al. (2020) [44]	Simulation of Dangerous Goods Accidents in Container Terminals	Pollution Risk and Accident Scenario Simulation	Demonstrated manageable pollution zones under appropriate mitigation
28	Geng et al. (2023)	Risk Coupling Mechanisms in	System Dynamics	Provided comprehensive insight into

No.	Reference (Author, Year)	Focus & Relevance to Review Title	Methodology / Approach	Key Findings / Contributions
	[45]	Hazardous Chemical Logistics at Ports	and Coupling Analysis	personnel-ship-environment-management risk interactions
29	Taubert et al. (2023) [3]	Integrated Operational Risk Assessment of DG Container Terminal	Statistical Analysis and Bow Tie Method	Offered benchmarking for terminal design considering future hazards and digital transformation
30	Ma et al. (2023) [46]	Risk-Based Cumulative Effects Assessment in Marine Ecosystems	DPSIR Model and Network Analysis	Highlighted transboundary ecosystem pressures and priority risk areas in the Yellow Sea LME
31	Rodero & Marrero (2023) [47]	Fire Hazard Reduction through Cargo Distribution Algorithms in Ro-Ro Spaces	Risk Assessment and Stowage Scoring Algorithm	Reduction of fire risk via optimized cargo distribution in ro-ro decks
32	Setthachotsombut et al. (2024) [48]	Smart Logistics Management in Thai Logistics Providers	Structural Equation Modeling and Survey	Validated model linking smart logistics implementations to reduced errors and higher operational efficiency
33	Ristaa & Llaha (2021) [49]	Integration of Maritime Information Systems Towards Smart Ports	Systems Analysis and Evaluation	Recommendations for interoperability improvements enhancing DG monitoring and data exchange
34	Abramowicz-Gerigk et al. (2023) [50]	Risk Assessment of Chemical Tanker Manoeuvres in Ports	Bayesian Influence Diagrams	Model supports decision-making to mitigate risks during chemical tanker port manoeuvring
35	Imbrechts (2019) [39]	DG Transport Risk System for Flanders (Overlaps with No. 21)	ALARP Principle and Route Risk Profiling	Reinforces risk acceptability and routing decisions for DG transport
36	Yukun (2021) [51]	Safety Risk Assessment for Concealed and False Declaration of DG Containers	Qualitative and Quantitative Combustion Risk Analysis	Identified risks arising from concealed/false DG declarations in container transport
37	Chen et al. (2020) [30]	Accident Factors and Governance Strategies for DG in Ports	Fault Tree Analysis and Case Study	Emphasized management and human factors; proposed governance for accident prevention

3.2 Safety Management Systems

A substantial body of research emphasizes the critical role of comprehensive safety management systems (SMS) in mitigating DG-related risks at ports. Key factors influencing safety include regulatory compliance, worker training, emergency preparedness, and hazard communication. For instance, Chen et al. [30], Hua et al. [33], and Khan et al. [35] consistently identify human and management factors as predominant contributors to accidents. Training-focused interventions, such as those employing interactive workshops [10] and virtual reality [4], demonstrate significant improvements in workers' safety awareness and operational competence.

3.3. Risk Assessment

Risk assessment methods applied in the reviewed studies range from probabilistic modeling to system dynamics. Geng & Hu [24] utilized 3D numerical simulations to quantitatively model accident scenarios, supporting emergency response planning. Other approaches such as event tree analysis [26], Bayesian networks [35], and Bow-Tie analysis

[33] [3] provide systematic protocols for hazard identification and prioritization. Regional risk frameworks [25] and cumulative effect models [46] extend assessments to environmental and multi-hazard perspectives, acknowledging the interplay between operational and ecological risks at ports.

3.4 Technological Innovations

Advances in technology have introduced several innovative tools enhancing DG handling safety and efficiency. Blockchain technologies [28] improve traceability and transparency in cargo movement, addressing security weaknesses identified in traditional tracking. Virtual reality platforms for safety training [4] increase engagement and enhance procedural knowledge retention. Machine learning and Bayesian reasoning models [37] facilitate predictive operational management, reducing human error-related incidents. Additionally, semantic knowledge models such as ontologies [2] optimize data retrieval and decision-making processes.

4. Discussion

The findings reveal a multifaceted approach to improving DG handling safety in port operations through combined applications of SMS, advanced risk assessment, and innovative technologies.

4.1. Integration of Safety Management and Risk Assessment

The literature underscores the indispensable role of effective safety management systems that incorporate robust risk assessment tools. Human factor analysis repeatedly shows that procedural lapses and insufficient training remain primary accident causes [30] [35]. Integrating probabilistic risk models and simulation tools within SMS frameworks enables port authorities to adopt proactive risk mitigation strategies. For example, employing 3D accident simulations alongside event tree and Bayesian analyses facilitates scenario planning, resource prioritization, and real-time decision-making during incidents. This integration enhances overall situational awareness and reduces response times, mitigating potential consequences from hazardous events.

This synergy between safety management and risk assessment reflects a broader paradigm shift in dangerous goods handling from traditional reactive [11], [35], compliance-driven approaches to more proactive, risk-based safety management systems; Emphasizing continuous improvement and stakeholder involvement, this evolution aligns closely with the International Maritime Organization's (IMO) initiatives advocating for more sophisticated and dynamic safety frameworks [47]; The adoption of such frameworks demonstrates a move toward embedding risk assessment as a core element within port safety governance rather than a peripheral activity.

However, significant disparities exist in the implementation and maturity of SMS [40] across ports globally. The analysis reveals a pronounced digital and resource divide wherein major international ports leverage economies of scale and invest heavily in advanced infrastructure and integrated safety technologies. In contrast, regional and smaller ports often face financial and technical limitations that impede the development of comprehensive safety management systems [4], [11]. This inconsistency not only limits their capacity to manage risks effectively but also creates vulnerabilities within the global logistics chain, especially considering that dangerous goods frequently pass through multiple port facilities during transport.

The emergence of safety culture as a critical success factor represents a fundamental shift from purely technical solutions to human-centered approaches. The 43% reduction in incident rates associated with mature safety cultures underscores the importance of organizational commitment beyond regulatory compliance [43]. This finding challenges traditional port management approaches that prioritize operational efficiency over safety culture development [43].

4.2 Technological Contributions to Port Safety and Efficiency

Despite promising technological advances in dangerous goods (DG) handling, the review

reveals critical challenges impeding seamless integration of these innovations within existing Safety Management Systems (SMS) and risk assessment frameworks. Most ports, especially smaller and regional facilities, lack standardized protocols that facilitate such integration, resulting in fragmented implementations. This fragmentation is further exacerbated by regulatory heterogeneity across countries, as highlighted in studies by Rukavina (2020) [41] and Ma & Chen (2020) [43], which complicates the harmonization of safety practices and technological interoperability. Addressing these challenges requires concerted policy efforts to align international regulations, notably the IMDG Code, with emerging technologies such as blockchain for ensuring robust DG tracking and transparency.

Supporting this technological-policy alignment, investment in workforce capacity building through immersive training tools is essential to overcome persistent human factor risks identified earlier in the review [7], [35]. Furthermore, the operationalization of smart logistics and machine learning-driven decision support systems must be prioritized to enable real-time monitoring, detection, and control of DG handling processes, thereby enhancing both safety and operational efficiency [49].

The predominance of qualitative risk assessment methods [27], [36] in smaller ports reflects the resource constraints and the complexity inherent in implementing quantitative tools. However, research consistently indicates the superior predictive performance of quantitative approaches, notably probabilistic methods such as Monte Carlo simulation, which have demonstrated a 58% improvement in identifying critical control points within port operations. Despite their effectiveness, these advanced modeling techniques see limited adoption (only about 10.8% of studies), primarily due to barriers rooted in technical expertise shortages and computational demands.

4.3 Technological Innovation Impact and Implementation Challenges

The impact and challenges of implementing specific technological innovations in dangerous goods (DG) safety at ports have undergone rapid development through the use of Internet of Things (IoT) technology [4] marking a transformative shift towards real-time monitoring and proactive safety management. Empirical results show a significant improvement in detection capabilities, with increases of 65% and 52% for temperature deviation monitoring and gas leakage detection, respectively, highlighting the potential of IoT to strengthen the Safety Management System (SMS) [52].

However, the effective implementation of IoT and other emerging technologies is hindered by challenges in data integration across heterogeneous systems [3] [37], cybersecurity vulnerabilities [37], and the need for ongoing maintenance. This aligns with broader concerns about the technical and organizational capacity required to maintain advanced technological infrastructure in port environments [11], [13].

Artificial intelligence (AI) applications integrated with virtual reality (VR) [4] shows promising results in predictive maintenance and operational optimization [43], [46]. owever, these technologies remain at a moderate level of adoption due to barriers such as a lack of algorithm transparency, stringent data quality requirements, limited availability of experts, and the absence of binding regulations regarding technological developments in the handling of dangerous cargo. These barriers require targeted capacity building and transparency frameworks to facilitate broader acceptance and trust among port operators [49].

Blockchain technology, on the other hand, offers significant potential for improving traceability and documentation integrity throughout the hazardous goods supply chain [34], [41]. Although previous studies have confirmed the potential of blockchain in addressing long-standing challenges related to ownership chains and reducing human error, the adoption of this technology is still limited by concerns regarding energy consumption [46], scalability, and integration with legacy port systems. Nevertheless, the ongoing evolution and refinement of blockchain solutions demonstrate sustained efforts to overcome these barriers, supported by a clear alignment

with regulatory compliance needs.

4.4 Integration Challenges and Opportunities

The superior performance of integrated approaches (55% reduction in incidents) validates the systems thinking approach to port safety management. However, the analysis reveals significant challenges in achieving effective integration across organizational boundaries, technological platforms, and regulatory frameworks [10].

The effectiveness of integrated KPIs in safety monitoring highlights the importance of holistic performance measurement. The 36% improvement in predictive capability associated with leading indicators suggests opportunities for proactive safety management. However, developing meaningful leading indicators requires sophisticated understanding of causal relationships between operational activities and safety outcomes [36], [41].

4.5 Regulatory and Policy Implications

The analysis reveals gaps between international regulatory frameworks and emerging technological capabilities [40], [47]. While the IMDG Code [29], [36] provides comprehensive technical requirements, its prescriptive approach may limit innovation in safety management approaches. The variation in regional implementation suggests a need for more flexible regulatory frameworks that accommodate technological advancement while maintaining safety standards.

The emergence of digital technologies creates new regulatory challenges related to data privacy, cybersecurity, and system interoperability. Current regulatory frameworks lack specific guidance for digital safety systems, creating uncertainty for port operators and technology providers [24], [37], [53].

5. Conclusions

This systematic review confirms that improving safety in the handling of dangerous goods at ports is highly dependent on the integration of risk-based safety management systems, the application of quantitative risk assessment methodologies, and the utilization of the latest technological innovations such as real-time sensors, blockchain systems, and digital twin simulations. Globally, world-class ports have demonstrated the significant effectiveness of implementing virtual reality-based technology and training in reducing accident incidents and enhancing emergency response readiness. However, there remains a significant gap between major ports and ports in developing countries, including Indonesia, which face challenges related to human resources, technological infrastructure, and the harmonization of international regulations.

The practical implication of these findings is the need for close collaboration between port stakeholders, national authorities, and technology developers to design adaptive and internationally standardized safety management systems. Investment in human resource capacity building through interactive training and the use of virtual simulations is key to accelerating technology adoption and mitigating human error risks. On the regulatory side, policy updates covering data security, digital system interoperability, and minimum safety standards are essential for Indonesian ports to keep pace with international best practices and enhance their competitiveness on the global stage.

As a follow-up effort, comprehensive field research must be conducted to evaluate the effectiveness of technologies such as artificial intelligence, digital twins, and blockchain in the context of Indonesian ports and ports with limited resources. This research needs to focus on identifying implementation challenges, context-based solutions, and measuring the sustainability impact on work safety and environmental protection. In addition, the development of pilot projects and longitudinal studies is recommended to strengthen learning and ensure the continuity of digital transformation in the handling of dangerous goods.

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