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Safety Risk Assessment of Lithium-Ion Batteries Through Fuzzy Multi-Criteria Decision Making Methods

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A B S T R A C T

Lithium-ion batteries (LIBs) are essential for the sustainability of electric vehicles (EVs), but their end-of-life (EOL) management is critical for maintaining the supply chain of valuable metals such as cobalt and lithium. Effective EOL management not only mitigates environmental risks but also supports economic stability and social well-being. This paper quantitatively assesses the safety risks associated with EOL LIB management using advanced methodologies. We introduce the Fuzzy Simplified Best-Worst Method (F-SBWM) along with a hybrid approach combining the Fuzzy Additive Ratio Assessment (F-ARAS) and Fuzzy Weighted Aggregated Sum Product Assessment (F-WASPAS) methods. Our objective is to identify and rank failure modes comprehensively, providing a robust framework for evaluating safety risks from multiple perspectives. This approach integrates risk analysis with fuzzy Multi-Criteria Decision Making (MCDM) to offer insights into relative safety risk resource improvements. The study identifies and ranks key safety risk sources based on their impact on EOL processes, highlighting significant environmental, economic, and social concerns. It emphasizes the need for effective strategies to reduce environmental harm, support economic sustainability by ensuring resource availability, and enhance public safety and trust. The results propose actionable improvements to increase the stability and sustainability of LIB supply chains, addressing the critical intersections of environmental protection, economic viability, and social responsibility.

1. Introduction

The use of lithium-ion battery (LIB) is expanding, especially with the recent growth of the electric vehicle market (Duffner et al. [16]). LIB technology is also used for aircraft, drones, grids, and storage (Jiang et al.

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[21]). This growth and multiplicity of applications has led to complex supply problems of LIB resources including lithium, nickel, manganese and cobalt. Resource and supply concerns have also arisen, making end-of-life (EOL) management of LIBs a global concern (Mossali et al. [27], Slattery et al., [35])— Because supply chain disruptions for these resources have been widely observed (Sun et al. [37]).

Common circularity *Re* practices include recycling, remanufacturing, repurposing, repairing, and reusing (Richa et al. [31])— each of which may have different operational implications in closing the circular material flow loop. Economic and environmental value is achieved by proper management of EOL LIB and has been studied. (Pagliaro and Meneguzzo [29]).

Social and safety concerns regarding spent LIBs have received limited attention and are virtually absent from circular economy research, despite being a critical issue in practice (Wrålsen et al. [42]). The safety of LIB EOL management can be influenced by the battery's chemical composition, operating environment, and usage conditions (Chen et al. [9]).

The lifecycle of LIBs is summarized in Figure 1 and is based on the Ellen MacArthur Foundation's (EMF) circular economy license model (Foundation [17]). Raw metals are extracted for LIB production, which are then used to manufacture the final product delivered to users. Used LIBs are eventually collected from users for EOL management, allowing for the recovery of valuable materials. Collecting spent LIBs from users is a prerequisite for circular economy actions (Bird et al. [5]). Figure 1 illustrates the complexity and risks of the circular economy process by showing the various operators involved in different activities, the component loop, and the technology loop.

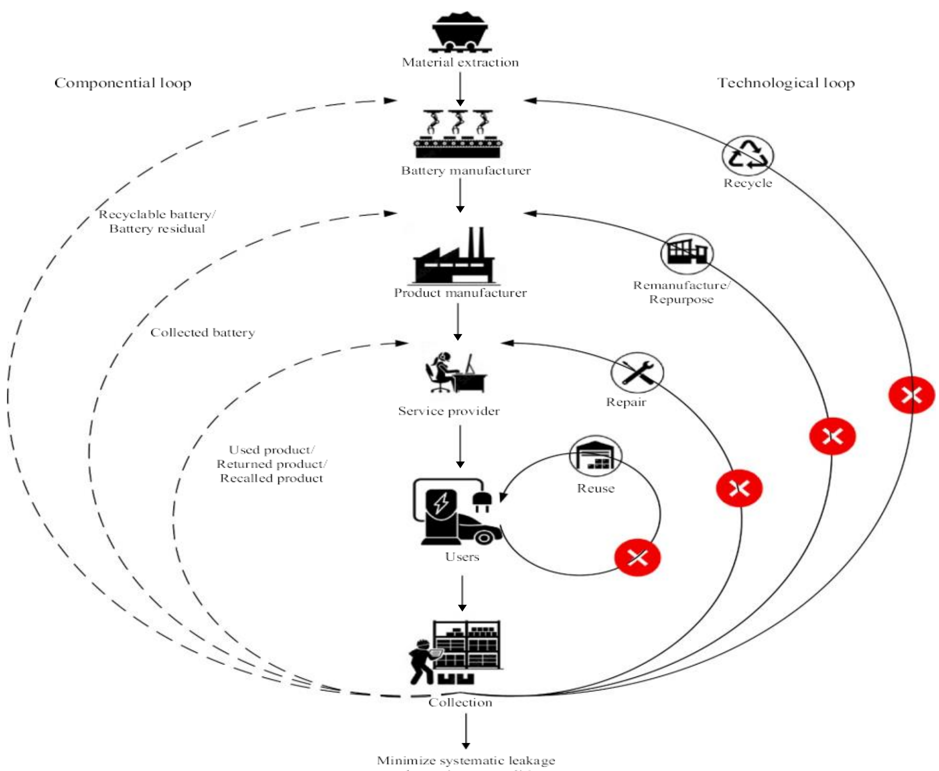


Figure 1. A butterfly model of a circular economy for lithium-ion batteries based on EMF (Chen et al. [13]).

Remanufacturing and repurposing can be considered as two similar CE technical methods (Alaoui et al. [2], Kampker et al. [22]). They involve changing a major component or aspect of batteries and using them. The difference between remanufacturing and reuse is that remanufacturing means returning spent LIBs to products for the same purpose. (Chen et al. [8]), and changing the usage is changing the use of batteries by changing the battery management system (Alaoui et al. [2], Yang et al. [43]). Batteries obtained from electric vehicles can be repurposed for energy storage—as an example. Recycling is the last technical CE loop for LIBs and may represent the CE final EOL LIB loop. (Chen et al. [8]).

The rapid expansion of lithium-ion battery (LIB) technology, particularly in the electric vehicle market and other critical applications such as aircraft, drones, and energy grids, has led to complex supply chain challenges involving key materials like lithium, nickel, manganese, and cobalt. These issues and concerns about resource scarcity underscore the urgent need for effective end-of-life (EOL) management of LIBs. Circular economy practices, including recycling, remanufacturing, repurposing, repairing, and reusing, are essential for closing the material loop. However, social and safety issues related to spent LIBs remain underexplored in circular economy research despite their critical importance. This paper aims to address these research gaps by examining the complexities and impacts of circular economy practices on safety, resource efficiency, and supply chain resilience in LIB EOL management.

Recycling represents the final technical CE loop for LIBs and is considered the ultimate EOL process in the circular economy framework (Chen et al. [8]). Batteries and battery residues that are deemed unfit for secondary use can be recycled to recover valuable materials for reuse in battery manufacturing and other applications (Shekhar et al. [33], Wang et al. [40]). However, safety risks associated with various EOL activities can lead to supply chain and material flow disruptions in CE-based LIB material management (Mossali et al. [27]). We have added more detailed examples of specific safety risks encountered in the EOL management of lithium-ion batteries (LIBs) to better contextualize the problem and emphasize its significance. The examples provided include:

- Thermal runaway: Improper handling and storage of used rechargeable batteries can result in thermal runaway, which can cause the battery temperature to rise uncontrollably, potentially causing a fire or explosion (Börger et al. [7]).
- Chemical exposure: Damaged or leaking batteries can release toxic chemicals such as lithium solvents, cobalt, and electrolytes, posing health risks to workers and environmental hazards (Zeng et al. [46]).
- Electrical hazards: Even at the end of their useful life, rechargeable batteries can retain a significant electrical charge. Short circuits or improper disassembly can result in electric shock or sparks, causing injury or fire (Blum & Long Jr [6]).
- Mechanical damage: Crushing, puncturing, or shredding a rechargeable battery without proper safety precautions can create flammable gases or thermal runaway (Shukla & Shankul. [34]).
- Environmental pollution: Improper disposal or recycling of LIBs can lead to soil and water pollution with toxic metals and chemicals, affecting local ecosystems and human health (Kilgo [23]).

Assessing supply chain disruptions due to safety risks can mitigate barriers to CE-based LIB management. The goals of this study include:

- Identify the sources of safety risks in LIBs CE technical loop practices.
- Assessing and ranking the impact of safety risk sources in LIBs EOL process activities that form the technical loop practices.
- Provide participants with insight into reducing safety risks in EOL LIB management and improving supply chain stability for circular economy activities for LIBs.

To address these challenges, this study introduces a comprehensive approach to assessing and managing safety risks in LIB EOL processes. The main research questions this study aims to resolve are:

- What are the specific sources of safety risk?
- What are the specific sources of safety risks in the EOL management of LIBs within a circular economy framework?
- How can these safety risks be quantified and ranked based on their impact on various EOL activities?
- What strategies can be employed to mitigate these risks and enhance the stability and sustainability of LIB supply chains?

Given the multi-stakeholder and multi-criteria nature of the problem context, our study introduces a combined methodology that integrates the Fuzzy Set-Based Weighting Method (FSBWM), Fuzzy Additive Ratio Assessment (F-ARAS), Fuzzy Weighted Aggregated Sum Product Assessment (F-WASPAS), and a hybrid approach of F-ARAS and F-WASPAS. This combined methodology aims to evaluate the concerns and support the goals of this study. The research is structured into four sequential phases:

- **Identification of Safety Risks:** The first step involves identifying six major sources of safety risks throughout the end-of-life (EOL) process activities, based on a literature review and expert input.
- **Risk Weighting:** The second step uses FSBWM to exemplify the weighting of these sources of safety risk.
- **Performance Assessment:** The third step involves evaluating the performance of these sources across different EOL activities using F-ARAS, F-WASPAS, and the proposed hybrid Multi-Criteria Decision-Making (MCDM) method.
- **Validation:** The final stage is to validate the methodology and results through feedback from experts.

Below, we address the potential limitations and assumptions made during our analysis:

Data Diversity and Quantity: Our study examines safety risks in the end-of-life (EOL) management of lithium-ion batteries (LIBs) using a blend of FSBWM, F-ARAS, and F-WASPAS methods. However, the range and volume of data collected, including expert opinions, may be restricted. This limitation could influence the accuracy and applicability of the results, as a more extensive dataset and a wider array of expert feedback might yield more thorough insights.

Fuzzy Methodology Constraints: Employing fuzzy methods such as F-SBWM, F-ARAS, and F-WASPAS adds inherent complexity and relies on theoretical models. The effectiveness of these fuzzy multi-criteria decision-making (MCDM) techniques is contingent upon the accuracy of the input data and the subjective judgments of the experts. Any variations in these inputs may impact the robustness and reliability of the risk assessments. Expert Feedback Limitations: While validating our results through expert feedback is essential, it may be influenced by the experts' personal interpretations and biases. Despite seeking input from a diverse group of experts, their individual perspectives and experiences could affect the validation process and, consequently, the outcomes.

We assume that the expert opinions obtained are both representative and reliable for assessing safety risks in LIB EOL management. This assumption relies on the experts' experience and expertise in the field; however, individual biases and limited knowledge in specific areas could influence the results. Additionally, the integration of FSBWM, F-ARAS, and F-WASPAS methods presumes that these methods are compatible and provide a coherent approach for evaluating and ranking safety risks.

The remainder of this research begins with a review of papers related to LIBs, safety risk sources, and methods in Section 2. Section 3 provides more details on the study methodology. Section 4 shows the results obtained from sample field data using the proposed method with expert input. Conclusions, limitations and future study steps are summarized in Section 5.

2. Background and literature

2.1. EOL activities of lithium-ion batteries

The supply of raw materials is one of the important issues facing the widespread use of LIBs. There are numerous social, economic and environmental issues in the supply chain of metals used for LIB production (Liu et al. [26]). Based on this situation, CE has become an important topic in the field of LIB (Mossali et al. [27]). CE is a system that combines reduction, reuse and recycling that supports the reduction of raw material consumption, reduction of environmental impact and improvement of economic efficiency (Kampker et al. [22]).

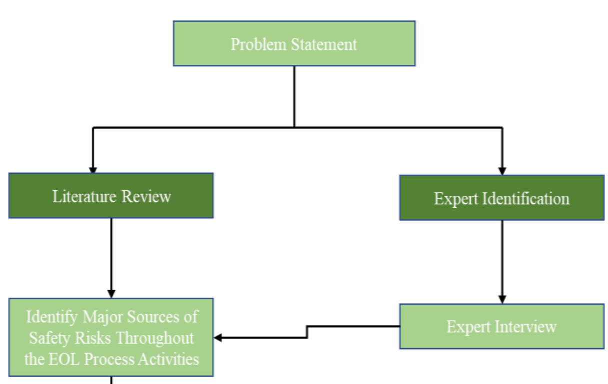


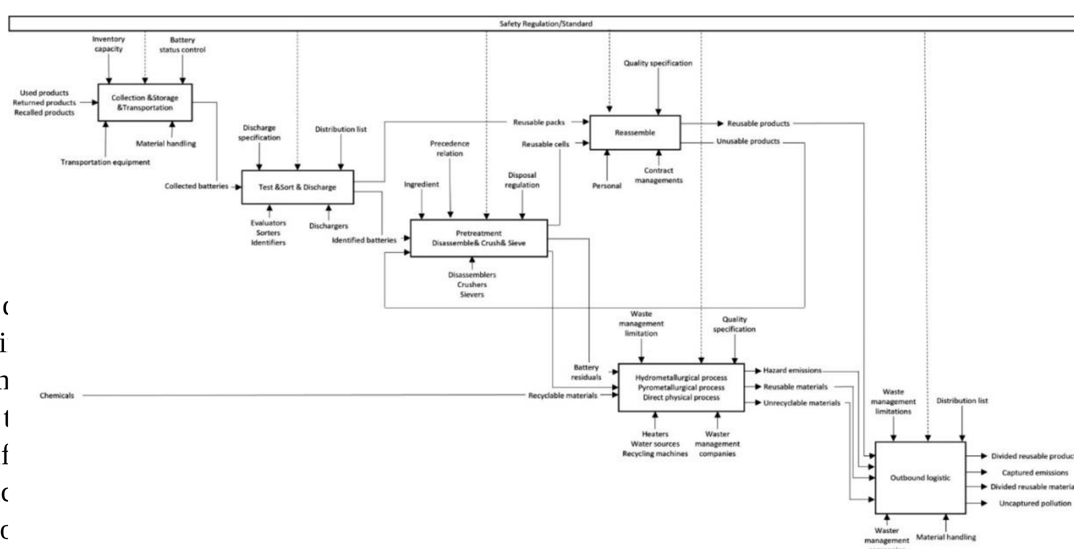
Figure 2. Research process flowchart**.**

Table 1 summarizes previous studies on LIB EOL management activities. These EOL activities include collection, testing, sorting, discharge, disassembling, crushing, sieving, reassembling, and recycling technologies (Alaoui et al. [2], Chen et al. [11], Kampker et al. [22], Hua et al. [20], Shekhar et al. [33], Wang et al. [40], Yang et al. [43]). Safety issues in these activities are listed in Table 1 in several studies (Chen et al. [10], Christensen et al. [14], Wang et al. [40]). Christensen et al. [14] discusses the safety challenges of LIBs, pointing out that their quick integration into everyday life has surpassed our understanding of their risks. It highlights deficiencies in current safety practices and stresses the importance of improved education and regulations to address these risks as we move towards low-carbon energy and transportation solutions. Similar research addresses the safety and management challenges of LiBs in electric vehicles (EVs) throughout their lifecycle. It highlights risks such as thermal runaway, fire, and explosion incidents, emphasizing the need for effective safety plans. The study also examines the environmental impacts of LiBs, focusing on creating a resource-efficient recycling system (Shukla & Shankul [34]). In review paper examines the environmental impacts of LIBs from production through usage and recycling, emphasizing the growing need for sustainable recycling as LIB waste increases. It highlights that reusing recovered materials in battery manufacturing can reduce environmental footprints, greenhouse gas emissions, and energy consumption. The study provides an overview of the environmental effects of LIBs across their lifecycle and underscores the importance of recycling for metal replenishment (Liu et al. [26]). However, measurement of safety issues and inclusion in decision-making has been neglected. The aim of our study is to evaluate and quantitatively analyze the sources of different safety risks and their impact on EOL activities, based on the importance of safety issues for CE of LIBs and the sustainability of the battery metal supply chain. This approach and results provide initial evidence for safety measures and management in this closed-loop system, but also evidence for a broader CE safety assessment.

Table 1. Studies of lithium-ion battery end-of-life management.

Author	Subject	Collection	Test	Sort	Discharge	Disassemble	Crush	Sieve	Reassemble	Hydrometallurgical, Pyrometallurgical, Direct physical process	Safety mention	Safety evaluations
(Olivetti et al., 2017)	EOL LIBs	√					√			√		
(Yang et al., 2021)	EOL LIBs	√					√	√		√		
(Zhang et al., 2018)	EOL LIBs			√	√	√			√	√		
(Ciez and Whitacre, 2019)	EOL LIBs									√		
(Zhang et al., 2020)	EOL LIBs		√							√		

(Mayyas et al., 2019)	EOL LIBs	√								√		
(Liu et al., 2018)	LIBs										√	
(Wang et al., 2019)	LIBs										√	
(Chen et al., 2021)	LIBs		√		√						√	
(Christensen et al., 2021)	LIBs	√	√		√	√	√		√	√	√	
(Zeng et al., 2015)	EOL LIBs	√								√		√
(Hua et al., 2020)	EOL LIBs		√			√	√		√	√		√
(Harper et al., 2019)	EOL LIBs	√	√		√	√	√		√	√		√
(Christensen et al., 202)	EOL LIBS				√	√						√
(Ren et al., 2023)	EOL LIBS	√	√		√	√	√		√			√
(Shukla & Shankul, 2024)	EOL LIBS	√	√		√	√			√			
(Liu et al., 2024)	EOL LIBS				√	√	√		√	√		
(Chen et al., 2023)	EOL	√	√	√	√	√	√	√	√	√		√
Current	**LIBs LIBs**	√	√	√	√	√	√	√	√	√	√	√



To further ... ll be examined later i... le et al. [4]) shown in ... and arrows exiting ... lude standards, specif... are mechanisms, suc...

Initially, pro... The widespread use, different capacities, and compositions in a wide variety of LIBs make collection an important topic (Zeng et al. [47]). Testing and sorting of EOL batteries is the next step - especially considering the quality of the collected materials and the estimation of battery lifetime is a significant challenge at this stage (Zhang et al. [49]).

EOL LIBs typically have internal energy storage, which leads to an important and relatively unique EOL LIB activity - battery discharge. (Bankole et al. [49], Liao et al. [25], Zhang et al. [48]). Battery pack disassembly is an important activity and obstacle in achieving CE for LIBs. This requires the separation of the battery's main components, such as the body, cathode material, diaphragm, and electrolyte. (Sommerville et al. [36]). Batteries and parts that cannot be further reused are crushed in a crusher and screened through a screen before being recycled. (Liu et al. [26], Vel´ azquez-Martínez et al. [39], Yang et al. [43], Zhong et al. [50], Zolfani & Chatterjee [5]). Recycling technologies include hydrometallurgical, pyrometallurgical and direct physical processes, the last material conversion activity in CE technologies. (Ciez and Whitacre, [15], Olivetti et al. [28]). In each stage, especially in the final stage, handling and transportation - outbound logistics - batteries and various materials are carried out after the completion of all activities.

2.2. An EOL system conceptualization of safety risk sources

As the management of end-of-life (EOL) lithium-ion batteries (LIBs) increases, so do safety risks (Liu et al., 2018). Two primary factors contribute to the safety risks associated with EOL LIB management. First, EOL LIBs enter the waste stream in various states and with different defects, which complicates safety management. These conditions include leakage, swelling, internal short circuits, external coating damage, and corrosion (Winslow et al. [41]). Second, the complexity and variability of EOL management activities make it challenging to monitor and control safety risks (Harper et al. [19]). Safety issues such as spontaneous combustion and explosions that occur during EOL management activities can disrupt the circular economy (CE) processes for LIBs (Chen et al., [13]). The final sources of safety problems including electrical, chemical, mechanical, environmental, inter-organizational, and managerial risks may arise from EOL activities, as illustrated in the IDEF model in Figure 3, which is based on the literature review.

The main sources of safety risk during EOL LIB CE management activities are shown in Table 2. This table is based on secondary literature search (see previous sections) and extracted from research by (Chen et al. [12]). For further consideration, electrical, chemical and mechanical safety risk sources are categorized as technical safety risk sources and environmental, inter-organizational and management dimensions as non-technical safety risk sources. Technical resources indicate safety risks due to the immaturity and uncertainty of LIB design and manufacturing technology. Non-technical safety risks arise from internal and external circular economy activities.

Table 2. Safety risk sources during the end-of-life activities from a circular economy perspective.

Safety Risk Sources	Explanation	Reference	
Technical	Electrical (EL)	Electrical hazard sources are identified such as over-discharge, and isolation concerns that can arise risks in different end-of-life activities.	(Christensen et al., 2021; Slattery et al., 2021)
	Chemical (CH)	The application of chemicals could cause hazardous pollutants and occurrence injury.	(Adeola, 2018; Chen et al., 2019; Harper et al., 2019; Vieceli et al., 2018; Waldmann et al., 2016; Zhou et al., 2020)
	Mechanical (ME)	The mechanical source is including physical damage, vibration, and ambient pressure change during EOL management.	(McDowall et al., 2007; Slattery et al., 2021; Xie et al., 2020)
Non-technical	Environmental (EN)	External physical environment, for example, ambient temperature, humidity, and air composition is an important source of LIBs safety risks.	(Chen et al., 2017; Fan et al., 2020; Harper et al., 2019; Lyu et al., 2020; Moreno-Camacho et al., 2019; Wang et al., 2019; Zhang et al., 2018)
	Inter-Organizational (OR)	Risks occur across organizations, such as lack of regulation by government, emergency response for fire protection departments, fire detection systems and labeling for all non-government organizations and	(Ciez and Whitacre, 2019; Hua et al., 2020; Huo et al., 2017; Yu et al., 2021)

	companies.	
Managerial (MA)	Managerial safety risk sources include the risks caused by inadequate managerial governance such as lack of safety design, manufacturer emergency response, overstock, lack of inventory coordination, insufficient operational training, and staff limited safety skills that might create safety risks.	(Fan et al., 2020; Huang et al., 2018; Moreno-Camacho et al., 2019; Slattery et al., 2021; Sommerville et al., 2020; Waldmann et al., 2016; Zhou et al., 2020)

3. Research methodology

In this research, a four-step method to evaluate the sources of safety risks and their impact on EOL activities from the perspective of CE practices has been carried out. The first step is to recognize the main safety risk sources and EOL management activities from a literature review. A questionnaire for the F-SBWM and F-ARAS and F- WASPAS and proposed hybrid MCDM methodology data acquisition is presented after determining an initial set of criteria informed by a literature review. Three experts are specified for preparing answers to the questionnaire during this initial stage; the characteristics of these experts are given in section 4.1. The outputs of the questionnaire are demanded for the latter steps of F-SBWM and F-ARAS and F- WASPAS and proposed hybrid MCDM execution. F-SBWM is used to obtained the weights of each safety risk source, and F-ARAS and F- WASPAS and the proposed hybrid MCDM approach are used to find their impact on each EOL activity.

Section 3.1 focuses on investigating the extent of a study that initially aims to tackle uncertainties in the external environment. The study achieves this by exploring the principles of fuzzy logic. The second stage analyzes the safety risk sources by applying F-SBWM and is further detailed in Section 3.2. The data for F-SBWM was obtained from the questionnaire developed in step 1 and from the experts' responses. The third stage excavates the EOL activities using a hybrid method of risk analysis and F-ARAS and F- WASPAS and the proposed hybrid MCDM methods as detailed in Section 3.3. The data severity of effect (S) and the likelihood of occurrence (O) data—obtained from the questionnaire responses from the experts—are used in the F-ARAS and F- WASPAS and the proposed hybrid MCDM approach. The results of Step 3 are ranked safety scores that indicate the safety impact of safety risk sources throughout the EOL activities.

3.1. Fuzzy Logic

In 1965, Professor L. A. Zadeh introduced the fuzzy set theory. This theory, extending classical set theory, proves beneficial in addressing practical challenges within uncertain environments.

A fuzzy set, denoted as $\tilde{a}$, is defined as a pair *(U, m)*, where *U* represents a set, and m: $U \to [0, 1]$ serves as the membership function, denoted as $\mu_{\tilde{a}}(x)$. The function $\mu_{\tilde{a}}(x)$ allows the mapping of each element x within a universe of discourse *X* to a real number in the range [0, 1].

Definition 1. If $\tilde{\xi}_1 = (a^L, a^M, a^U)$ and $\tilde{\xi}_2 = (b^L, b^M, b^U)$ When two triangular fuzzy numbers are subjected to addition, the resultant fuzzy number, as described in Eq. (1), will also exhibit a triangular shape.

$$\tilde{\xi}_1 \oplus \tilde{\xi}_2 = (a^L + b^L, a^M + b^M, a^U + b^U) \qquad (1)$$

where $\xi^{(2)}$ and $\xi^{(3)}$ are the middle value and right-side value of the triangular fuzzy number $\tilde{\xi}$, respectively.

Definition 2. If $A = (a^L, a^M, a^U)$ and $B = (a^L, a^M, a^U)$ are two triangular fuzzy numbers, then their distance, denoted by d(A,B), is a triangular fuzzy number $C = (c^L, c^M, c^U)$ whose values c_i can be calculated using the following Eq. (2):

(2)

where in Eq. (3), (4):

$$\begin{cases} \Gamma(A) = \dfrac{a^L + 4a^M + a^U}{6} \\ \Gamma(B) = \dfrac{b^L + 4b^M + b^U}{6} \end{cases} \tag{3}$$

$$s_i = \left(a_i - \Gamma(A) + b_i - \Gamma(B)\right)/2 \quad i = 1,2,3 \tag{4}$$

Furthermore, the membership function is illustrated in Eq. (5).

$$\mu_x = \begin{Bmatrix} 0 & if & x \prec a_1 \\ \dfrac{x - a^L}{a^M - a^L} & if & a_1 \le x \le a_2 \\ 1 & if & x = a_2 \\ \dfrac{x - a^M}{a^U - a^M} & if & a_2 \le x \le a_3 \\ 0 & if & x \succ a_3 \end{Bmatrix} \tag{5}$$

Fuzzy numbers can represent linguistic variables. The relationship between linguistic variables and TFN are presented in Tables 3.

Table 3. Relationships between linguistic variables and triangular fuzzy numbers (Sabripoor et al., [32]).

Linguistic Terms	Fuzzy Scales
Equally importance (EI)	(1,1,1)
Weakly important (WI)	(1,2,3)
Moderate importance (MI)	(2,3,4)
Moderate plus importance (MP)	(3,4,5)
Strong importance (SI)	(4,5,6)
Strong plus importance (SP)	(5,6,7)
Very strong importance (VS)	(6,7,8)
Extreme importance (EX)	(7,8,9)

3.2. Obtain weights for safety risk sources using F-SBWM

BWM is widely applied in operations and supply chain management (Bai et al. [3], Gupta and Barua [18], Kusi-Sarpong et al. [24], Liao et al. [25], Zolfani and Chatterjee [51]). This tool was developed as an alternative decision support tool to MCDM (Rezaei [30]) to address some of the complexities of the AHP method related to pairwise comparisons, but it is based on mathematical programming optimization and multi-objective optimization approaches. Similar to the traditional BWM, F-SBWM involves the identification of a set of criteria as a foundational step in the decision-making process. The decision maker then designates the most and least important criteria. Subsequently, fuzzy reference comparisons, involving linguistic terms and TFNs, are performed. The expert's fuzzy preferences vector is established, and the significance of each criterion is computed through straightforward calculations and fuzzy operators, eliminating the need for mathematical programming models.

During the fuzzy comparisons of the best criterion to the other criteria, the importance of the best criterion is determined. Utilizing the weight of the best criterion, the weights of the remaining criteria are also computed, forming the best-to-others vector. Additionally, in the fuzzy comparisons of the other criteria to the worst criterion, the importance of the worst criterion is determined. The weights of the other criteria are then derived using the weight of the worst criterion, resulting in the others-to-worst vector. Finally, these two vectors are amalgamated to derive the ultimate weights of the decision criteria. This approach substantially streamlines the decision-making process, reducing the time required. Importantly, and since there are no mathematical programming models in this method, the decision maker does not need to use software packages.

Proceeding further, the stages of the F-SBWM method are outlined as follows:

Step 1: This step nvolves defining decision criteria in the format of and selecting both the most significant and least significant criteria.

Step 2: The preference of the best criterion over each of the other criteria is established using linguistic terms and Triangular Fuzzy Numbers (TFNs) in the structure of $\tilde{a}_{Bj} = (a^L_{Bj}, a^M_{Bj}, a^U_{Bj})$.

Step 3: The preference of each criterion over the least important criterion is determined using linguistic terms and TFNs in the format of $\tilde{a}_{jw} = (a^L_{jw}, a^M_{jw}, a^U_{jw})$.

Step 4: The priority of each criterion is computed through reference comparisons of the best criterion against the other criteria, represented by $\tilde{w}_j^1 = (w_j^L, w_j^M, w_j^U)$. Equation (6) is utilized to calculate the priority of the best criterion over each of the criteria. Subsequently, the weight of the best criterion is determined. By substituting the weight of the best criterion into Equation (7), the weights of the remaining criteria are also derived.

$$\tilde{w}_j^1 = \frac{1}{\sum_j \frac{1}{\tilde{a}_{Bj}}} \tag{6}$$

$$\tilde{w}_j^1 = \frac{\tilde{w}_B^1}{\tilde{a}_{Bj}} \qquad \forall j \tag{7}$$

Step 5: The priority of each criterion is determined through reference comparisons of each criterion against the worst criterion, expressed as $\tilde{w}_j^2 = (w_j^L, w_j^M, w_j^U)$. Equation (8) is employed to calculate the priority of each criterion over the worst criterion. Concurrently, the weight of the worst criterion is computed. By substituting the weight of the worst criterion into Equation (9), the weights of the other criteria are also calculated.

$$\tilde{w}_w^2 = \frac{1}{\sum_j \tilde{a}_{jW}} \tag{8}$$

$$\tilde{w}_j^2 = \tilde{a}_{jW} . \tilde{w}_w^2 \qquad \forall j \tag{9}$$

Step 6: The ultimate weights of the decision criteria are computed using Equation (10).

$$\tilde{w}_j^* = \frac{\tilde{w}_j^1 + \tilde{w}_j^2}{(2,2,2)} \tag{10}$$

Step 7: The center-of-area method stands out as the most practical and direct technique for the defuzzification process, as outlined in Equation (11):

$$\tilde{w}_j^* = (w_j^{*L}, w_j^{*M}, w_j^{*U}) \rightarrow w_j^* = \frac{w_j^{*L} + 4.w_j^{*M} + w_j^{*U}}{6} \tag{11}$$

3.3. Ranking the end-of-life activities about safety performance using F-ARAS

ARAS, introduced by Zavadskas and Turskis [44], is grounded in the idea that understanding complex phenomena in the world can be achieved through straightforward relative comparisons. This method not only assesses the performance of alternatives but also computes the ratio of each alternative to the ideal one. In the ARAS approach, the decision team assigns relative importance to evaluation criteria and rates feasible alternatives based on numerical values. In practical scenarios, determining precise weights for criteria and alternatives can be challenging for decision-makers. To address this challenge, a fuzzy approach is employed, using fuzzy numbers instead of crisp numbers, to better adapt to real-world cases. Consequently, fuzzy logic and the ARAS technique are combined to create the F-ARAS method, enhancing the accuracy of problem formulation in real-world scenarios.

The fuzzy ARAS technique facilitates a comprehensive analysis by allowing the decision team to prioritize alternatives' preferences in the presence of vague or imprecise information. The procedural steps of the fuzzy ARAS method are outlined as follows:

Step 1: The construction of a Fuzzy Decision-Making Matrix (FDMM) involves assigning performance values ($\tilde{x}_{ij}$) and attribute weights ($\tilde{w}_j$) as matrix entries. The selection of linguistic ratings is integral to this process. $\tilde{X} = \left[\tilde{x}_{ij}\right]_{m\times n}$ capturing preferences for m viable alternatives (rows) evaluated across n attributes (columns).

Step 2: Determining a hypothetical ideal value. The calculated ideal values for the criteria according to Equation (12):

$$\tilde{x}_{0j} = \begin{cases} \max\limits_i \tilde{x}_{ij}, if \max\limits_i \tilde{x}_{ij} \text{ is preferable} \\ \min\limits_i \tilde{x}_{ij}, if \min\limits_i \tilde{x}_{ij} \text{ is preferable} \end{cases} ; i = 0,1,2,\ldots,m \,|\, j = 0,1,2,\ldots,n \quad (12)$$

Step 3: FDMM is normalized j according to Equation (13):

$$\tilde{\tilde{x}}_{ij} = \begin{cases} \dfrac{\tilde{x}_{ij}}{\sum_{i=0}^{m} \tilde{x}_{ij}}, if \max\limits_i \tilde{x}_{ij} \text{ is preferable} \\ \dfrac{1/\tilde{x}_{ij}}{\sum_{i=0}^{m} 1/\tilde{x}_{ij}}, if \min\limits_i \tilde{x}_{ij} \text{ is.preferable} \end{cases} ; i = 0,1,2,\ldots,m \,|\, j = 0,1,2,\ldots,n \quad (13)$$

Step 4: Calculate the weighted normalized FDMM $\hat{\tilde{X}}_{ij}$ according to Equation (14):

$$\left[\hat{\tilde{X}}_{ij}\right]_{m\times n} ; \hat{\tilde{x}}_{ij} = \tilde{\tilde{x}}_{ij}\tilde{w}_j ; i = 0,1,2,\ldots,m \,|\, j = 0,1,2,\ldots,n \quad (14)$$

Step 5: Calculate values of the optimality function, total relative importance of i^{th} alternative according to Equation (15):

$$\tilde{S}_i = \sum_{j=0}^{n} \hat{\tilde{x}}_{ij}, i = 0,1,2,\ldots,m \quad (15)$$

It's noteworthy that the outcomes of fuzzy performance assessment for individual alternatives are expressed as fuzzy numbers $\tilde{S}_i$. The center-of-area method emerges as the most practical and straightforward approach for the process of defuzzification and compute according to Equation (16):

$$S_i = \frac{1}{3}(S_{i\alpha} + S_{i\beta} + S_{i\gamma}) \quad (16)$$

Step 6: The degree of utility for an alternative is ascertained through a comparison of the analyzed variant with the ideally optimal one, S_0. The equation employed to compute the utility degree K_i for an alternative x_i according to Equation (17):

$$K_i = \frac{S_i}{S_0}, i = 0,1,2,\ldots,m \quad (17)$$

Step 7: alternatives are ranked according to the value of K_i, indicating that a higher K_i value corresponds to increased desirability of the option.

3.4. Ranking the end-of-life activities about safety performance using F-WASPAS

MADM method, namely WASPAS, was introduced in by Zavadskas et al. [45]. This subsection extends WASPAS to the fuzzy environment. The merit of using a fuzzy approach is to assign the relative importance of

attributes using fuzzy numbers instead of precise numbers. WASPAS method is still developed so that it is possible to apply this approach to solving various decision-making problems. For example an extension of the WASPAS method using fuzzy sets can be found in Turskis et al. [38]. The WSM approach calculates the total score of the alternative as a weighted sum of the criteria. The WPM approach was created to prevent alternatives that have poor attributes or criterion values. Zavadskas et al. used the multiplicative exponential weighting method (or WPM) to solve dynamically changing environment problems.
The problem solution process by applying the F-WASPAS method is shown below:

Step 1: The construction of a Fuzzy Decision-Making Matrix (FDMM) involves assigning performance values ($\tilde{x}_{ij}$) and attribute weights ($\tilde{w}_j$) as matrix entries. The selection of linguistic ratings is integral to this process. $\tilde{X} = \left[\tilde{x}_{ij}\right]_{m\times n}$ capturing preferences for m viable alternatives (rows) evaluated across n attributes (columns).

Step 2: FDMM is normalized according to Equation (18):

$$\tilde{\bar{x}}_{ij} = \begin{cases} \dfrac{\tilde{x}_{ij}}{\max\limits_i \tilde{x}_{ij}}, if \max\limits_i \tilde{x}_{ij} \text{ is preferable} \\ \dfrac{\min\limits_i \tilde{x}_{ij}}{\tilde{x}_{ij}}, if \min\limits_i \tilde{x}_{ij} \text{ is preferable} \end{cases}, i = 1,2,\ldots,m \,\middle|\, j = 1,2,\ldots,n \tag{18}$$

Step 3a: Calculate the weighted normalized fuzzy decision matrix $\hat{\tilde{X}}_q$ for WSM according to Equation (19):

$$\left[\hat{\tilde{X}}_q\right]_{m\times n}; \hat{\tilde{x}}_{ij} = \tilde{\bar{x}}_{ij}\tilde{w}_j, i = 1,2,\ldots,m \,|\, j = 1,2,\ldots,n \tag{19}$$

Step 3b: Calculate the weighted normalized fuzzy decision matrix $\hat{\tilde{X}}_p$ for WPM according to Equation (20):

$$\left[\hat{\tilde{X}}_p\right]_{m\times n}; \bar{\hat{\tilde{x}}}_{ij} = \tilde{\bar{x}}_{ij}^{\tilde{w}_j},, i = 1,2,\ldots,m \,|\, j = 1,2,\ldots,n \tag{20}$$

Step 4: Calculate values of the optimality function, total relative importance of i^{th} alternative according to Equations (21) and (22):

$$\tilde{Q}_i = \sum_{j=1}^{n} \hat{\tilde{x}}_{ij}, i = 1,2,\ldots,m \tag{21}$$

$$\tilde{P}_i = \prod_{j=1}^{n} \bar{\hat{\tilde{x}}}_{ij}, i = 1,2,\ldots,m \tag{22}$$

It's noteworthy that the outcomes of fuzzy performance assessment for individual alternatives are expressed as fuzzy numbers $\tilde{Q}_i$ and $\tilde{P}_i$. The center-of-area method emerges as the most practical and straightforward approach for the process of defuzzification according to Equations (23) and (24):

$$Q_i = \frac{1}{3}(Q_{i\alpha} + Q_{i\beta} + Q_{i\gamma}) \tag{23}$$

$$P_i = \frac{1}{3}(P_{i\alpha} + P_{i\beta} + P_{i\gamma}) \tag{24}$$

Step 5: The calculated value of the integrated utility function for an alternative using the F-WASPAS method can be ascertained through according to Equation (25):

$$K'_i = \lambda Q_i + (1-\lambda)P_i, 0 \le \lambda \le 1 \tag{25}$$

It's noteworthy that λ equation's value is derived from the provided formula according to Equation (26), nevertheless, it is important to note that in the majority of research studies, this value is typically assumed to be 0.5.

$$\lambda = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} Q_i + \sum_{i=1}^{n} P_i} \tag{26}$$

Step 6: alternatives are ranked according to the value of K, indicating that a higher K value corresponds to increased desirability of the option.

3.5. Ranking the end-of-life activities about safety performance using hybrid MCDM approach

Extensive attention has been directed toward Multiple Criteria Decision-Making (MCDM) methods, leading to the proliferation of diverse approaches within this field. Because each MCDM method in the literature employs distinct logic to rank available options in decision problems, it is common to encounter divergent outcomes when applying multiple MCDM methods to the same problem. The ranking of options is inherently tied to the chosen approach. While instances of similar rankings across different methods for a specific problem are feasible, such occurrences are infrequent due to the limited commonality in logic among diverse methods.
In this study, we have introduced an innovative approach by amalgamating 2 established fuzzy MCDM methods based on utility functions and similarity. Following logical principles, was developed through various approaches, ultimately resulting in the creation of a novel method for ranking options. Emphasizing the importance of an effective integration method for evaluating the ultimate desirability score for each alternative, we subsequently provide a detailed elaboration on the specifics and steps of the proposed method.

Step 1: The scores assigned to the identified failure cases must be confined to the range of 0 to 1. The ranking indexes for F-ARAS and F-WASPAS are represented by K_i and K_i', respectively.

Step 2: Calculating the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS) involves utilizing the following maximum (η^+) and minimum (η^-) values according to Equations (27) and (28):

$$\eta^+ = \max_C \{ARAS_c, WASPAS_c\} \tag{27}$$

$$\eta^- = \min_C \{ARAS_c, WASPAS_c\} \tag{28}$$

Step 3: Computing the distance of between each failure mode with FPIS and FNIS, the distance of each failure mode from the positive (ψ_c^+) and negative (ψ_c^-) ideal solutions according to Equations (29) and (30):

$$\psi_c^+ = \sqrt{(ARAS_c - x_1^+)^2 + (WASPAS_c - x_3^+)^2}, \qquad c = 1, 2, \ldots, m \tag{29}$$

$$\psi_c^- = \sqrt{(ARAS_c - x_1^-)^2 + (WASPAS_c - x_3^-)^2}, \qquad c = 1, 2, \ldots, m \tag{30}$$

Step 4: The calculation of the Ultimate Utility Index (UUI) aims to prioritize available options within the context of Multiple Criteria Decision-Making (MCDM). In this approach, the ranking of options considers the separation distance from both the positive ideal solution and negative ideal solution utilizing three MCDM methods, as per Equation (31):

$$UUI = \left(\psi_c^- \Big/ \sum_{C=1}^{m} \psi_c^- \right) - \left(\psi_c^+ \Big/ \sum_{C=1}^{m} \psi_c^+ \right), \qquad -1 \le UUI \le 1 \tag{31}$$

Step 5: Organize the alternatives in descending order based on the Ultimate Utility Index (UUI), indicating that a higher UUI value corresponds to a more favorable option.

4. Initial investigation and illustration

This section provides specific insights into the methodology using real expert opinions. This expert input shows the effect of safety risk sources on EOL LIBs activities. By measuring sources of safety risk throughout

EOL LIB activities, perceived safety problems in the management of EOL LIBs can initiate the process of reducing safety risk.

4.1. Expert background

Three experts contributed to providing input for this study. The experts are from different organizations, regions, and departments as explained in Table 4. Experts are divided into three subsets. Experts 1 is from industry, experts 2 is from academia and experts 3 is from the government.

4.2. Calculation of safety risk source weights

Expert input was obtained to determine the best and worst criteria as the greatest and least influential sources of safety risk. The results of all experts are summarized in Table 4. There are some divergences in most (Best) and least (Worst) impactful safety risk sources. Two experts think the most impactful safety risk source is ME, another expert think MA is the most impactful source. Two experts believe that EN is the least impactful safety risk source and another expert each have differing opinions and think EL is the least impactful safety risk source.

Table 4. Expert respondent backgrounds

Expert Subsets	Experts	Organization	Expertise	Experience (Year)	Education Background
Industry	Expert 1	Industry engineer	Recycling Facility	13	Master of Science
Academic	Expert 2	Industrial Engineering	Researcher	5	Ph. D
Government	Expert 3	Electrical and Electronics Engineer	Labor and Social Security Training Expert	7	Master of Science

The subsequent stage involves assessing the comparative influence of the most impactful risk sources in relation to others, as well as gauging the preference of all sources against the least impactful one using a scale ranging from 1 to 9. Following the collection of evaluations from experts, the subsequent step is to compute the weight assigned to each criterion through the implementation of the F-SBWM Method. This method is employed to generate weights for each expert, and ultimately, a consensus is derived from all expert opinions regarding the relative impact of criteria. The average is calculated using Equation (11) defuzzification to obtain a precise numerical value indicating the importance of each criterion.

The results are presented through the visualization of safety risk source weights in Figure 4. Mechanical risks emerge as the most significant contributors, overshadowing other sources. In contrast, environmental risks occupy the position of being the least impactful among the identified risk sources. Managerial risks follow closely behind mechanical risks as the second most impactful safety risk sources.

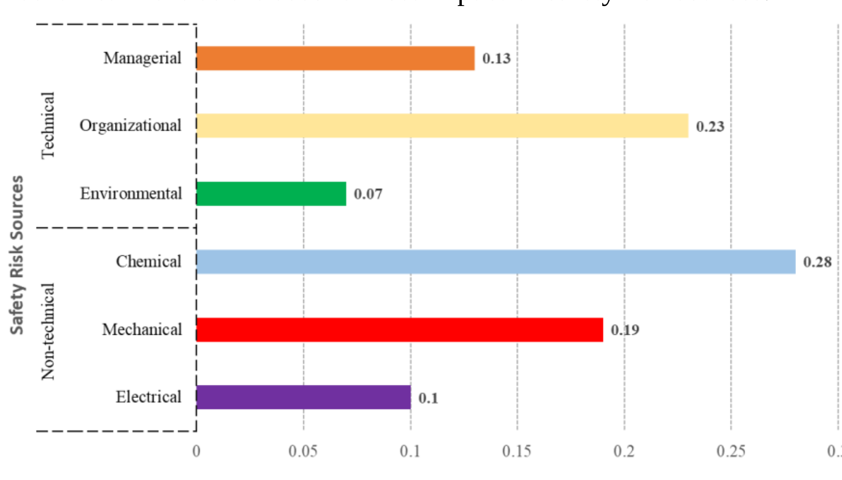


Figure 4. Weights of safety risk sources according to F-SBWM.

Furthermore, the cumulative weight of technical safety risk sources surpasses that of non-technical ones. This suggests that technical factors play a more substantial role in influencing the safety risks associated with EOL management activities. The findings emphasize that technical sources are the most crucial factors influencing the safety risk of EOL management activities. External environmental sources are found to have a relatively minor impact on EOL management activities. Interestingly, despite being the fourth-ranked source of risk, managerial risks are identified as having a significant role in safety risks according to the results.

4.3. Evaluation of the end-of-life activities

Upon completion of the weight calculations for all safety risk sources, the subsequent phase involves determining the impact of these sources on diverse End-of-Life (EOL) management activities, particularly those pertaining to Mechanical and Electrical (ME) activities, as elucidated in Section 2.1. To accomplish this assessment, the methodology employs the F-ARAS, F-WASPAS, and a hybrid MCDM method. The F-SBWM safety risk source weights are harnessed to support the evaluation in F-ARAS, F-WASPAS, and the hybrid MCDM. Subsequent to this stage, we proceed to calculate the K index within the F-ARAS method, the K index within the F-WASPAS method, and the rankings of failure modes using three MCDM methods, all of which are meticulously outlined in Table 5.

Table 5. Results of the two MCDM methods

Method	ARAS		WASPAS	
	K_i	Rank	K_i'	Rank
Collection	0.634536355	8	0.594368913	7
Test	0.696155951	4	0.661488677	5
Sort	0.650839029	7	0.616680252	6
Discharge	1	1	0.908328141	1
Disassemble	0.791817006	3	0.746236538	3
Crush	0.816275853	2	0.768886502	2
Sieve	0.529632784	9	0.48327729	9
Reassemble	0.69231343	5	0.669031348	4
Hydrometallurgical, Pyrometallurgical, Direct physical process	0.659950513	6	0.57443159	8

Table 5 presents the computed metrics for each method, and based on these metrics, the available options (failure modes) have been systematically prioritized. Building on the insights gleaned from Table 5, Table 6 illustrates the results obtained through the F-Hybrid MCDM method.

Table 6. Results of the proposed F-Hybrid MCDM method

	ψ_c^+	ψ_c^-	UUI	Rank
Collection	0.48180294	0.152794332	-0.081133981	9
Test	0.391472766	0.24390421	-0.015874882	6
Sort	0.454941616	0.180242349	-0.061579709	7
Discharge	0	0.633966516	0.264943282	1
Disassemble	0.263844361	0.371332913	0.075786496	3
Crush	0.230648071	0.404644129	0.099697459	2
Sieve	0.633966516	0	-0.190779365	10
Reassemble	0.389787096	0.246920154	-0.01410721	5
Hydrometallurgical, Pyrometallurgical, Direct physical process	0.476571674	0.159034012	-0.07695209	8
$\sum$	3.32303504	2.392838615	1.25E-16	

The suggested strategy for identifying, controlling, and analyzing existing risks across diverse domains, including services and industrial sectors, is well-suited for practical implementation. F-ARAS, F-WASPAS, and the proposed method, as detailed in Tables 4 and 5, identify all primary fault modes listed in Table 7.

Furthermore, in Figure 5, rankings resulting from the two fuzzy decision-making methods and the proposed approach are illustrated. Referring to Table 6 and Figure 5, the top 5 risks, scoring the highest and having a more significant impact, can be characterized as follows:

Safety considerations during the discharge of lithium-ion batteries are crucial to prevent potential hazards and ensure the reliable operation of these energy storage devices.

Discharging a lithium-ion battery generates heat. If the heat is not properly managed, it can lead to thermal runaway—a self-sustaining and uncontrolled increase in temperature. Thermal runaway can result in fires or explosions, posing significant safety risks to users and surrounding environments.

Table 7. The ranking leading five fault methods by the three Methods

	F-ARAS	F-WASPAS	Proposed Method
1	Discharge	Discharge	Discharge
2	Crush	Crush	Crush
3	Disassemble	Disassemble	Disassemble
4	Test	Reassemble	Reassemble
5	Reassemble	Test	Test
6	Hydrometallurgical, Pyrometallurgical, Direct physical process	Sort	Sort
7	Sort	Collection	Hydrometallurgical, Pyrometallurgical, Direct physical process
8	Collection	Hydrometallurgical, Pyrometallurgical, Direct physical process	Sort
9	Sieve	Sieve	Sieve

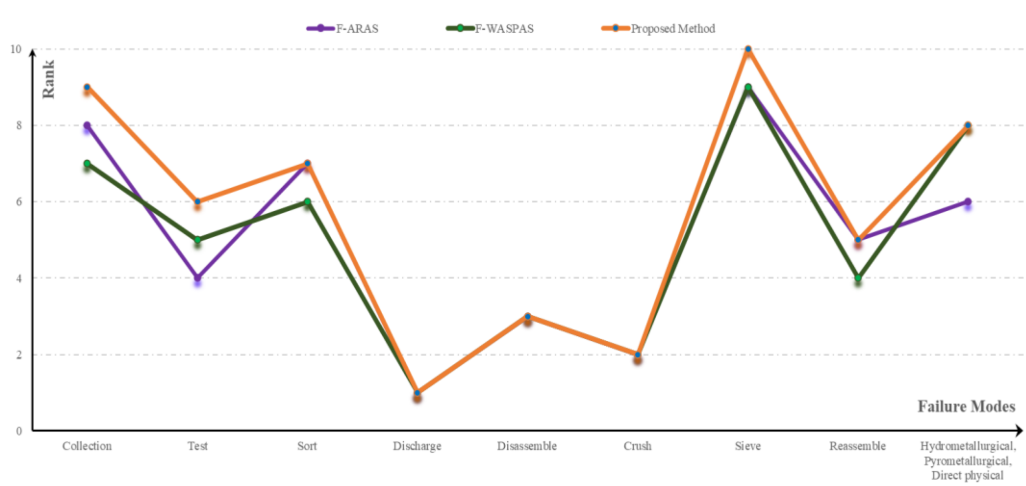


Figure 5. Ranking results.

High discharge rates or prolonged discharging can cause the battery cells to overheat. Proper safety mechanisms, such as thermal management systems and overcurrent protection, are essential to prevent excessive temperature rise and maintain safe operating conditions. In summary, ensuring safety during the discharge of lithium-ion batteries involves implementing robust design features, employing advanced battery management systems, and adhering to safety standards. This multifaceted approach helps mitigate risks, protect users and the environment, and enhance the overall reliability of lithium-ion battery technology.

4.4. Managerial Insights

This study provides key insights for managers involved in end-of-life (EOL) management of lithium-ion batteries (LIBs) within the framework of a circular economy. The main managerial takeaways from this research are:

Prioritize Safety Risk Assessment: Safety risks associated with LIBs, especially during EOL management, can significantly affect resource availability, environmental sustainability, and public safety. Managers should prioritize safety risk assessments as a core part of their EOL strategies. Implementing advanced methodologies, such as the Fuzzy Simplified Best-Worst Method (F-SBWM) combined with Fuzzy Additive Ratio Assessment (F-ARAS) and Fuzzy Weighted Aggregated Sum Product Assessment (F-WASPAS), provides a comprehensive understanding of these risks.

Address Technical and Managerial Concerns: The study indicates that both technical issues related to battery design and non-technical managerial concerns are significant sources of safety risks. Managers should ensure that both technical improvements in battery design and robust managerial practices are addressed to mitigate these risks.

Adopt a Flexible Risk Management Approach: The introduction of the fuzzy hybrid MCDM approach offers a flexible and reliable framework for assessing and ranking safety risks. Managers should consider adopting similar approaches to enhance their risk management strategies. The combination of F-ARAS and F-WASPAS methods with F-SBWM helps align outcomes with expert opinions and improves the robustness of risk assessments.

Integrate Multi-Criteria Decision-Making (MCDM) Methods: Utilizing fuzzy MCDM methods enables a more detailed and comprehensive evaluation of safety risks. Managers should integrate these methods into their decision-making processes to better identify and rank risks based on their environmental, economic, and social impacts.

Evaluate Across Different Contexts: The impact of safety risks varies across different activities and industries. Managers should conduct context-specific evaluations and stakeholder mapping to ensure that their risk management strategies are tailored to their specific operational settings.

Encourage Longitudinal Research: The study highlights the need for longitudinal research as technology and EOL management practices evolve. Managers should stay informed about emerging research and advancements in battery technology to continually refine their safety risk management practices.

By incorporating these insights, managers can enhance the stability, sustainability, and efficiency of LIB supply chains, contributing to a more resilient and circular economy.

5. Conclusion, limitations, and future research

If safety considerations related to EOL management are effectively considered, the circular economy for LIBs can be extended. There is significant potential for economic, environmental and social value for metal supply with effective EOL management of LIBs. As mentioned above, investigation and evaluation of safety issues during EOL management activities are emerging and much needed .However, the evaluation of the impact of safety risks on EOL-reverse logistics management with CE activities is less prominent and relatively limited.

This study presented a four-step approach to investigate sources of safety risks and their impact on EOL activities. Overall, feedback was positive, but improvements were identified to help further address practical concerns as well as inform future research. In order to address the limitations, a flexible approach is proposed, utilizing the fuzzy method. This study seeks to not only resolve the identified issues through the F-FMEA method but also to surmount the constraints inherent in F-FMEA methods. The objective is to achieve more comprehensive and reliable results in the analysis. This paper introduces a fuzzy hybrid MCDM approach designed to identify and rank risks impacting safety in lithium-ion battery circularity activities .The proposed approach offers a novel contribution to the field by addressing critical gaps left by previous methods in end-of-life (EOL) management of lithium-ion batteries (LIBs). While existing methods have made strides in evaluating safety risks, they often fall short in comprehensively integrating multiple perspectives on risk assessment. This study introduces the Fuzzy Simplified Best-Worst Method (F-SBWM) and combines it with a hybrid approach using Fuzzy Additive Ratio Assessment (F-ARAS) and Fuzzy Weighted Aggregated Sum Product Assessment (F-WASPAS) methods. This innovative combination allows for a more nuanced and detailed analysis of safety risks associated with EOL LIB management. By leveraging fuzzy Multi-Criteria Decision Making (MCDM), the approach provides a robust framework for identifying and ranking failure modes based on their environmental, economic, and social impacts. This comprehensive assessment not only improves understanding of safety risks but also supports the development of targeted strategies to enhance resource availability, mitigate environmental harm, and bolster public safety. The unique integration of these methodologies addresses the limitations of previous approaches, offering actionable insights to improve the stability and sustainability of LIB supply chains.

The results illustrate that a major source of safety risks is related to technical battery design issues. Non-technical causes such as managerial concerns are found to be significant safety risk sources. Furthermore, the analysis shows that the impact of safety risks varies widely across activities – but their relative importance varies and requires careful examination across industries and products. Stakeholder roles and stakeholder mapping of issues and concerns that affect and are affected by activities should be carefully considered and evaluated. Also, compare the results of your research with the following three similar studies:

The study in Aikhuele [1] focuses on the reliability and safety of lithium-ion battery (LIB) components, particularly the electrolyte. Our work also emphasizes safety risks but within the context of end-of-life (EOL) LIB management. While Aikhuele [1] employs a proactive reliability-centered maintenance approach, our study uses a hybrid Fuzzy Simplified Best-Worst Method (FSBWM) along with F-ARAS and F-WASPAS methods to quantify and rank safety risks. Both studies underline the importance of safety concerns, but our work extends the focus to EOL management, a critical phase in LIB life cycles, offering a new perspective that complements the reliability-centered approach of Chen et al. [9].

Chen et al. [12] explores safety risks in EOL LIB management with a circular economy (CE) perspective, using a combination of BWM and TOPSIS methodologies for risk analysis. Our study aligns with this by also addressing safety risks during the EOL stage but introduces the FSBWM and hybrid F-ARAS and F-WASPAS methods for a more nuanced and comprehensive risk assessment. The novelty of our approach lies in the integration of fuzzy multi-criteria decision-making (F-MCDM) methods, which enhance the robustness of risk quantification and ranking, providing deeper insights into safety risk resource improvements.

Similar to our research, Chen et al.'s study [12] identifies safety as a critical concern in EOL LIB management within closed-loop supply chains. The study uses the TOE framework to evaluate safety issues, while our work goes further by proposing a detailed methodology for assessing and ranking safety risks through FSBWM and hybrid fuzzy MCDM methods. This approach allows us to not only identify potential hazards but also to prioritize them effectively, contributing valuable findings to the discourse on safety in closed-loop systems.sa

Our research builds upon the foundation laid by previous studies while introducing innovative methodologies for assessing and ranking safety risks in EOL LIB management. By comparing our findings with those in the literature, we highlight the novelty of our approach and its potential contributions to advancing safety risk management in the broader context of LIB sustainability and circular economy frameworks. As observed in this study, we used two methods to rank options: F-ARAS and F-WASPAS. The results in Table 4 show that the methods vary in performance across different criteria, leading to different rankings of options depending on the method. To achieve more reliable results, a combined approach was introduced to better align the outcomes with expert opinions and this approach ensures more robust results.

Developmentally, future research can be carried out on sources of safety risk and EOL management activities in other CE settings. As CE and EOL LIBs management activities change as battery technology and other future technologies advance, more longitudinal research is needed. This is a fertile and essential area of research for sustainable economic and environmental contributions of these practices.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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