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Review Article

SYSTEMIC FAILURES IN LITHIUM-ION BATTERY FIRE FATALITIES: A CASE STUDY OF THE TERRA DRONE BUILDING

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Abstract
This study analyzes a fatal fire incident at the six-story Terra Drone building in Jakarta, Indonesia, which resulted in 22 deaths due to toxic smoke inhalation. An instrumental case study, combined with root cause analysis, was employed, supported by international literature and a national regulatory review. The investigation found that the fire was triggered by the fall of a 30,000 mAh lithium polymer (LiPo) battery from a storage pile on the ground floor, initiating a thermal runaway event. The analysis identified six systemic safety management failures: absence of standard operating procedures for hazardous battery storage, lack of an occupational health and safety officer, inadequate safety training, absence of a designated storage facility, lack of fire protection systems (smoke detectors, alarms, and appropriate suppression media), and inadequate evacuation routes. The rapid release of toxic gases during Li-ion battery thermal runaway, combined with improper storage in a main evacuation path and the absence of passive and active fire protection, created a fatal scenario. The study recommends stronger regulatory enforcement, adoption of NFPA 855, multi-layer fire detection and suppression systems, and improved safety culture through training and routine audits.

Keywords: Fire Protection System, Hazardous Material Management, Lithium-Ion Battery Fires, Thermal Runaway.

INTRODUCTION

There has been an exponential growth in the use of lithium-ion (Li-ion) batteries over the last decade, driven by the portable technology revolution and the global energy transition toward electrification (Jossen, 2015; Chen et al., 2021; Xu et al., 2021). In Indonesia, the adoption of this technology in the commercial and industrial sectors, including in the operations of technology companies such as PT Terra Drone Indonesia, has increased rapidly without an adequate understanding of its inherent safety risks (Kompas, 2025). The fire incident at the Terra Drone Building on December 9, 2025, which killed 22 people, serves as a stark reminder and a critical case study of the fatal consequences that can occur when high-energy-density technology is introduced into an environment that is not equipped with adequate safety infrastructure (Figure 1).

Figure 1. Terra Drone Building Fire Incident

The characteristics of Li-ion battery fire hazards are fundamentally different from those of conventional solid-material fires. The core risk lies in the phenomenon of thermal runaway—an uncontrolled exothermic chain reaction within the battery cell triggered by mechanical, thermal, or electrical failure (Wang et al., 2012; Wang et al., 2019; Qiu & Jiang, 2022; Chen et al., 2021; Huang et al., 2021; Wang et al., 2023; Jiang et al, 2025). This process releases combined hazards in the form of intense heat (often exceeding 800°C), pressurized jets of flame, projectiles of cell fragments, and, most critically in building environments, large volumes of highly flammable and toxic gases (Ribière et al., 2012; Wang et al., 2019; Mao et al., 2024). Gas components such as hydrogen fluoride (HF) and carbon monoxide (CO) released during thermal runaway possess acute lethal toxicity, potentially causing victims to collapse within minutes without respiratory protection (Chen et al., 2021; Xu et al., 2021). The rapid escalation of these hazards often exceeds the response capacity of conventional fire safety systems designed for ordinary fire scenarios (Sebastian, 2022; Snyder & Theis, 2022).

International literature has extensively documented the hazard characteristics, failure mechanisms, and mitigation strategies associated with Li-ion battery fires, particularly in the context of electric vehicles (EVs) and grid-scale energy storage systems (ESS) (Liu & Sun, 2021; Larsson & Mellander, 2014; Wang et al., 2019; Lyu et al., 2020; Conzen et al., 2023). Standards such as NFPA 855 (Standard for the Installation of Stationary Energy Storage Systems) have been developed to provide comprehensive guidance on spatial design, detection, suppression, and safety distances (NFPA, 2023a). However, a significant research gap remains regarding the application of these safety principles in the context of commercial medium-scale storage and use in multi-story office buildings, as in the case of Terra Drone (Sebastian, 2022; Jia et al., 2025). Furthermore, integrative analyses examining the interaction between non-compliance with national regulations (e.g., building codes and occupational health and safety regulations) and the absence of specific technical standards remain limited (Conzen et al., 2023; Wang et al., 2025).

This study aims to fill this gap by analyzing the Terra Drone incident as an instrumental case study. The specific objectives of this article are: (1) to reconstruct the chronology and mechanism of failure based on police findings and the hazard characteristics of Li-ion batteries; (2) to identify the root causes of system failure through an analysis of the gaps between field practices, applicable national regulations, and international best standards; and (3) to develop comprehensive and actionable policy, technical, and managerial recommendations to prevent the recurrence of similar tragedies in Indonesia and in countries with similar regulatory contexts.

Although numerous studies have examined the fire hazards and thermal runaway characteristics of lithium-ion batteries, most previous research has focused on electric vehicles, battery testing, or large-scale energy storage systems (Wang et al., 2019; Xu et al., 2021; Chen et al., 202; Zhang et al., 2023). Limited studies have investigated lithium-ion battery fire risks in commercial buildings, particularly in the context of operational storage practices and workplace safety management (Conzen et al., 2023; Jia et al., 2025).

Furthermore, previous studies tend to emphasize the technical aspects of battery behavior, while relatively few studies analyze the interaction between technological hazards, building safety systems, regulatory compliance, and organizational safety management (Snyder & Theis, 2022; Conzen et al., 2023). In the context of developing countries such as Indonesia, research that integrates technical hazard characteristics with national regulatory compliance and safety management practices remains limited. Therefore, there is a clear need for an integrative analysis that examines how failures in safety management, regulatory compliance, and fire protection systems interact with lithium-ion battery hazards to produce catastrophic consequences in buildings.

RESEARCH METHOD

This study employed a qualitative case study approach to analyze the fire incident at the Terra Drone building in Jakarta. The case study method was selected to examine the incident in depth and to understand the technical, regulatory, and organizational factors contributing to the disaster. The analysis was supported by Root Cause Analysis (RCA) to identify the underlying causes of the incident. The population of this study included documents, reports, regulations, and scientific publications related to lithium-ion battery fire hazards and building fire safety systems. The research sample consisted of investigation reports, national regulations, international standards, and relevant scientific literature. A purposive sampling technique was used to select sources based on their relevance and credibility.

The primary research instrument was document analysis, supported by a review checklist used to identify key safety aspects, such as battery storage practices, fire protection systems, evacuation routes, and regulatory compliance. Data were collected through document review and literature analysis from credible sources, including investigation reports, national regulations, international standards, and peer-reviewed scientific publications. The use of multiple sources enabled data triangulation to improve research reliability. Data analysis was conducted through incident reconstruction, gap analysis, and Root Cause Analysis (RCA) using the 5-Whys method and a fishbone diagram to identify technical, procedural, human, and organizational factors contributing to the incident.

Research data were compiled from primary and secondary sources using a triangulation technique to validate the findings. This triangulation approach ensured the reliability of findings by cross-verifying incident data, scientific literature, regulatory frameworks, and international safety standards. The primary data were obtained from official investigation reports by the Indonesian National Police published through trusted national media outlets, namely *Kompas.com* and *Detik.com* (Kompas, 2025; Detik, 2025). These reports contain factual findings regarding the chronology of events, the initial cause of the fire (a falling battery), storage conditions, and six indications of management negligence.

Scientific Literature Review, A systematic review of Scopus/Web of Science–indexed publications discussing thermal runaway characteristics, smoke toxicity, and the effectiveness of extinguishing systems for Li-ion batteries (Wang et al., 2012; Chen et al., 2021; Liu & Sun, 2021). Regulatory Analysis, An in-depth analysis of relevant national regulations, including Regulation of the Minister of Public Works No. 26/PRT/M/2008 concerning technical requirements for fire protection systems in buildings, Decree of the Minister of Manpower No. KEP.186/MEN/1999 concerning workplace fire response units, and Decree of the Minister of Manpower No. KEP.187/MEN/1999 concerning the management of hazardous chemicals. Analysis of International Standards, A review of NFPA 855 (2023), NFPA 101: Life Safety Code (2023), and guidelines from the UN Model Regulations (United Nations, 2019) regarding the transport of dangerous goods.

Incident Reconstruction and Hazard Scenarios

Based on police findings, the incident began when a 30,000 mAh LiPo battery fell from a storage pile in the inventory/warehouse room on the ground floor (Kompas, 2025). The fall of the battery, which was likely caused by unstable stacking, the absence of proper storage racks, or careless handling, caused severe internal mechanical damage to the cell. This damage triggered an internal short circuit, rapidly increasing the temperature and initiating a thermal runaway process (Wang et al., 2012). The resulting sparks immediately ignited other batteries stored densely and irregularly nearby, causing massive and rapid thermal runaway propagation.

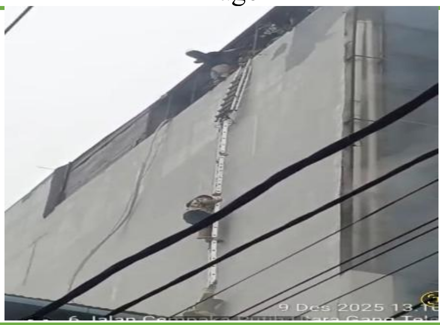
The thermal runaway process of the accumulated battery packs released large amounts of heat energy and a mixture of highly toxic and flammable gases. Based on the literature, the main gases released included hydrogen (H_2), methane (CH_4), carbon monoxide (CO), and, most dangerously, hydrogen fluoride (HF), originating from the decomposition of the lithium hexafluorophosphate ($LiPF_6$) electrolyte (Chen et al., 2021; Sturk et al., 2015). HF is a highly toxic corrosive gas with an Immediately Dangerous to Life and Health (IDLH) concentration of only 30 ppm and can cause fatal pulmonary edema within a short exposure period (NIOSH, 2019). The release of these gases and dense smoke occurred at a scale and speed that was unexpected by building occupants.

Regulatory Gap and Violation Analysis

An in-depth analysis indicates that this incident was not an unexpected "accident," but rather a logical consequence of a series of regulatory violations and systemic safety gaps that can be clearly traced to existing regulations (see Table 1). The analysis integrates findings from incident reconstruction, scientific literature, and regulatory review using a triangulation approach. This triangulation approach ensured the reliability of findings by cross-verifying incident data, scientific literature, regulatory frameworks, and international safety standards.

Table 1. Regulatory Gap and Violation Analysis

No	Image	Note
1.		Terra Drone building before the fire
2.		Terra Drone is building after the fire
3.		Terra Drone building during the fire (starting from the first floor)
4.		The condition of the rooftop on the seventh floor, six floors below were already filled with smoke from the first floor.

No	Image	Note
5.		Evacuation through the rooftop using stairs.

Root Cause Analysis

Based on the previously identified gaps, the 5 Whys analysis revealed a deep systemic root cause: 1. Why did 22 people die? Because they were exposed to high concentrations of toxic gases (HF and CO) inside the building and were unable to escape. 2. Why were they unable to escape? Because the vertical evacuation route (the stairwell) was rapidly blocked by smoke and fire, and no alternative evacuation routes or refuge areas were available. 3. Why were smoke and fire able to quickly block the stairwell? Because the source of the fire (the battery storage area) was located adjacent to, or directly along, the main exit path on the first floor, and there were no fire-rated walls or compartmentation systems to contain the spread. 4. Why were hazardous materials placed in such a critical location? Because there was no formal risk assessment of battery storage activities, no designated occupational health and safety personnel, and no standard operating procedures (SOPs) regulating the storage of hazardous materials. 5. Why were there no risk assessments, occupational health and safety personnel, or standard operating procedures? Because of a weak safety culture at the management level, which prioritized logistical convenience and low operating costs over human safety, as well as regulatory enforcement failures by the relevant authorities responsible for overseeing building and occupational safety regulations.

Therefore, the root cause of this tragedy was a combination of weak organizational safety culture and insufficient regulatory enforcement, which together allowed multiple technical and procedural violations to occur without corrective intervention (Figure 2).

Figure 2. RCA Fire in Terra Drone Building

Table 2. Gap Analysis between Conditions at Terra Drone and Applicable Regulations and Standards

Safety Aspect	Factual Conditions at Terra Drone (Based on Investigation)	Applicable Regulations/Standards	Identification of Gap/Violation	Impact on Incident
Management of Hazardous Goods	There were no standard operating procedures (SOPs) for battery storage. Batteries were stacked unsafely. There were no occupational health and safety officers.	Decree of the Minister of Manpower No. 187/1999 (Art. 2, 5): it is mandatory to identify, label, develop SDS and SOPs for B3 wastes. Decree of the Minister of Manpower No. 186/1999: It is mandatory to form a fire response team.	Li-ion batteries are classified as B3 waste (Class 9). There was no B3 waste management whatsoever. There was no person responsible for fire mitigation.	A disorganized storage system was a direct trigger. There was no risk oversight.
Locations & Compartments	Batteries were stored on the first floor, near the main exit, in an open space.	Regulation of the Minister of Public Works No. 26/2008 & NFPA 101: Evacuation route must be void of danger. NFPA 855 (15.4): It is recommended to have a separate room that can withstand fire for at least 2 hours.	Hazard sources were located in the primary evacuation route. There was no compartmentalization.	Gas and flames immediately blocked the only exit, trapping the occupants upstairs.
Detection & Alarm Systems	There were no smoke sensors and fire alarms.	Regulation of the Minister of Public Works No. 26/2008 (Art. 6.3): It is mandatory to install fire detection and alarm systems. NFPA 855 (10.2): It is recommended to install heat (rate-of-rise) and gas (CO/HF) detectors.	There was no detection system whatsoever. There was no early warning.	Residents were unaware of the danger until smoke/heat reached them, and the evacuation time was lost
Extinguishing System	There were no fire extinguishers specific to LiPo batteries. There was no adequate fixed sprinkler system.	Regulation of the Minister of Public Works No. 26/2008 (Chapter 5): It is mandatory to install a suppression system based on hazard classification. NFPA 855 (10.5): It is recommended to install high-debit	There was no extinguishing system. The initial fire could not be contained.	The escalation from a single thermal runaway to an unstoppable mass fire.

Safety Aspect	Factual Conditions at Terra Drone (Based on Investigation)	Applicable Regulations/Standards	Identification of Gap/Violation	Impact on Incident
		sprinklers (OHH) or water mist for ESS.		
Evacuation Route	There were no clear and safe evacuation routes.	Regulation of the Minister of Public Works No. 26/2008 (Article 7.2) & NFPA 101: It is mandatory to have at least two protected, well-lit, and visibly marked exit routes.	Total failure in the provision of *means of egress*. Total	The victims were trapped with no option: descend into the source of the fire or climb up to the dead-end rooftop.
Training and Preparedness	There was no fire safety training for employees.	Decree of the Minister of Manpower No. 186/1999 & Regulation of the Minister of Public Works No. 26/2008: It is mandatory to have emergency plans and provide training for building occupants.	Employees did not know how to react, emergency procedure or the locations of fire extinguishers/alternative evacuation routes.	Evacuees became panicked and disorganized, leading to fatalities.

RESULTS AND DISCUSSION

Convergence of Technological Hazard and Regulatory Failures

The Terra Drone incident is a clear example of the convergence of failures, where the intrinsic dangers of new technology intersect with gaps and failures in existing risk management systems. Li-ion batteries pose a novel hazard in the form of thermal runaway accompanied by rapid toxic gas release. Meanwhile, the national regulatory framework, particularly Regulation of the Minister of Public Works No. 26/2008, is actually quite comprehensive in regulating basic building safety, including requirements for fire detection and alarm systems, fire suppression systems, and emergency exits. Similarly, Regulation of the Minister of Manpower No. 187/1999 explicitly mandates the management of hazardous chemicals (B3). The problem is not the absence of regulations, but rather the mismatch between “static regulation and dynamic technology,” combined with widespread non-compliance that often goes undetected or unpunished.

Recent studies emphasize that lithium-ion battery incidents often occur due to a combination of technological hazards and organizational or regulatory failures rather than purely technical malfunctions (Conzen et al., 2023; Wang et al., 2025). The thermal runaway process can release large quantities of flammable and toxic gases within seconds, significantly accelerating fire growth and reducing evacuation time in enclosed buildings (Liang et al., 2023; Mao et al., 2024). Without appropriate risk management and early detection systems, such hazards can escalate rapidly beyond the control of conventional fire protection systems.

This research provides a comprehensive analysis of the Terra Drone fire incident by integrating incident reconstruction, regulatory gap analysis, and root cause analysis. Through this approach, the study identifies critical weaknesses in safety management, building fire protection systems, hazardous material storage practices, and regulatory compliance. Based on these findings, the study proposes several practical recommendations to improve lithium-ion battery safety management in commercial buildings.

Failure of Defense-in-Depth

The placement of battery storage on the first floor was a critical mistake that violated the fundamental principles of NFPA 101: *Life Safety Code* and the concept of defense-in-depth. This principle states that if one layer of defense fails (e.g., the fire suppression system), the next layer (compartmentalization) must limit the damage, and the final layer (evacuation routes) must remain accessible. At Terra Drone, all layers of defense were either absent or failed simultaneously, effectively turning the building into a "death trap."

Research on lithium-ion battery safety indicates that effective risk mitigation requires a multi-layered safety strategy integrating early detection, compartmentalization, suppression systems, and safe storage design (Qiu & Jiang, 2022; Xu et al., 2022). In high-energy battery systems, the failure of a single protection layer can quickly propagate into a cascading failure affecting the entire facility, particularly when batteries are stored in confined environments without dedicated fire protection infrastructure (Jia et al., 2025; Li et al., 2024).

Implications for Regulation and Future Standards

These findings highlight critical implications for policymakers and engineers in strengthening regulatory frameworks and technical safety standards for lithium-ion battery management. They are also highly relevant for occupational health and safety practitioners, particularly in Indonesia and other developing countries facing rapid technological adoption with evolving safety risks.

Binding Specific Standard Requirements

General regulations, such as Regulation of the Minister of Public Works No. 26/2008, should be supplemented with specific Indonesian National Standards (SNI) that explicitly adopt and adapt the technical requirements of NFPA 855 for commercial-scale Li-ion battery storage in buildings. These standards must clearly prohibit storage in evacuation routes and mandate the use of isolated storage rooms. Similar regulatory strengthening has been recommended in international studies addressing emerging risks associated with battery energy storage systems (Snyder & Theis, 2022; Sebastian, 2022).

Integration of Advanced Detection Systems

Conventional fire detection systems are inadequate for lithium-ion battery hazards. Mandatory installation of hydrogen fluoride (HF) and carbon monoxide (CO) gas detectors in battery storage areas should be required, as HF gas is one of the earliest indicators of thermal runaway and provides critical early warning (Chen et al., 2022). Recent studies confirm that gas-based early warning systems significantly improve the detection of pre-runaway conditions in lithium-ion battery failures (Wang et al., 2023; Liang et al., 2023).

Proper Fire Suppression Strategy

The "large-volume water" recommendation from NFPA 855 and DNV GL research (2020) should be used as a reference. Sprinkler systems in battery storage areas should be designed for Group A hazards (high challenge) with adequate flow rates and discharge durations. Alternatives such as high-pressure water mist systems combined with gas suppressant additives should also be considered for high-value spaces (Liu et al., 2020). Recent experimental studies also demonstrate that water-based suppression systems remain among the most effective approaches for controlling lithium-ion battery fires and limiting thermal propagation (Mao et al., 2024; Wang et al., 2025).

Improving the Effectiveness of Supervision

Government authorities, both local governments (responsible for technical building verification) and labor agencies (responsible for occupational health and safety supervision), must strengthen the capacity of inspectors and conduct routine and unannounced safety audits (spot inspections) of buildings that potentially store hazardous materials. Administrative and criminal sanctions must also be enforced consistently. Strengthening regulatory enforcement is widely recognized as a critical component in managing emerging technological risks in complex socio-technical systems (Conzen et al., 2023; Wang et al., 2025).

Preventing similar tragedies requires systemic improvements in the management of lithium-ion battery risks. Based on the findings of this study, several integrated policy, technical, and institutional measures are proposed to strengthen safety governance and enhance systemic resilience.

Policy and Regulatory Recommendations (Short–Medium Term)

Issuance of Specific Regulations

The Ministry of Public Works and Public Housing and the Ministry of Manpower should immediately issue a joint ministerial regulation on the safe storage and use of lithium-ion batteries in buildings. This regulation should integrate:

- NFPA 855 principles for technical requirements (e.g., separation distances, compartmentalization, gas detection, and specialized fire suppression systems).
- Provisions of Regulation of the Minister of Manpower No. 187/1999 on hazardous chemical (B3) management, including standard operating procedures (SOPs), labeling, safety data sheets (SDS), and mandatory training.
- A strict prohibition on battery storage in evacuation routes, along with a requirement for special operational permits issued by the local fire department.

Intensive Public Outreach and Law Enforcement

The government should launch a national awareness campaign and coordinated enforcement program involving the Ministry of Public Works and Public Housing, the Ministry of Manpower, and local fire departments. This initiative should include surprise inspections and regulatory enforcement in commercial and industrial buildings that store or use lithium-ion batteries.

Technical and Operational Recommendations: Multi-Layer Protection System

Detection

Mandate the installation of hydrogen fluoride (HF) and carbon monoxide (CO) gas detectors connected to dedicated audible alarm systems in all lithium-ion battery storage rooms.

Fire Suppression

Require the installation of high-discharge sprinkler systems (minimum 0.6 gpm/ft^2) with a minimum 90-minute water supply, or water mist systems with suitable additives specifically designed for battery fire hazards.

Compartmentalization

Relocate battery storage to isolated rooms constructed with 2-hour fire-resistance-rated barriers, equipped with automatic fire doors and dedicated exhaust ventilation systems fitted with chemical filtration.

Evacuation Routes

Evaluate and ensure the availability of at least two physically separated evacuation routes, equipped with photoluminescent signage and emergency lighting to ensure visibility during power failures.

Management and Human Capacity Recommendations (Long Term): Strengthening Safety Culture and Competence

Implementation of Occupational Health and Safety Management Systems

Mandate the implementation of an Occupational Health and Safety Management System (OHSMS) in accordance with Government Regulation No. 50/2012.

Specialized Training on Lithium-Ion Battery Hazards

Require dedicated training programs for:

- All employees: hazard awareness and two-way evacuation procedures
- OHS officers and battery handlers: SOPs, personal protective equipment (PPE), and chemical emergency response
- Firefighters: lithium-ion fire suppression tactics (e.g., mass cooling), HF exposure hazards, and decontamination procedures

National Capacity Building

- Establish national research and testing facilities for lithium-ion battery fire hazards in Indonesia.

- Integrate lithium-ion battery hazard modules into engineering education, occupational health and safety management programs, and firefighter certification training.

CONCLUSION

The Terra Drone building fire was a fatal consequence of a multi-level systemic failure in managing Li-ion battery risks. The root causes included a lack of safety culture at the corporate level and failures in regulatory oversight. The combination of the hazardous characteristics of thermal runaway, particularly the rapid release of toxic gases, the placement of the hazard source in a critical location (an evacuation route), and the complete absence of key layers of the fire protection system (i.e., detection, suppression, compartmentalization, and safe evacuation routes) created the conditions for a catastrophic disaster. This tragedy clearly demonstrates that compliance with existing building safety and occupational health and safety regulations, if properly implemented and enforced, could have prevented or significantly mitigated the resulting fatalities.

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AUTHOR CONTRIBUTIONS

The contributions of each author are described as follows. All authors actively participated in the research and writing of this article and share responsibility for its content, including the development of the concept, research design, analysis, and manuscript revision. MD: Conceptualization, Methodology, Data Curation, Writing – Original Draft Preparation. KIM & MJ: Writing – Review and Editing.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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