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Original Article

Analysis of Safety 5.0 in Li-ion Battery Manufacturing within Industry 5.0: Preventing the Domino Effect

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Abstract *- Lithium-ion batteries store a large amount of energy, which can create serious safety risks such as domino-effect failures, where one problem triggers another. Traditional risk assessment methods mainly identify hazards but often fail to show how modern manufacturing processes are connected to these risks. This study addresses this gap by developing a simple and unified safety assessment framework using HIRA, AHP, and TOPSIS methods. A questionnaire survey was conducted with ten experts from battery manufacturing and industrial safety to collect data. The AHP analysis showed that domino-effect potential (0.42) and severity (0.27) are the most important factors in evaluating risks, while the consistency ratio (0.09) confirmed that the experts' judgments were reliable. The identified hazards were then ranked using the TOPSIS method. The results showed that thermal runaway is the most critical hazard with a score of 0.89, followed by fire and explosion with a score of 0.78 because of their high intensity and ability to spread quickly. These findings emphasize the need to consider chain reactions in industrial safety assessments. The proposed framework can also support advanced technologies such as AI-based and predictive risk management systems.*

Keywords *- AHP, DE, Industry 5.0, HIRA, Li-ion, TOPSIS.*

1. Introduction

Li-ion have become an important component of modern energy systems due to their high energy density, long cycle life, and many applications in electric vehicles, renewable energy storage, and easy-to-carry electronic devices. Li-ion battery manufacturing has significantly increases due to global demand for clean energy Technologies [18, 19]. However, Li-ion battery manufacturing involves complex and potentially hazardous processes, including electrode preparation, electrolyte handling, cell assembly, and formation cycling. During the formation stage, the battery undergoes its first controlled charge-discharge cycle, leading to the formation of a Solid Electrolyte Interphase (SEI) layer on the anode surface.

This layer is essential for stabilizing battery performance and preventing unwanted side reactions. However, due to formation conditions, it results in overheating of the battery, gas formation, and internal DE Effects which increase the risk of terminal runaway and DE failure. The use of inflammable electrolytes, reactive Materials and high electrical energy can cause a safety risk in an industrial area. Including some more risk failures like thermal instability, internal short circuits and material-related issues can also cause risk assessment in Li-ion Battery system [1, 3]. The major key challenges arise due to the interconnected nature of hazards. Traditional approaches majorly focus on individual hazards and failed to address interactions.

In Li-ion battery manufacturing systems, safety risks are highly complex, where a single hazard can trigger out cascading failures known as the Domino Effect. As a result, some traditional methods often fails to identify and prioritize critical hazards properly. Even conventional methods, such as Failure Mode and Effects Analysis, rely heavily on some manual assessments and are unable to capture the complexity of modern manufacturing systems. [25, 32]. With the upcoming techniques of Industry 5.0, manufacturing system is relying towards human centric, intelligent and resilient features. The concept of Safety 5.0 further increases the strength of advanced technologies in such a way [9, 29].

Despite the significant advancements in Li-ion battery safety research, various critical challenges remain unresolved in the safety systems of manufacturing environments. Existing studies have primarily focused on the thermal runaway mechanisms, battery materials, failure analysis, or conventional risk assessment approaches. However, limited attention has been given to the interconnected nature of manufacturing hazards that can initiate or transmit the domino-effect failures across various production stages.

Table 1. Transition of Safety Paradigms from 1.0 to 5.0

Sno	Safety Stage	Period	Key Concept	Main Characteristics
1	Safety 1.0	Early 1900s	Engineering Controls	Earlier approaches to safety were largely centered on hardware-based solutions, including the installation of machine guards, the incorporation of safety valves in boilers, and the use of physical barriers to prevent worker injuries such as crushing or burns. In comparison to the early 1900s, at that time, human-centric behaviour does not receive that much attention, and that's why it was considered a secondary part.
2	Safety 2.0	1950s–1980s	Human Factors	Safety professionals recognised that a large number of accidents occur day by day because of human tentative behaviour, which cause to failure and risk. However, precise attention was given to the training program, safety rules and regulations, and risk awareness.
3	Safety 3.0	1980s–2010	Systems Thinking	
4	Safety 4.0	2011–2019	Digital Safety	Digitally established technologies like IoT, connected sensors and data analytics. These technologies further help the safety team to monitor conditions on a real-time basis, automatically detect hazards, and use precise historical data to predict the chances of an accident happening.
5	Safety 5.0	2019–Present	Human-Centric Intelligent Safety	Safety 5.0 brings AI, DTs, collaborative robots, and predictive analytics together with a firm commitment to human well-being. The goal is a safety system that adapts, learns, and responds to changing conditions with the worker's welfare as its highest priority.

Moreover, the existing research rarely incorporates Safety 5.0 principles with structured multi-criteria decision-making approaches such as HIRA, AHP, and TOPSIS to support intelligent, human-centric, and proactive safety management. Therefore, there is a necessity for a comprehensive framework that systematically analyses, identifies, evaluates, and prioritizes safety risks while considering the domino-effect potential approach in Li-ion battery manufacturing under the Industry 5.0 paradigms.

In the above context, the present study emphasis an integrated framework that combines Hazard Identification and Risk Assessment (HIRA), the Analytic Hierarchy Process (AHP), and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to evaluate the domino-effect-based safety risks in Li-ion battery manufacturing systems. These frameworks suggest to systematically identifies, prioritizes, and ranking critical manufacturing hazards while incorporating the principles and safety guidelines of Safety 5.0 to support the intelligent, human-centric, and proactive industrial safety management approaches. The real fact of this study lies in the development of a unified, operative Safety 5.0 framework that integrates Hazard Identification and Risk Assessment (HIRA), the Analytic Hierarchy Process (AHP), and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for safety risk assessment in Li-ion battery manufacturing. Unlike previous studies, which majorly focuses on the individual hazards, thermal runaway mechanisms, or standalone risk assessment methods, the proposed framework is systematically used to evaluate the manufacturing hazards based on their domino-effect potential. Additionally, the integration of Safety 5.0 principles with Industry 5.0 concepts introduces a structured decision-making framework for an intelligent, human-centric, and proactive safety management approach in advanced battery manufacturing environments.

1.1. Overview of Li-ion Battery Manufacturing Process

Li-ion battery production involves systematic steps designed to ensure uniformity, efficiency, and operational safety. The process begins with electrode Fabrication. The electrodes were prepared using a slurry coating process. This involves solvent evaporation and mechanical compression to achieve the required structural and physical properties. Next, cell assembly is carried out by arranging electrodes and separators in structured configurations. An electrolyte solution is mixed to make ionic pathways between the electrodes. The assembled cells then undergo formation cycles and ageing processes to stabilize their electrochemical Behavior and improve the long-term performance. Then, testing is conducted to evaluate the quality, reliability, and safety of cells. At each stage of the manufacturing process, there is a potential risk of safety-related issues, including material contamination, internal sort circuits, and thermal instability. If not properly controlled, these issues can escalate into progressive failures, potentially leading to chain reactions or Domino type incidents in industrial manufacturing environments.

1.2. Key Materials in Li-ion Batteries

Li-ion batteries have several functional components to determine their performance and safety. The cathode is made up of materials like lithium iron phosphate or nickel manganese cobalt, which impact both energy capacity and thermal stability, and the anode is made up of graphite, which enabling the insertion and release of lithium ions during charge and discharge cycles. A polymer separator is placed between the electrodes to prevent internal short circuits while allowing ion transport. The electrolyte, which contains lithium hexafluorophosphate, is act as the medium for ionic conduction within the cell. The current collectors made of aluminium (cathode) and copper(anode) helped electrons to flow. In these way, the overall study recognised that the selection, purity and compatibility of these materials specifically affect both electrochemical performance and safety of Li ion batteries.

2. Literature Review

In the above study, the Li ion batteries are being used widely in energy systems, and for that, their safety has become a major concern. Most research focuses on how these batteries behave under heat and how failures can develop. Most of the time, it has been recognised that such behaviours are not that easy to predict. For instance, [1] analysed thermal characteristics and reported that irregular heat distribution can trigger thermal runaway and fire under critical conditions. Similarly, [3] investigated internal structural changes at the time of failure, and excessive heat generation is a major cause of fire and explosion hazards. Others have highlighted the role of internal defects and material properties. For example [4], it has been reported that internal short circuits, over-charging, and separator failure increase safety risk. Additionally, [5] reported that the material instability and manufacturing defects play an important role in safety risk. Moreover, it had been examined that the impact of the manufacturing process on the battery system and safety. Study [17] showed that the electrode parameters, such as slurry composition and drying conditions, directly affect battery behaviour. Although [21], the industrial challenges and defects occurring during coating, calendaring and assembly stages, which can limit the reliability and increase the safety risk. Risk assessment approach has also been applied to analyse safety in battery systems [25]. Failure Mode and Effects Analysis (FMEA) is used to analyse critical failure modes and [32] reported improved methods to enhance safety risks. However, some approaches depend on subjective judgement and cannot capture the complex interactions between multiple hazards. Due to the rapid growth of IoT, researchers have started exploring the Industry 5.0 concept in manufacturing. For example, [9] human-centric approaches, while [29] IoT based framework and digital twin technologies to improve the monitoring and decision-making process. Furthermore, these approaches help in real-time data analysis and predict safety issues. Even with these new approaches, many studies still focus either on battery performance or on individual hazard analysis. Frameworks that consider hazard interactions, DE mechanisms, and advanced decision-making techniques in Li-ion battery manufacturing. Therefore, this study aims to address this gap by developing a detailed safety assessment framework that integrates HIRA, AHP, and TOPSIS within the context of Industry 5.0 and Safety 5.0.

Table 2. Unaddressed Issues

S.No	Author	Year	Unaddressed Issues
1	Chen et.al., [1]	2005	Although the study gives a detailed thermal analysis of Li-ion batteries, it mainly focuses on cell-level thermal modeling and does not point out safety risks occurring during large-scale battery manufacturing processes.
2	Finegan et .al., [3]	2015	Although analyzed the internal failure mechanisms of Li-ion batteries have been analysed during TR, limited research has focused on preventive safety strategies during the battery manufacturing process.
3	Jin et.al., [4]	2017	Focuses on general safety factors and accident cases related to Li-ion batteries, but it does not tell about advanced safety frameworks or the use of intelligent safety management systems in Industry 5.0-based manufacturing environments.
4	Saini [5]	2017	It explains improvements in manufacturing safety and performance. Its main focus is on battery design and materials. It does not give much importance to human-centred and smart safety systems that are becoming important in modern manufacturing setups.
5	Adrien M. Bizeray et.al., [6]	2018	In this paper, improvements are made in electrochemical modeling and parameter estimation, mainly related to battery diagnostics. Still, manufacturing safety risks, prevention of thermal runaway during production, and intelligent safety approaches are not considered.

6	Morello et.al., [7]	2018	Some studies have introduced advanced battery management methods, but there is still a lack of research on real-time monitoring and predictive safety systems for reducing thermal risks in Li-ion batteries.
7	Wu et.al., [8]	2019	Studied thermal runaway and material-related safety issues, only limited attention has been given to connecting manufacturing safety with advanced monitoring systems and Industry 5.0 concepts. Also, comprehensive methods for evaluating safety risks at different stages of battery manufacturing are still not well developed.
8	Bisschop *et. al.,* [10]	2020	Safety management and emergency response are mainly discussed in the context of electric vehicles. However, the focus remains on operational safety and accident handling, without covering safety challenges during manufacturing.
9	Duan et.al., [11]	2020	indicated that although many studies focus on improving material-level safety of Li-ion batteries, limited research addresses integrated safety management and real-time monitoring in practical battery systems.
10	Yi et.al., [13]	2021	Although the study focuses on defect detection in Li-ion batteries, it does not address safety management during battery manufacturing or the application of Industry 5.0 technologies for improving manufacturing safety**.**
11	Kaliaperumal et.al., [14]	2021	Although the study provides a comprehensive review of Li-ion battery failure mechanisms and mitigation strategies, it mainly focuses on general battery reliability and safety mechanisms. The research does not specifically address safety management during Li-ion battery manufacturing processes. Alternatively, the integration of Industry 5.0 technologies to improve manufacturing safety and prevent DE failures.
12	Xie et.al., [15]	2021	Although the TR behavior of Li-ion batteries has been experimentally studied, limited research focuses on developing integrated monitoring and prevention strategies to reduce TR risks and toxic emissions in real battery systems.
13	Chen et .al. (2021) [17]	2021	Although previous studies have reviewed Li-ion battery safety issues and mitigation strategies, limited research has focused on integrated safety management and risk prevention during Li-ion battery manufacturing processes.
14	Anandavel et.al., [16]	2021	DT technology has been proposed for Li-ion battery monitoring, limited studies focus on its practical implementation for improving safety and risk prevention in battery manufacturing and operation systems.
15	Aydin Örül et.al., [22]	2023	Although the study provides a detailed overview of Li-ion battery manufacturing processes and challenges, it mainly focuses on production efficiency and quality improvement. The research does not specifically examine battery manufacturing safety within the Industry 5.0 framework, particularly the role of human-centric automation, AI-based safety monitoring, and risk prevention strategies in manufacturing environments.
16	Oh et.al., [20]	2023	Although the study investigates accidents occurring during non-application stages of Li-ion batteries, it mainly focuses on incident analysis and environmental impacts. Furthermore, the research does not particularly explore advanced safety frameworks for Li - ion battery manufacturing systems, including AI-based, smart manufacturing and human-centric approaches.
17	Alves et.al., [23]	2023	The basic idea of human-centric approaches has been discussed in these evaluations, but still, there are limited industrial examples that showcase how these concepts can be applied in real-time manufacturing environments.
18	Konwitschny et.al., [24]	2024	Focuses on manufacturing system design and equipment adaptation instead of advanced safety management or Industry 5.0-based safety improvements.
19	Maddipatla et.al. [25]	2024	One study encompasses a prototype assembly system for next-generation batteries, but its major focus is on manufacturing design and equipment adaptation. It rarely focuses on advanced safety management or the use of Industry 5.0 technology for improving safety in battery manufacturing.
20	Song et.al., [26]	2024	Focuses on failure mode analysis of cylindrical batteries but lacks Industry 5.0 safety features like real-time monitoring and smart safety systems.
21	Yuan et.al., [27]	2024	A similar study focuses on improving thermal stability based on cathode material analysis. While this helps in understanding material performance, it does not address safety risks

			during manufacturing or the role of smart safety monitoring systems in production environments.
22	Zaheer et.al., [28]	2024	In a few cases, a real-time monitoring system for battery safety is established, but the major focus remains on battery operation and health monitoring. It does not extend to advanced safety frameworks for manufacturing, particularly within Industry 5.0 environments that include AI-based safety analytics.
23	Wang et.al., [31]	2025	Although the study reviews accident characteristics and environmental impacts, it mainly focuses on incident analysis and risk management during battery handling and lifecycle stages. It does not specifically address advanced safety frameworks for Li-ion battery manufacturing within Industry 5.0 environments.
24	J. Dai et.al., [32]	2025	Although several studies have improved risk assessment methods for Li-ion battery manufacturing, most research still focuses on general safety evaluation rather than comprehensive safety management during the manufacturing stage. In addition, existing methods often do not integrate advanced smart manufacturing concepts such as Industry 5.0. Therefore, further research is required to develop integrated safety assessment frameworks that combine intelligent decision-making techniques with human-centric and automated manufacturing environments.
25	Zhao et.al., [33]	2025	Although TR behavior at different state of charge levels has been experimentally analyzed, limited research focuses on developing effective safety monitoring and prevention strategies to control TR risks in Li-ion battery systems.
26	Lei Yao et al., [35]	2025	Although Lei Yao et al. (2025) reviewed Li-ion battery safety Issues, integrated lifecycle safety monitoring and multi-fault prediction methods for battery systems are still limited.

The reviewed literature indicates substantial progress in Li-ion battery safety research, particularly in understanding the thermal runaway mechanisms, battery materials, failure analysis, and battery management systems. Recent studies have also highlighted the potential of Industry 5.0 technologies, including Artificial Intelligence (AI), the Internet of Things (IoT), and Digital Twins, to enhance a real-time monitoring system, predictive maintenance application, and intelligent manufacturing system. However, most existing studies investigate these aspects independently with accurateness and gives limited attention to the interconnected nature of manufacturing hazards that can hinder the domino-effect failures across various production stages. Furthermore, only a limited number of studies have introduced structured multi-criteria decision-making techniques with Safety 5.0 principles to support the systematic hazard evaluation and risk prioritization safety. Subsequently, The existing approaches are predominantly based on qualitative assessments or conventional risk analysis methods, giving limited emphasis on intelligent, human-centric, and proactive safety management approaches.

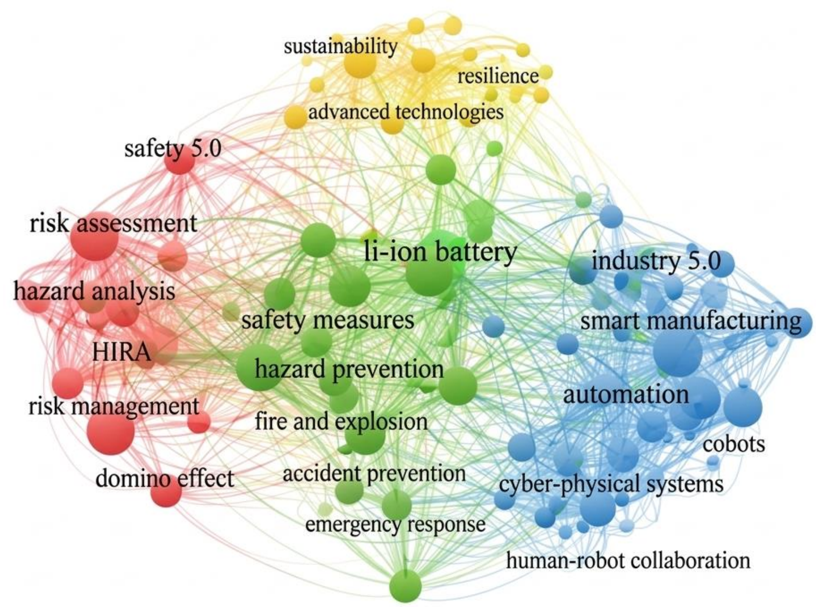

Fig. 1 VO Sviewer-based bibliometric network visualisation of research on Safety 5.0 in Li-ion battery manufacturing within Industry 5.0

Consequently, still it remains a need for a comprehensive framework that combines hazard identification, quantitative risk prioritization, and Industry 5.0 technologies to support the safety decision-making approach in Li-ion battery manufacturing environments. The proposed HIRA–AHP–TOPSIS framework encompasses this gap by introducing a structured methodology for evaluating and prioritizing manufacturing hazards based on their domino-effect potential.

Figure 1 Represent The network map, which illustrates the co-occurrence of key research keywords collected from scientific literature. The size of each node represents the frequency of keyword occurrence, while the distance and link strength indicate the degree of association between terms. The visualization reveals four major clusters: (i) risk assessment and hazard analysis (red), (ii) Li-ion battery safety and prevention strategies (green), (iii) Industry 5.0 and smart manufacturing technologies (blue), and (iv) sustainability and resilience-driven advanced systems (yellow). The interconnected structure specifically highlights the hybrid integration required to hinder the domino effect. The biometric network visualization highlights the upcoming research landscape at the intersection of safety 5.0 and Industry 5.0 in Li ion safety battery manufacturing systems. The intersection of Safety 5.0 and Industry 5.0 in Li-ion battery manufacturing. The red cluster focuses on traditional.

Safety engineering approaches such as HIRA, risk assessment, and hazard investigation, which form the foundation for identifying potential DE. The green group clearly shows the positive focus on Li ion battery system, hazard prevention, fire and explosion risk assessment and emergency risk strategies. The blue cluster reflects the emergence of the Industry 5.0 model, which includes automation, smart manufacturing, and human-robot collaboration, indicating a shift toward intelligent and human-centric safety systems. The yellow cluster highlights sustainability, resilience, and advanced technologies, pointing out the importance of integrating environmental and adaptive safety concerns. The strong association among clusters suggests that preventing DE in battery manufacturing requires a unified framework that combines risk assessment methodologies with advanced Industry 5.0 technologies.

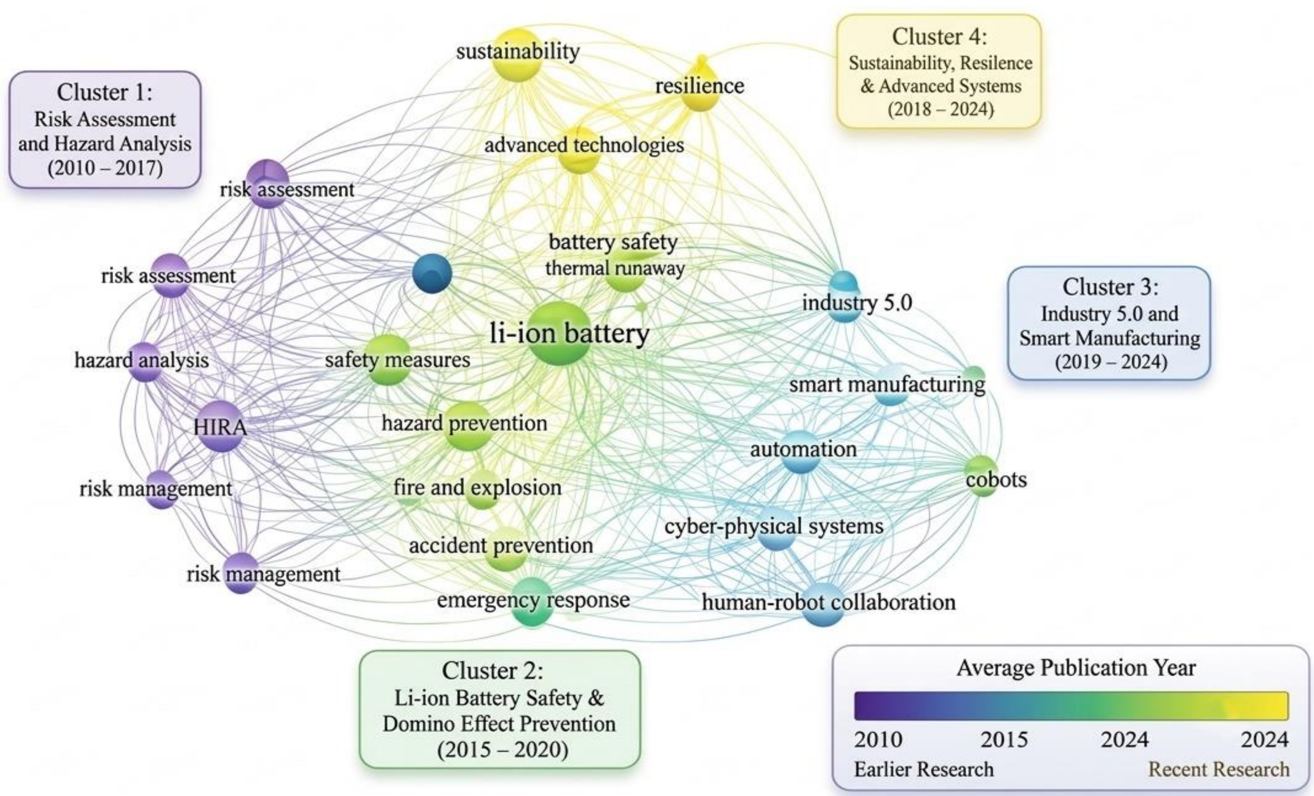

Fig. 2 Overlay Visualization of Keyword Co-occurrence Based on Publication Year in Li-ion Battery Manufacturing Research

Figure 2 shows the overlay visualization of keyword co-occurrence based on the average publication year in Safety 5.0- and Industry 5.0-related Li-ion battery manufacturing research. It highlights how research themes have developed over time, where darker colors represent old studies and brighter colour indicates current work. The figure shows a clear growth in the field. Old studies (2018 to 2020), shown in purple and blue colour, mainly focused on old safety methods such as risk assessment, hazard analysis, HIRA, and DE modeling. As research progressed (2021 to 2022), the focus shifted toward Li-ion battery safety, hazard prevention, fire and explosion analysis, and emergency response, building the main research area.

In recent years (2023 to 2025), represented by green to yellow colours, there has been a observable shift toward Industry 5.0 concepts, including smart manufacturing, automation, and human–robot collaboration. At the same time, topics such as sustainability, resilience, and Safety 5.0 reflect a move toward more intelligent, human-centric, and sustainable safety systems.

Overall, this progression highlights an important research gap and supports the need to integrate Safety 5.0 with Industry 5.0 for preventing domino effects in Li-ion battery manufacturing.

Fig. 3 Density Visualization of Keyword Co-occurrence in Li-ion Battery Manufacturing Research.

Figure 3 shows the density map of research themes based on keyword frequency and co-occurrence. Warmer colors (yellow/Red) indicate areas with high research activity, while cooler color (green/blue) represent topics that are still emerging or less explored. The map clearly shows that risk assessment, hazards analysis, and HIRA are highly concentrated, which means most studies still focus on traditional Safety methods.

The dense area around Li-ion batteries and safety measures represents the main focus of this research field. On the other hand, topics like Industry 5.0, smart manufacturing, ad cyber- physical System appear in lower-density areas, suggesting that these are still developing and need more attention.

Similarly, Sustainability and resilience appear as moderate- density clusters, indicating a gradual shift towards a more advanced and future-oriented safety approach. Overall, this pattern points to a research gap, especially in integrating Safety 5.0 with Industry 5.0 for preventing Domino effects in Li-ion battery manufacturing.

3. Methodology

Fig. 4 Research Methodology Flow chart

3.1. Research Design

This study adopts an integrated quantitative framework to identify, evaluate, and prioritize safety risks in Li-ion battery manufacturing. The primary objective is to determine the hazards that are most likely to initiate DE accidents in industrial production systems. Li-ion battery production involves linked thermal, chemical, and electrical processes, which makes risk interactions highly complex. Therefore, a combined multi-criteria decision-making approach was used to capture both direct and flowing risks. The proposed framework represents HIRA, AHP, and TOPSIS to identify, evaluate, and prioritize manufacturing. To ensure the transparent accuracy of evaluation, the numerical inputs required for AHP and TOPSIS were recognised through an expert questionnaire survey. It requires a minimum of ten domain experts from battery manufacturing, industrial safety, maintenance and academia, ensuring a real and acceptable, well-recognised evaluation.

3.2. Hazard Identification and Risk Assessment

The Li ion battery manufacturing system is majorly divided into various stages, such as raw material handling, electrode preparation, cell assembly, electrolyte filling, formation cycling, testing and packaging. Therefore, HIRA was used to analyse or detect the major hazards present at each stage. On the basis of old studies, industrial observations, and expert judgements, the main hazards recognised are thermal runaway, fire and explosion, dust explosion, electrolyte leakage, and electrical shock. These hazards are reported in the industrial environment, which supports their selection in this evaluation. These point of view on selection helped in understanding which hazards require more attention in safety. The interconnected nature of these hazards shows that failures in one stage can affect other stages, making it important to study domino-type effects across the process.

3.3. Data Collection Through Expert Questionnaire

Quantitative data for this study were collected through a structured questionnaire survey. The experts were selected using a purposive sampling technique, which is based on their professional experience, skills, knowledge and domain expertise in Li-ion battery manufacturing, industrial safety, maintenance, and academia in a detailed study. The priority level of selection criteria required each expert to possess a minimum of five years of relevant professional or research experience, and demonstrated with the entire knowledge of battery safety, hazard identification, risk assessment, or safety management systems. This approach mainly ensures that the collected judgments using a few techniques were technically reliable and appropriate for multi-criteria decision-making analysis and interpretation. The questionnaire consisted of two sections. In the first section, experts performed pair wise comparisons of five safety evaluation criteria using Saaty's 1–9 scale for AHP analysis. In the second section, the same experts evaluated each identified hazard against the selected criteria using a rating scale of 1–10 for TOPSIS analysis. The five evaluation criteria considered in this study were: probability of occurrence (C1), severity of consequences (C2), detect ability of hazard (C3), domino effect potential (C4), and environmental impact (C5). Before collecting the prior data, first of all, the questionnaire was reviewed to ensure that the clarity, relevance, and completeness of the evaluation criteria and hazard description were appropriate. Although the Minor revisions were taken to improve the wording and readability of the questionnaire. Furthermore, the reliability and consistency of the expert judgments or opinions were verified using the AHP Consistency Ratio (CR). However, The obtained CR value of 0.09 was below the acceptable threshold of 0.10, which confirms that the pairwise comparisons were sufficient for decision-making analysis. Further, the study involves ten domain expertise, which is considered an appropriate sample size for AHP-based multi-criteria decision-making studies. In AHP, the quality and consistency of the expert judgments or their opinions are more essential than a large number of respondents. The final selected experts possessed to relevant industrial and academic experience in Li-ion battery manufacturing, industrial safety, maintenance, and risk assessment, ensuring technically reliable evaluations. The acceptable Consistency Ratio (CR = 0.09) supports the reliability and consistency of the collected responses accurately.

3.4. AHP-Based Criteria Weight Determination

The AHP method was employed to determine the relative importance of the evaluation criteria. Based on the aggregated responses obtained from the expert questionnaire survey, a pair-wise comparison matrix was constructed to evaluate the relative significance of each criterion. After normalization and calculation of priority vectors, the weights of the criteria were determined and used for further risk analysis. These weights reflect the relative importance of each criterion in assessing safety risks within Li-ion battery manufacturing systems.

Table 3. Safety Evaluation Criteria

Code	Criterion	Description
C1	Probability of Occurrence	Probability that the hazard will materialize under normal or unusual operating conditions.
C2	Severity of Consequences	Magnitude of potential harm, including injuries, fatalities, equipment loss, or production disruption.
C3	Detect the ability of Hazard.	Degree to which existing monitoring systems can identify the hazard before it escalates.
C4	Domino Effect Potential	Capacity of the hazard to trigger cascading secondary failures across interconnected systems.
C5	Environmental Impact	Scope of potential damage to the surrounding environment, including

Table 4. AHP Pair wise Comparison Matrix

Criterion	C1	C2	C3	C4	C5
Probability(C1)	1	1/3	3	1/5	3
Severity (C2)	3	1	5	1/3	5
Detect ability (C3)	1/3	1/5	1	1/7	3
Domino Effect (C4)	5	3	7	1	7
Environmental (C5)	1/3	1/5	1/3	1/7	1

After normalization and row averaging, the priority weights were obtained. In the study, the final AHP-derived weights used for risk analysis were

Table 5. AHP Criteria Weights

Criterion	Code	Weight	Percentage
Probability of Occurrence	C1	0.13	13%
Severity of Consequences	C2	0.27	27%
Detect the ability of Hazard.	C3	0.08	8%
Domino Effect Potential	C4	0.42	42%
Environmental Impact	C5	0.10	10%

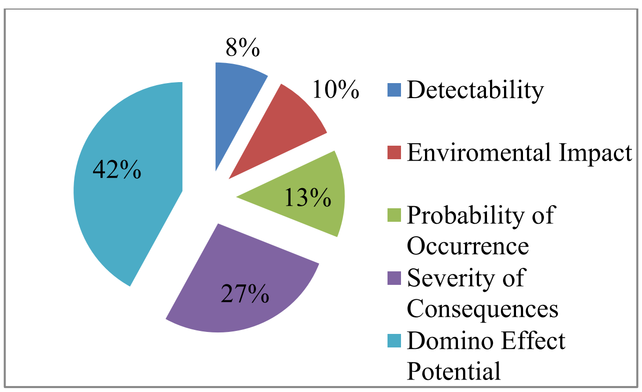

Fig. 5 AHP Criteria Weights for Safety risk Evaluation

In these study, the result indicates that the domino effect is the most emerging evaluation criteria based on severity. Although the hazard which trigger fails to present the greatest concern over Li ion battery production environment, so that they can move forward into large-scale industrial incidents.

3.5. Consistency Check

To clarify expert judgements, the consistency of the pairwise comparison matrix was recognised using the Consistency Ratio (CR). The evaluation shows a CR value of 0.09, which is below the acceptable threshold of 0.10. This ensures that the expert evaluation is at an acceptable level of consistency and therefore reliable in making decision power.

3.6. TOPSIS-Based Hazard Ranking

TOPSIS was used to prioritize the identified hazards using the criteria weights derived from AHP. The hazard decision matrix, designed based on expert questionnaire responses, is presented below:

3.6.1. Decision Matrix

Table 6. TOPSIS Decision Matrix

Hazard	C1	C2	C3	C4	C5
Thermal Runaway	8	9	4	9	7
Fire / Explosion	7	9	5	8	7
Dust Explosion	6	8	5	7	6
Electrolyte Leakage	6	7	6	6	8
Electrical Shock	5	6	7	4	4

3.6.2. Normalisation, Weighting, and Ranking

The decision matrix was normalized and multiplied by AHP weights. The positive and negative ideal solutions were calculated, followed by distance and closeness coefficients.

Table 7. TOPSIS Final Ranking

Hazard	Closeness Coefficient	Rank	Risk Level
TR	0.89	1st	CRITICAL
Fire / Explosion	0.78	2nd	CRITICAL
Dust Explosion	0.61	3rd	HIGH
Electrolyte Leakage	0.47	4th	MEDIUM
Electrical Shock	0.13	5th	LOWER

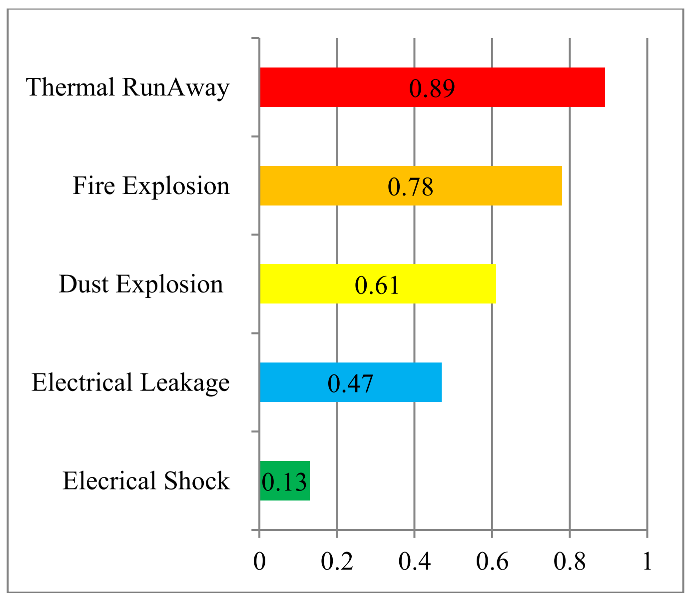

Fig. 6 Hazard Risk Ranking TOPSIS Analysis Result

The results show that thermal runaway is the most critical hazard in Li-ion battery manufacturing. This is mainly because these hazards are more severe, can spread easily as DE-type failures, and are difficult to detect in the early stages. This observation is the same with what is generally seen in similar industrial systems. In most of the cases, they become difficult to control. On the other hand, electrical shock is important from a worker safety point of view, but it has a lower chance of affecting the overall system, so it is ranked lower. The high ranking of thermal runaway also shows that it can trigger Chain reactions, which makes it an important area to focus on for improving safety measures. Therefore, giving more attention to this hazard can help in reducing larger system failures.

3.7. Integration of Safety 5.0 Concepts

The final risk classification was incorporated within the framework of Safety 5.0, emphasizing the role of intelligent and adaptive safety systems in Li-ion battery manufacturing. The above findings represent that the high-priority hazards, such as thermal runaway and fire/explosion events, require more proactive safety mechanisms to minimize their impact and prevent domino-effect failures precisely. Therefore, this study also recommends the integration of AI-based monitoring systems, IoT sensors, real-time safety networks, and Digital Twin technologies to enhance the hazard detection, provide early warning alarm, and reduce domino-effect risks in advanced Li-ion battery manufacturing environments in a proper sufficient manner without any consequences It should be noted that the AI, IoT, and Digital Twin components discussed in this study are developed as future implementation strategies for better safety and security but were not experimentally implemented or validated within the scope of the present research project. Their inclusion preferably demonstrates how the proposed HIRA, AHP, and TOPSIS framework can be integrated within the Industry 5.0 technologies to support the intelligent, human-centric, and proactive safety management approach in future Li-ion battery manufacturing systems.

3.8. Discussion and Comparison with Existing Studies

The findings of this study are furthermore consistent with the previous research reporting thermal runaway as the most critical safety hazard in Li-ion battery systems [1, 3]. Similarly, Wu et al. [8] emphasized the necessity of thermal stability and fire prevention in battery safety. However, unlike these studies, the current research extends beyond hazard identification by integrating majorly on HIRA, AHP, and TOPSIS within a Safety 5.0 framework to prioritize the manufacturing hazards according to their domino-effect potential. In fact, while recent Industry 5.0 studies have highlighted AI, IoT, and digital twin technologies for intelligent manufacturing [9, 32], they do not provide a structured based decision-making framework or approach for manufacturing safety risk prioritization. Therefore, the proposed framework bridges to cover this gap by combining conventional risk assessment with intelligent decision-support techniques for proactive safety management approaches.

Table 8. Comparison table

Aspect	Existing Studies	Present Study
Research focus	Primarily focused on thermal runaway and individual hazard	Evaluates major manufacturing hazards across the Li-ion battery production process
Risk assessment approach	Conventional methods (FMEA, HIRA qualitative analysis)	Integrated HIRA-AHP-TOPSIS Framework
Hazard evaluation	Individual hazard analysis	Domino-effect-based hazard prioritization
Industry 5.0 integration	The Industry 5.0 concept discussed the conceptual	Practical Safety 5.0 decision-making framework
Risk prioritization	Limited or qualitative hazard ranking	Quantitative hazard ranking using TOPSIS

3.9. Integration of Safety **5.0** *Concepts*

The proposed Safety 5.0 framework has practically applicable in Li-ion battery manufacturing systems by supporting systematic hazard identification, risk prioritization, and safety decision-making across different production stages. The integration of HIRA, AHP, and TOPSIS enables safety expertise to identify the critical hazards, prioritize preventive actions, and improve overall manufacturing safety. Furthermore, these frameworks provides a core foundation for the future integration of Industry 5.0 technologies, such as AI-based monitoring systems, IoT sensors, and Digital Twin platforms, to support the predictive safety management and real-time risk monitoring with pros and cons. However, this study has certain limitations or drawbacks that should be acknowledged. These proposed framework is based on the expert judgments or opinions and has not been validated using the real-time industrial datasets or through the practically implementation of AI, IoT, and Digital Twin technologies. Additionally, a comprehensive sensitivity analysis or study was beyond the scope of the present study. Future research should focus on validating the framework in real industrial environments and evaluating its robustness through major sensitivity analysis and real-time industrial applications of monitoring data systems.

4. Conclusion

This study describes a systematic approach for safety risks in Li ion battery production by combining HIRA, AHP and TOPSIS within a Safety 5.0 approach. The results authorize that the thermal runaway and fire-related events remain the most crucial concern because of their high severity. In fact, in such situations, failure can easily spread quickly and turn into DE incidents, which increases the risk of larger problems. This can lead to severe industrial damage and safety issues that are uncontrollable. This framework helps in identifying hazard's in a more organised way and makes it easier to decide which risk needs more focus. It supports technologies like AI, IoT and digital twin for real-time monitoring and predicting safety issues.

In battery manufacturing systems, it is necessary to understand how the process works with proper guidelines, rules and regulations. Consequently, the proposed framework suggests a practical and systematic decision-support approach for prioritizing the manufacturing hazards and contributes to the advancement of Safety 5.0 implementation in Industry 5.0, which enables Li-ion battery manufacturing environments.

Future Scope

This study would be beneficial when this was used in actual industrial datasets in real-time conditions, so that it will give a clear understanding. It might also be helpful to explore AI methods, because these can support early hazard detection and improve the accuracy of prediction. In addition, digital twin models can be considered to examine possible failure situations and understand their impact on system safety. The approach developed in this study could also be relevant for other high-risk areas such as the chemical and energy sectors.

Conflicts of Interest

The authors declare that there are we have no conflicts of interest related to this publication. The study was completed freely, without any commercial or financial influences that could be considered a potential conflict.

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