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Review article

Management strategies and recycling technologies: Lessons learned and roadmap for sustainable circular battery waste management in Saudi Arabia

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ABSTRACT

Waste battery generation is a global challenge, particularly in the absence of a structured policy and regulatory framework. However, this waste stream presents a significant opportunity to recover critical metals that are limited in supply worldwide, such as lithium, cobalt, nickel, graphite, and manganese. This study provides the first academic assessment of waste battery generation, policy initiatives, and management practices in Saudi Arabia. Currently, there is no concrete policy framework or systematic assessment addressing waste battery management in the country, which poses significant challenges for implementing sustainable solutions. This study aims to guide policymakers, government organizations, businesses, and academic researchers by offering management strategies and technology options tailored to the Saudi context. It begins by assessing the current state of waste battery generation, policy initiatives, and management practices, identifying critical bottlenecks in the existing system. The study then conducts an in-depth evaluation of best-practice policies and management strategies, such as the EU Battery Regulation, case studies (e.g., INOBAT, Switzerland; BEBAT, Belgium), and the technologies employed by 49 global commercial recycling companies, including pyrometallurgy and hydrometallurgy. Based on these insights, the study proposes a roadmap for waste battery management in Saudi Arabia. Additionally, several future research directions are suggested to foster interdisciplinary collaboration, offering valuable guidance to academic researchers. Policymakers, businesses, and stakeholders can utilize these findings to develop sustainable and efficient waste battery management and recycling strategies.

1. Introduction

The green and sustainable energy transition, climate change mitigation, resource conservation, and material circularity have garnered significant attention from researchers and policymakers as they address some of the world's most pressing challenges [1–4]. With the proliferation of large-scale energy storage devices, electric vehicles (EVs), consumer electronics, and other essential applications, batteries of various chemistries have greatly enhanced the quality of life and contributed to decarbonization pathways, such as through EVs in the transportation sector. Battery design and manufacturing involve the use of a range of materials, including critical rare earth elements like cobalt (Co), lithium (Li), and nickel (Ni); base metals like copper (Cu), aluminum (Al), and zinc (Zn); as well as hazardous metals like lead (Pb) and cadmium (Cd) [5].

Despite the efforts in some European countries and globally, material recovery from end-of-life (EoL) batteries has not received adequate attention until recently. In many cases, household portable batteries are still being disposed of in landfills due to insufficient collection systems and the lack of a comprehensive policy and regulatory framework for waste battery management and recycling [6]. One of the emerging types of waste batteries is lithium-ion batteries (LIBs), which contain valuable metals; however, currently, only 5%–7% of LIBs are recycled globally [7]. Recycling waste batteries is a critical pathway to advancing the circular economy, alongside alternatives like the remanufacturing and secondary use of batteries. According to Ellen Macarthur Foundation, "…in a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting" [8]. Fig. 1 illustrates the competitive advantage of recycling various metals, highlighting the reductions in production energy demand and carbon footprint compared to primary production from virgin materials.

Globally, several countries have achieved high rates of waste battery collection and recycling. Notably, European countries began establishing battery collection and recycling operations in the 1990s [10]. China

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List of abbreviations			
Al	Aluminum	Li	Lithium
ARF	Advanced Recycling Fees	LABs	Lead–acid batteries
AI	Artificial intelligence	LFP	Lithium Iron Phosphate
Co	Cobalt	LCO	Lithium Cobalt Oxide
Cu	Copper	LTO	Lithium Titanium Oxide
Cd	Cadmium	MJ	Mega-joule
CO_2	Carbon-dioxide	MENA	Middle East and North Africa
CHF	Swiss Franc	Mn	Manganese
CRAs	Co-regulatory arrangements	MFA	Material flow analysis
EoL	End-of-life	MIP	Mixed-integer programming
EU	European Union	MILP	Mixed-integer linear programming
EUR	Euro	Ni	Nickel
E-waste	Electronic waste	NMC	Nickel-manganese-cobalt
EEE	Electrical and electronic equipment	Ni-Cd	Nickel-Cadmium
EVs	Electric vehicles	Ni-MH	Nickel-Metal Hydride
EPR	Extended Producer Responsibility	NTCRS	National Television and Computer Recycling Scheme
Fe	Iron	OECD	Organization for Economic Co-operation and Development
FOEN	Federal Office for the Environment	ORRChem	Chemical Risk Reduction Ordinance
GCC	Gulf Cooperation Council	POM	Put-on-market
ICT	Information and communication technology	Pb	Lead
ICE	Internal combustion engine	PIF	Public Investment Fund
KSA	Kingdom of Saudi Arabia	PVDF	Polyvinylidene fluoride
kt	Kilotons	R&D	Research and development
KAEC	King Abdullah Economic City	REEs	Rare earth elements
KAUST	King Abdullah University of Science and Technology	SASO	Saudi Standards, Metrology, and Quality Organization
LIBs	Lithium-ion batteries	SIRC	Saudi Investment Recycling Company
		UPS	Uninterruptible power supplies
		Zn	Zinc
		ZMO	Zinc Manganese oxide

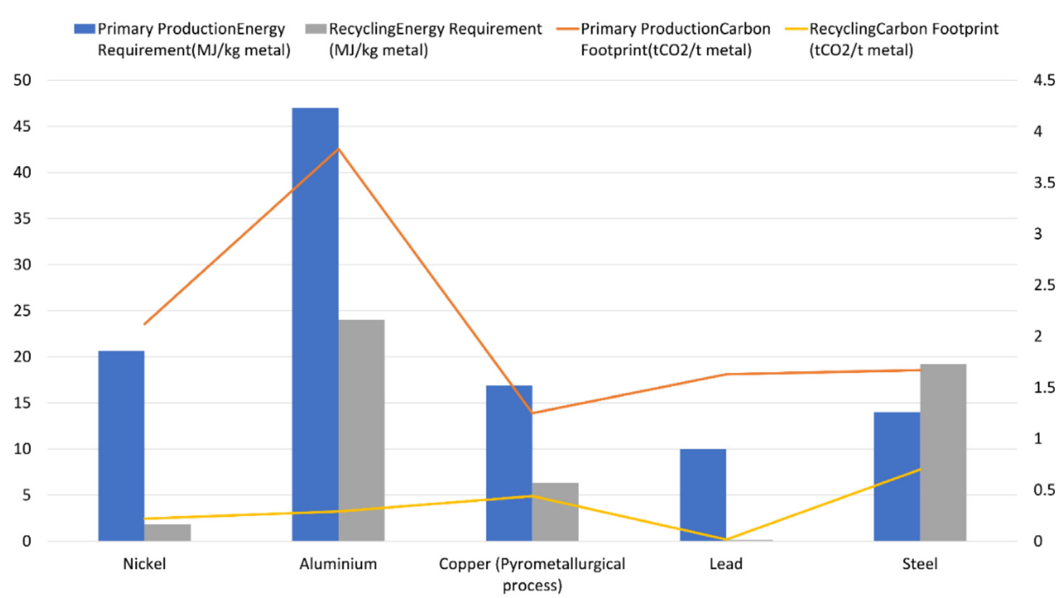

Fig. 1. Benefits of recycling compared to virgin materials in terms of energy requirements and CO_2 emission. *Source:* Kala and Mishra [9].

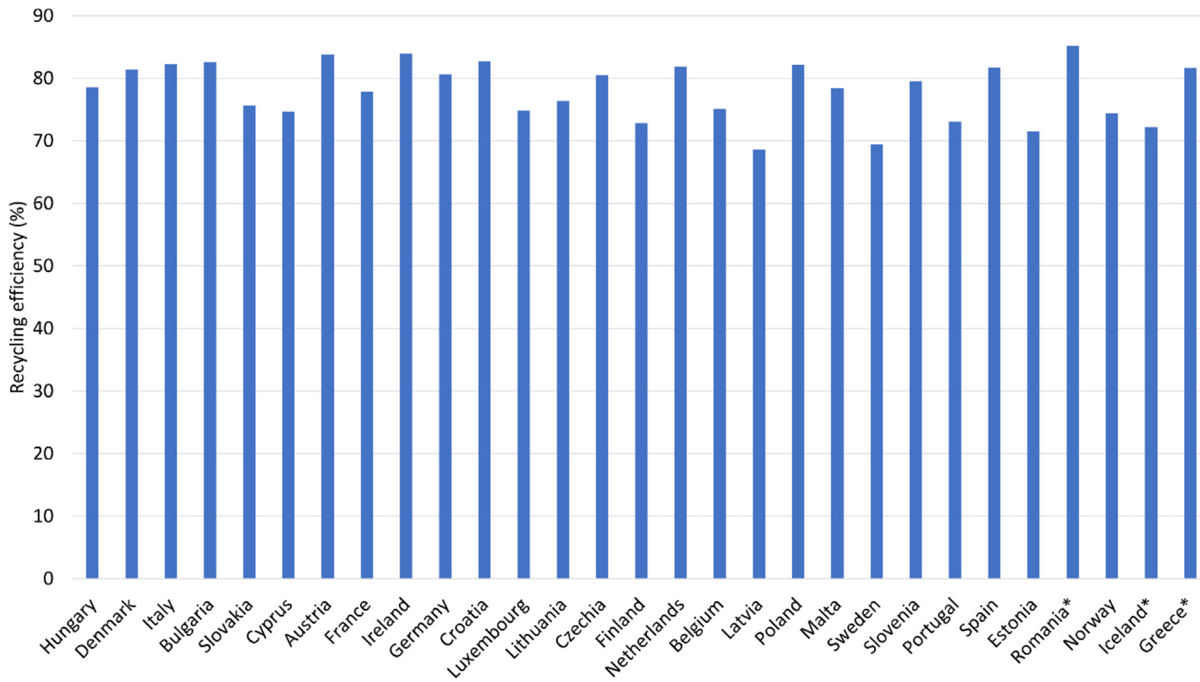

Fig. 2. Average recycling efficiencies of various types of batteries (e.g., lead–acid, nickel-cadmium and other batteries) in EU countries for the year 2021. (Note: *for the year 2020).
Data source : Eurostat [14].

is now recognized as one of the countries with the most substantial recycling capabilities, particularly for LIBs [11], However, only about 30%–40% of battery materials are currently recycled within the country [12]. The new European Union (EU) battery regulations [13] have underscored the global importance of material circularity for critical minerals found in waste batteries. Fig. 2 highlights some of Europe's leading countries in battery collection and recycling rates. Ireland and Austria exhibit some of the highest average recycling efficiencies across various battery types, while Hungary and Denmark achieve recycling efficiencies exceeding 94% for lead–acid batteries. Denmark and Poland have also demonstrated significant advancements in recycling efficiency for nickel-cadmium batteries.

In the Global South, particularly in West Asian countries, waste battery recycling has not received significant attention. Although recent focus has been placed on electronic waste (e-waste) recycling—since many e-waste items contain battery components and accumulators—regional assessments of waste batteries and strategies for circular economy development are largely absent from the academic literature. In the Gulf Cooperation Council (GCC) countries, sustainability issues have recently gained attention within national agendas, as well as among policymakers and researchers. In the Kingdom of Saudi Arabia (KSA), waste management and circular economy are emerging topics of discussion, with the government planning substantial investments in infrastructure to address various waste streams, including batteries, plastics, and electronics [15]. While batteries have been identified as a key focus area, a roadmap for sustainable and circular battery waste management and recycling remains undeveloped in the context of Saudi Arabia.

Current waste management regulations and decrees lack detailed guidance on how to operationalize the national mission of "Reuse of product and material in the industry" as outlined in Saudi Vision 2030 [16]. Additionally, there is a lack of understanding and a systemic approach to waste management, particularly concerning management options and the selection of key technologies, as evidenced by academic literature. For example, Osra, Ciner and Özcan [17] examined used car batteries, specifically lead–acid batteries, as hazardous waste and proposed an integrated management system for the Makkah region. Moossa, Qiblawey [18] highlighted the absence of proper e-waste and battery scrap management systems in the Middle East and North Africa (MENA) region, despite Saudi Arabia being the leading generator of e-waste within the region. Akhmetov, Manakhov and Al-Qasim [19] conducted a review of LIB cathode recycling approaches, including pyrometallurgy, hydrometallurgy, and direct restoration methods, to provide insights into future large-scale battery recycling industry development. However, their findings were generalized and did not offer specific directions for academic researchers focused on Saudi Arabia. While current battery research primarily concentrates on sustainable battery manufacturing—a critical aspect of the battery supply chain—there is a notable lack of focus on waste management perspectives.

This study aims to guide policymakers, government organizations, businesses, and academic researchers by offering management strategies and technology options tailored to the Saudi context with a roadmap. After reviewing the current state of waste batteries, specially sources, policy and regulations, and initiatives in Saudi Arabia (presented in Section 2) and European battery regulations, case studies, and the recycling technologies employed by global companies (presented in Section 3), the roadmap has been proposed enabling the application of the strategies and technologies for sustainable battery waste management in Saudi Arabia. This comprehensive approach has not been previously undertaken in academic literature.

The novelty of this study lies in its examination of the current state of waste battery management within the context of Saudi Arabia. It identifies bottlenecks and recent developments in policies and regulations related to battery waste, and it highlights initiatives undertaken by government organizations. The study also includes two European case studies, along with core components of EU battery regulations, to illustrate essential elements of a waste battery management system and benchmark key management strategies. Furthermore, this study identifies major commercial waste battery recycling companies, providing key information on their processing capabilities, recycling technologies, material recovery patterns, and the types of batteries they handle. This holistic perspective offers valuable insights for the Saudi government as it considers adopting similar technologies. Additionally, the paper outlines key research areas for academic researchers in Saudi

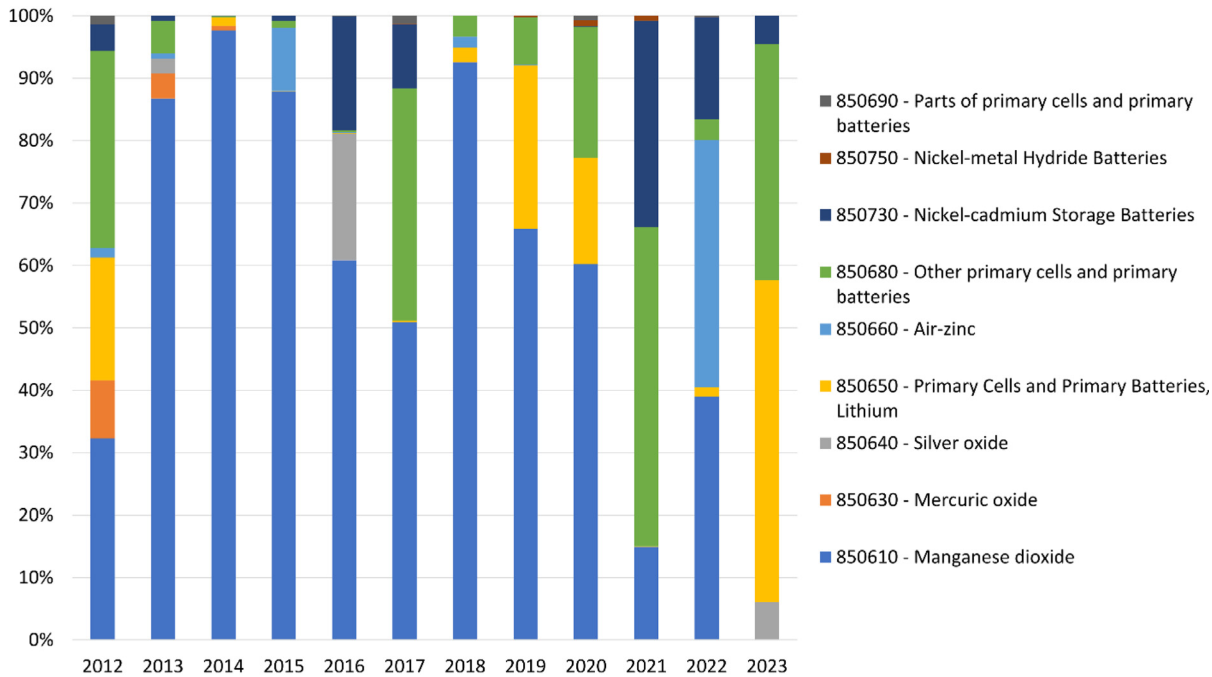

Fig. 3. Various types of battery import from 2012 to 2023 in Saudi Arabia.
Data source : UN Comtrade Database [20].

Arabia to explore. These approaches can also be applied to other countries currently planning to implement waste battery management and technology adoption strategies.

The article is organized as follows: After this brief introduction, Section 2 describes the current state of waste battery management in Saudi Arabia, highlighting present and future sources of waste battery generation, as well as policy and regulatory measures and initiatives that are currently in place. Section 3 reviews global best practices in management strategies and technology options, with a focus on the EU battery regulation, relevant case studies, and commercially available technologies used by recyclers worldwide. Section 4 describes a roadmap based on the lessons learned from the strategies and technologies in the context of Saudi Arabia. Section 5 outlines few future research directions for waste battery management and recycling. Finally, Section 6 concludes the article.

2. Current state of battery waste management in Saudi Arabia

Currently, there is no waste battery management system in Saudi Arabia [18]. Furthermore, there are no concrete statistics on the volume of waste battery generation in the country. The absence of a well-established regulatory framework for managing this waste stream is a significant challenge [21]. Recent developments in electronic waste (e-waste) regulations and initiatives suggest that the government is taking proactive steps to manage waste that otherwise ends up in landfills via public waste collection containers. Waste is not sorted either before or after disposal from residential units. As of 2021, unsorted waste disposal accounted for 79.14% (approximately 7.5 million tons) of total waste generation [22]. Nearly all waste generated from residential units is disposed of in public containers.

Each year, Saudi Arabia generates between 110 and 130 million tons of waste [23,24]. The types of batteries imported into Saudi Arabia provide some indication of potential waste generation. According to data from the UN COMTRADE database [20], substantial quantities of manganese dioxide batteries, various primary cells, and more recently, lithium-based batteries are imported into the country (Fig. 3). In the database, specific types of batteries can be identified by HS-codes. Song, Hu [25] previously used the HS-codes (as seen in Fig. 3) for identifying the battery imports from the database for China. Similar approach has been taken for Saudi Arabia in Fig. 3. Based on these statistics, it is clear that if waste batteries are not properly collected and managed for recycling, they will likely end up in landfills, resulting in significant environmental impacts and economic losses.

2.1. Sources of waste batteries in the KSA

2.1.1. Oil, gas and other heavy service industries

In Saudi Arabia, the oil and gas industry is a major industrial sector, with Aramco as the global leader in oil production [4]. According to Safe Management [26], LIBs are extensively used by oil and gas companies for various applications, including downhole tools, drilling, measurement, testing, wireline, and well intervention activities. For stationary power backup in "on-shore" and "off-shore" operations, sealed and vented lead–acid batteries are typically utilized, while nickel-cadmium batteries are preferred for operations conducted in extreme temperatures [27]. These batteries serve as primary or backup power sources for the industry, indicating that Saudi Aramco, as the leading oil producer, uses significant quantities of various battery types and should be considered a major source of industrial battery waste. Recent research from the Aramco Research Center in Russia, in collaboration with Saudi Aramco, has highlighted the challenge of battery waste in the industry, particularly through a study on LIB cathode recycling [19].

2.1.2. E-waste

The integration of technology in both government and private sectors, along with the widespread adoption of consumer electronics—particularly among younger generations—has led to extensive use of various electrical and electronic equipment (EEE), such as cameras, laptops, mobile phones, telephones, uninterruptible power supplies (UPS), and control systems, all of which rely on LIBs as their primary power source [26]. Fig. 4 illustrates the LIB content across different types of electrical and electronic equipment (EEE). On a regional level, Makkah, Riyadh, and the Eastern Province are hotspots for e-waste generation, particularly from small information and communication technology (ICT) devices like mobile phones. Notably, some electronic

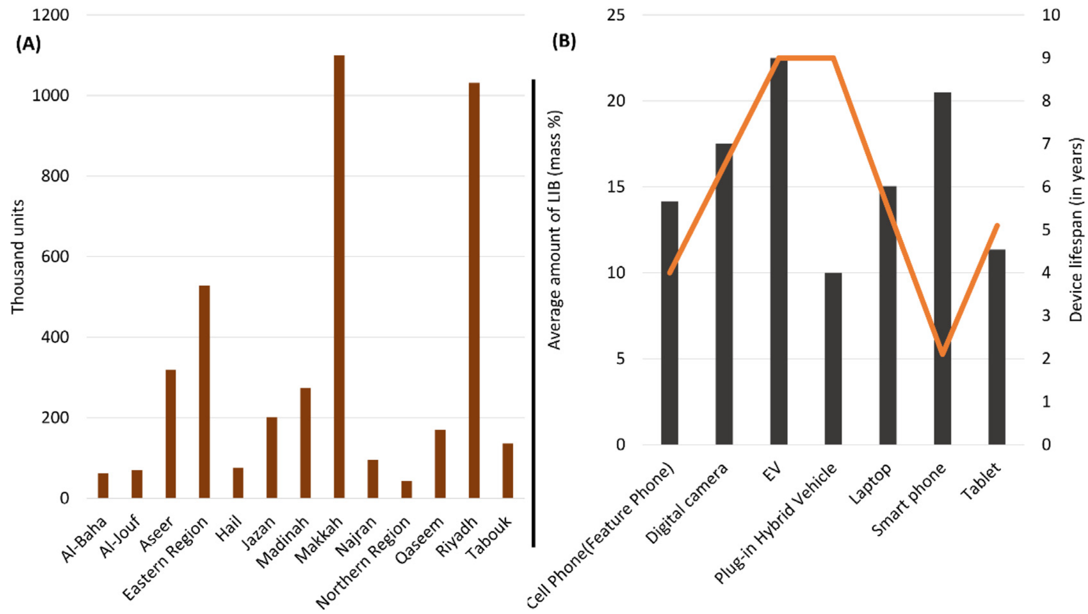

Fig. 4. (A) Number of generated wastes from small ICT device (e.g., mobile phones, game console) across the regions in Saudi Arabia (Data source: [22]) and (B) LIBs content in various EEE and their lifespan, adapted from Kala and Mishra [9].

devices, such as smartphones, contain a high proportion of LIBs relative to their total mass but have relatively short lifespans. This indicates that without proper management and recycling, a significant amount of recyclable LIBs may end up in the waste stream, typically in landfills. Additionally, EVs are emerging as a substantial source of LIBs.

In 2019, Saudi Arabia's total put-on-market (POM) volume of various EEE was 785 kilotons (kt), making it the second-largest in the region after Egypt (1.1 million tons) [28]. According to the regional e-waste monitor report [28], Saudi Arabia was one of the largest e-waste generating countries among Arab states in 2019, producing 595 kilotons of e-waste—21% of the total e-waste generated in the region—with a per capita generation rate of 16.3 kg. Additionally, a study by Ahmad Filimban, Al-Faraj and Oti [29] reported that Saudi Arabia generates approximately 378,000 tons of e-waste annually within the GCC countries. However, the country has a low recycling rate of 10%–15%, predominantly managed by the informal sector.

Informal e-waste recycling is a well-documented issue that poses significant environmental risks due to the crude recycling methods used by informal enterprises. As with waste batteries, there are currently no regulations or policies governing e-waste management in Saudi Arabia [28]. The absence of regulatory oversight and enforcement indirectly enables the informal sector to engage in recycling activities. A substantial portion of e-waste is exported from Saudi Arabia to countries such as China and India, despite existing legislation on the transboundary movement of hazardous waste. However, the country offers tax exemptions and incentives for formal recycling facilities [28]. The Saudi government is currently drafting regulations to support the environmentally sound management of e-waste.

2.1.3. Lead–acid batteries and electric vehicles (EVs)

Internal combustion engine (ICE) vehicles are widespread in Saudi Arabia. According to recent data from Statista, vehicle sales in the country were around 522,000 units in 2015, increased to 645,000 units in 2023, and are projected to reach 600,000 units by 2029 [30] (Fig. 5 (A)). Lead–acid batteries (LABs) are integral to ICE vehicles and are considered a major source of waste batteries [31]. However, there are no concrete statistics on the volume of waste LABs generated in Saudi Arabia.

Based on passenger vehicle sales figures in Saudi Arabia, a model can be developed to estimate the amount of waste LABs generated in the country. Using sales data from 2015 to 2029 (projected) [30], the average weight of LABs in passenger vehicles is considered to be 17 kg [32], with an average lifespan of 3 years (typically ranging from 3 to 5 years) [33]. The replacement rate is assumed to be 0.8, suggesting that each vehicle undergoes one battery replacement during its lifetime, particularly due to the hot climate in Saudi Arabia. A disposal rate of 90% (0.9) is also assumed, representing the proportion of batteries disposed of through proper channels. Equations (1 – 3) were applied to estimate the amount of waste LABs generated from 2015 to 2029.

To estimate the number of batteries reaching EoL in year t, both the batteries initially installed in vehicles sold in previous years (assuming they reach EoL after L years) and replacement batteries for vehicles sold before that year were considered. The number of waste batteries generated in year t can be represented by Eq. (1), while Equation (2) expresses the quantity of disposed batteries, and Eq. (3) calculates the disposed battery weight. In Eq. (1), the first term estimates the EoL of initial batteries sold with vehicles in year i, while the second term estimates the EoL of replacement batteries installed in vehicles that had initial batteries replaced after L years.

$$B_t = \sum_{i=t-L}^{t-1} V_i + R. \sum_{j=t-2L}^{t-L} V_j \tag{1}$$

$$B_t^{disposed} = B_t \times D \tag{2}$$

$$W_t = B_t^{disposed} \times W \tag{3}$$

Where, V_t : vehicle sales in year t; L: average lifespan of a LAB in years; R: replacement rate of batteries for each vehicle over its lifetime; D: disposal rate; W: average weight of a lead–acid battery.

Based on the estimations, Fig. 5 (B) illustrates the amount of waste LABs generated from passenger vehicles from 2015 to 2029. It is estimated that waste LAB generation was 1.45 million units (over 24,000 tons) in 2015, increased to 2.31 million units (39,372 tons), and is projected to reach approximately 2.87 million units (48,849 tons) by 2029, representing a 59.74% increase from 2018.

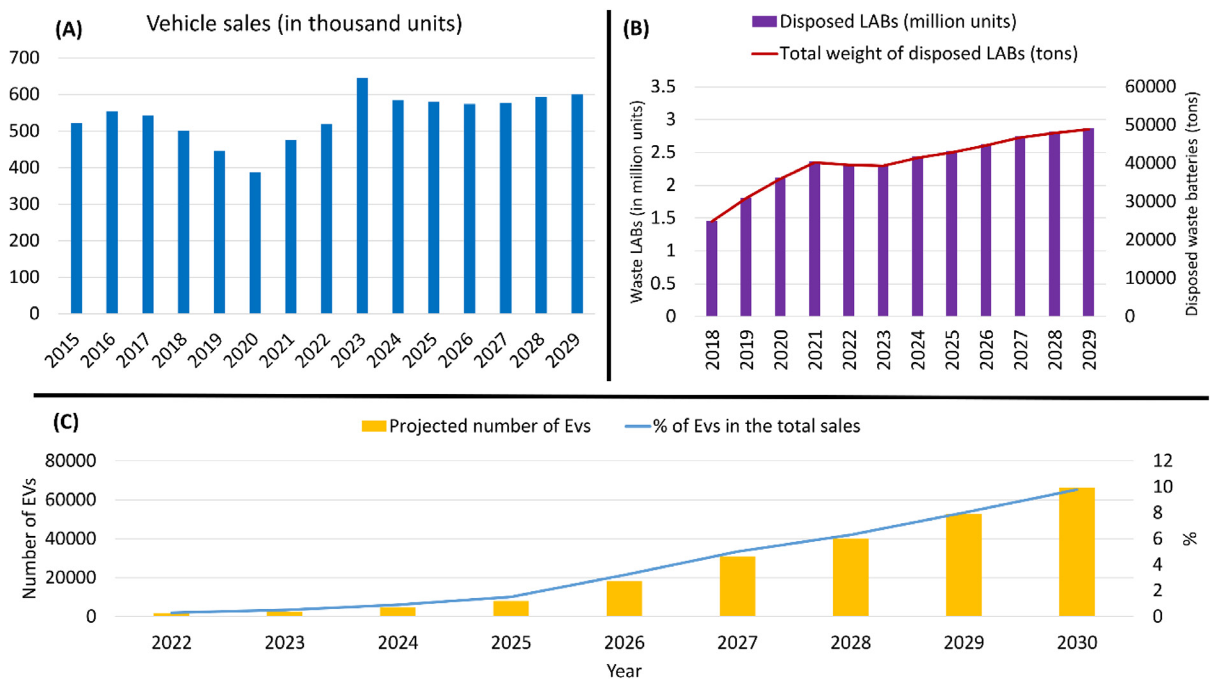

Fig. 5. (A) Vehicle sales in Saudi Arabia from 2015 to 2019 (projected) [Data source: Statista [30]](B) Projected EV sales over the years and percentage of EVs in total sales volume [Data Source: SIDF [34]].

Globally, EVs are considered a major source of waste LIBs [35]. Waste LIBs from EVs contain various high-value materials, including cobalt (Co), nickel (Ni), manganese (Mn), lithium (Li), aluminum (Al), and iron (Fe) [36]. As of 2016, 32 countries accounted for global production of nickel–manganese–cobalt (NMC) batteries, which are one of the primary battery types used in EVs. Key contributors to NMC battery production include Australia (for lithium, nickel, and manganese), China (for graphite and manganese), Chile (for lithium), India (for graphite), South Africa (for manganese), and the Philippines (for nickel) [37].

Although ICE vehicles currently dominate in Saudi Arabia due to the widespread availability of fossil fuels, it is anticipated that EVs will gradually enter the Saudi transport sector. As part of the country's transport sector decarbonization plan, Lucid Motors, a US-based EV manufacturer, recently established a manufacturing plant at King Abdullah Economic City (KAEC) with an annual production capacity of 155,000 vehicles. Additionally, the Saudi Public Investment Fund (PIF), the national fund driving economic transformation under Vision 2030, has developed a joint venture with Taiwanese company FOXCONN to create the Saudi EV brand CEER, which will have an annual production capacity exceeding 150,000 vehicles. According to projections, by 2030, EV sales in Saudi Arabia will reach approximately 66,379 units, accounting for 9.8% of total vehicle sales [34]. Fig. 5 (C) illustrates the market penetration and projected sales of EVs in Saudi Arabia.

From a materials perspective, Saudi Arabia is likely to face significant challenges if waste battery materials, particularly LIBs and other EV batteries, are not strategically collected and recycled. The country lacks proven reserves of key materials required for EV battery manufacturing. While some minerals, such as phosphate, aluminum, gold, and copper, are available domestically [38], Saudi Arabia would benefit from complementing virgin mining with urban mining initiatives. Companies like Ma'aden, a major mining enterprise in Saudi Arabia, could focus on recovering valuable materials from waste batteries to support sustainable resource management.

2.2. Policy and regulations

Currently, Saudi Arabia lacks specific policies and regulations for waste battery recycling, including waste lithium batteries [26]. Furthermore there is no specific guidelines and policy related to waste lithium batteries in the country [26]. In light of international research efforts aimed at developing sustainable and comprehensive waste battery policies and regulations, several critical components have been identified, as presented in Table 1. These include a harmonized regulatory framework, extended producer responsibility, infrastructure and technology for collection and recycling, environmental and health impact considerations, and policy incentives. These elements are essential for shaping an effective waste battery management and recycling policy.

Hotta, Kojima and Visvanathan [39] also identified several policy instruments that could enhance recycling efforts, such as: (1) waste separation and the sorted collection of recyclable materials, (2) community-based recycling collection, (3) awareness campaigns promoting sorted collection, (4) waste discharge fees, (5) deposit-and-refund systems, (6) EPR-based recycling policies, (7) industrial symbiosis and waste exchange programs, (8) voluntary initiatives or green purchasing practices prioritizing recycled goods, and (9) financial support for recycling businesses and industries.

In Saudi Arabia, the Saudi Standards, Metrology, and Quality Organization (SASO) plays a leading role in establishing regulations and policies related to batteries. According to the latest guidelines from SASO, several key aspects are emphasized for waste battery management, including: (1) aligning with international standards for safety and environmental protection, (2) incorporating labeling requirements for battery recycling and waste management, (3) obligating suppliers to provide recycling guidance, safety labeling, and ensure environmental compliance, (4) mandating that suppliers obtain a certificate of conformity to adhere to Saudi standards for battery management, and (5) requiring labels that include information on recycling, supplier details, product characteristics, and country of origin [67].

Table 1
Policy and regulatory aspects of waste battery management and recycling.

Key component	Description	Recommendations	Reference
Harmonized regulatory framework	Establish unified and standardized regulations across regions to manage battery recycling and disposal.	- Develop global collaboration for standardized policies and practices. - Implement consistent regulations across regions.	Heath, Ravikumar [40], Zanoletti, Carena [41], Sayilgan, Kukrer [42], Winslow, Laux and Townsend [43], Toro, Moscardini [44], Hossain, Murtaugh [45], Swain [46], Kang, Huang [47], Rufino Júnior, Riva Sanseverino [48], Zhang, Gao [49]
Extended producer responsibility	Involve manufacturers in the lifecycle management of batteries, ensuring responsibility for end-of-life disposal.	- Implement EPR schemes for manufacturers. - Encourage sustainable design and disassembly of batteries through EPR incentives.	Heath, Ravikumar [40], Noudeng, Quan and Xuan [50], Zanoletti, Carena [41], Sayilgan, Kukrer [42], Winslow, Laux and Townsend [43], Toro, Moscardini [44], Hossain, Murtaugh [45], Skeete, Wells [51], Gao, Zhang [52], Gao, Zhang [52]
Recycling infrastructure and technology	Support the development of recycling technologies and infrastructure through government initiatives.	- Provide government incentives and subsidies for recycling infrastructure. - Ensure policies evolve with technological advancements.	Heath, Ravikumar [40], Noudeng, Quan and Xuan [50], Zanoletti, Carena [41], Sayilgan, Kukrer [42], Winslow, Laux and Townsend [43], Liu, Liu [53], Zheng, Salim [54], Sun, Jin [55], Gao, Zhang [52]
Collection & disposal systems	Implement effective collection programs and clear guidelines for the safe disposal of waste batteries.	- Establish specific collection and disposal programs. - Develop guidelines for the safe handling and disposal of hazardous materials.	Zand and Abduli [56], Ma, Lu [57], Sobianowska-Turek, Urbańska [58], Zhang, Gao [49]
Environmental & health considerations	Address environmental and health impacts of battery disposal, focusing on pollution prevention and safety.	- Create regulations to prevent pollution from heavy metals and organic compounds. - Ensure health and safety standards are enforced in waste battery management.	Skeete, Wells [51], Zand and Abduli [56], Siqi, Guangming [59], Kang, Huang [47], Sobianowska-Turek, Urbańska [58], Zeng, Li and Liu [60]
Incentive system	Introduce incentives for both consumers and companies to participate in recycling and develop sustainable practices.	- Offer consumer incentives for recycling participation. - Provide subsidies and penalties to promote compliance and sustainable practices	Heath, Ravikumar [40], Zanoletti, Carena [41], Winslow, Laux and Townsend [43], Toro, Moscardini [44], Liu, Liu [53], Zheng, Salim [54], Sun, Jin [55], Gao, Zhang [52], Ma, Lu [57]
Monitoring and compliance	Establish systems to track the lifecycle of batteries, ensuring compliance with regulations and proper management.	- Implement a comprehensive monitoring system for battery lifecycle tracking. - Require data auditing and verification to ensure regulatory compliance.	Li, Yang [61], Lai, Huang [62]
Hazardous material management	Develop specific guidelines for the management of hazardous battery components, such as black mass.	- Categorize hazardous materials appropriately under regulatory frameworks. - Enforce strict safety standards for transportation, storage, and recycling of hazardous materials.	Gianvincenzi, Mosconi [63], Zhang, Huang [64], Liu, Liu [53], Zhu, Chen [65]
Public awareness and education	Increase public awareness and stakeholder collaboration to enhance participation in battery recycling initiatives.	- Conduct public education campaigns on the importance of battery recycling. - Foster collaboration among governments, manufacturers, recyclers, and consumers to develop effective policies.	Kang, Huang [47], Islam and Iyer-Raniga [66], Sun, Jin [55]
Economic feasibility and sustainability	Ensure that recycling technologies and policies are economically viable and support long-term sustainability goals, including green energy transitions.	- Conduct economic feasibility studies for recycling technologies. - Promote the development of green and sustainable battery technologies through policy support and incentives.	Skeete, Wells [51], Swain [46], Zhang, Gao [49]

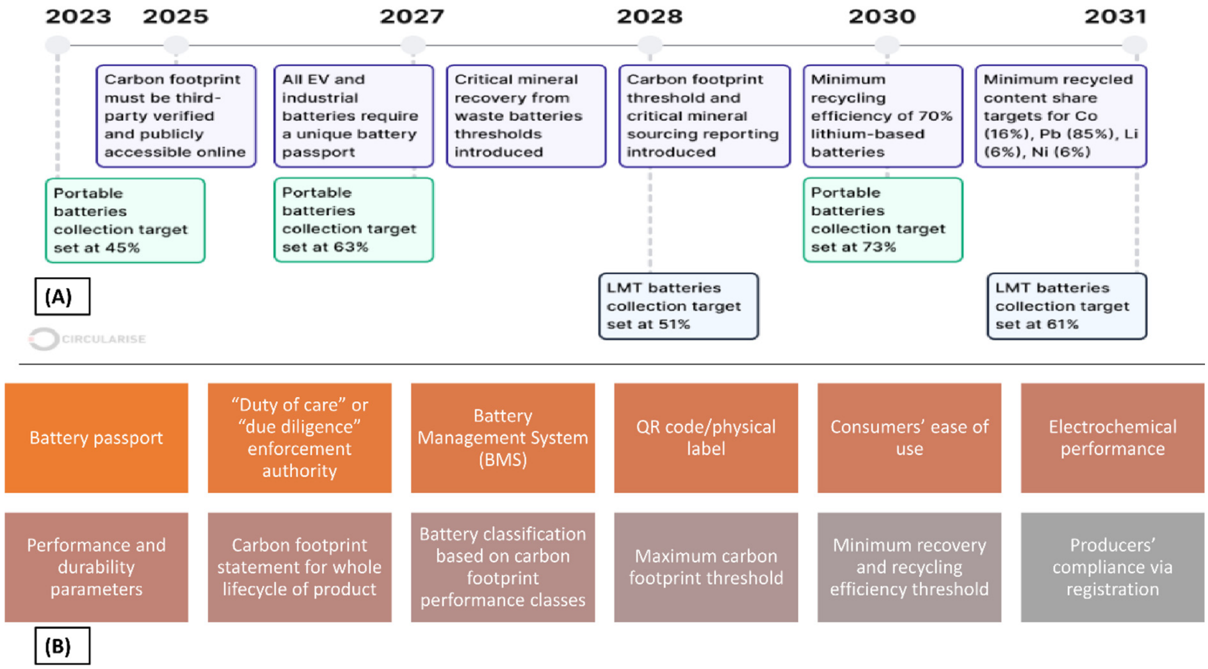

Fig. 6. (A) Timeline of implementing EU battery regulation (from 2023 to 2031) (adopted from [68]) and (B) Key features of the EU battery regulation, adapted from European Commission [13]. Note: LMT — Lightweight means of transport.

2.3. Initiatives

A major player in waste management and recycling in Saudi Arabia is the Saudi Investment Recycling Company (SIRC), which was established by Royal Order and is fully owned by the PIF. SIRC is responsible for recycling fourteen different types of waste, including batteries [69].

Tadwir Al Jazirah is a recycling company located in the Eastern Province that has the capacity to recycle waste batteries [70]. Another recycler, Safe Management for Industrial Waste Co., uses a macro-encapsulation process primarily for the disposal of LIBs in landfills, aiming for an environmentally sound approach [26], However, this method may not be a sustainable solution for managing both high-value and contaminant materials from a resource conservation perspective.

At the community level, King Abdullah University of Science and Technology (KAUST) provides recycling guidelines for KAUST township residents, directing them to designated campus locations for disposing of waste batteries (e.g., single-use and rechargeable household batteries such as alkaline, zinc-carbon, button-cell, and single-use lithium). The university also offers e-waste recycling services through a program in partnership with a local recycler that employs manual and mechanical dismantling and shredding processes. KAUST collaborates with Averda, a UK-based company responsible for waste collection and processing [71].

3. Global best practice in battery recycling

Global best practices in waste stream management and the application of various technologies can be adapted for the Saudi context. The following subsections discuss management strategies and technology options suitable for implementation.

3.1. Management strategies

3.1.1. EU battery regulation and directive

In waste battery management, countries within the EU are at the forefront in terms of policy and regulation, management structure, and technology deployment. The EU introduced a new Battery Regulation in August 2023, aimed at ensuring sustainability for batteries placed on the EU market and fostering a robust European battery industry and value chain. The key features of this regulation are shown in Fig. 6. The regulation prioritizes product standards and environmental obligations. Core principles under product standards include CO_2 footprint assessment during production, performance and durability requirements, and due diligence obligations. For environmental obligations, the regulation emphasizes recycled content, material recovery, compliance and monitoring, and standardization. Notably, the regulation also introduces a "battery passport", which provides unique identification and includes statistics on battery performance, durability, and essential characteristics.

Historically, the regulation is grounded in the Extended Producer Responsibility (EPR) mechanism. According to the Organization for Economic Co-operation and Development (OECD), EPR is an environmental policy approach that extends a producer's responsibility to the post-consumer stage of a product's life cycle. The OECD [72] characterizes an EPR policy by:

1. Shifting responsibility (physically and/or economically; fully or partially) upstream to the producer, thereby reducing the burden on municipalities.

2. Providing incentives for producers to incorporate environmental considerations into product design.

While other policy instruments often target a single point in the supply chain, EPR aims to integrate signals related to environmental characteristics across the entire product chain, influencing both products and production processes.

Under the EPR scheme, many European countries have achieved significant efficiencies in waste battery collection and recycling. Research by Islam, Huda [73] and Statista [74] indicates that Switzerland and Belgium have the highest battery recycling rates in the region, exceeding 70%. This success is attributed not only to advanced technology and the availability of recycling facilities in Europe but also to unique management strategies, regulatory frameworks, and operational structures that implement EPR. The following subsections present two case studies—INOBAT in Switzerland and BEBAT in Belgium—dedicated waste battery management systems responsible for these achievements. These case studies offer valuable insights for Saudi Arabia as it considers implementing a tailored system that accounts for financial and logistical aspects.

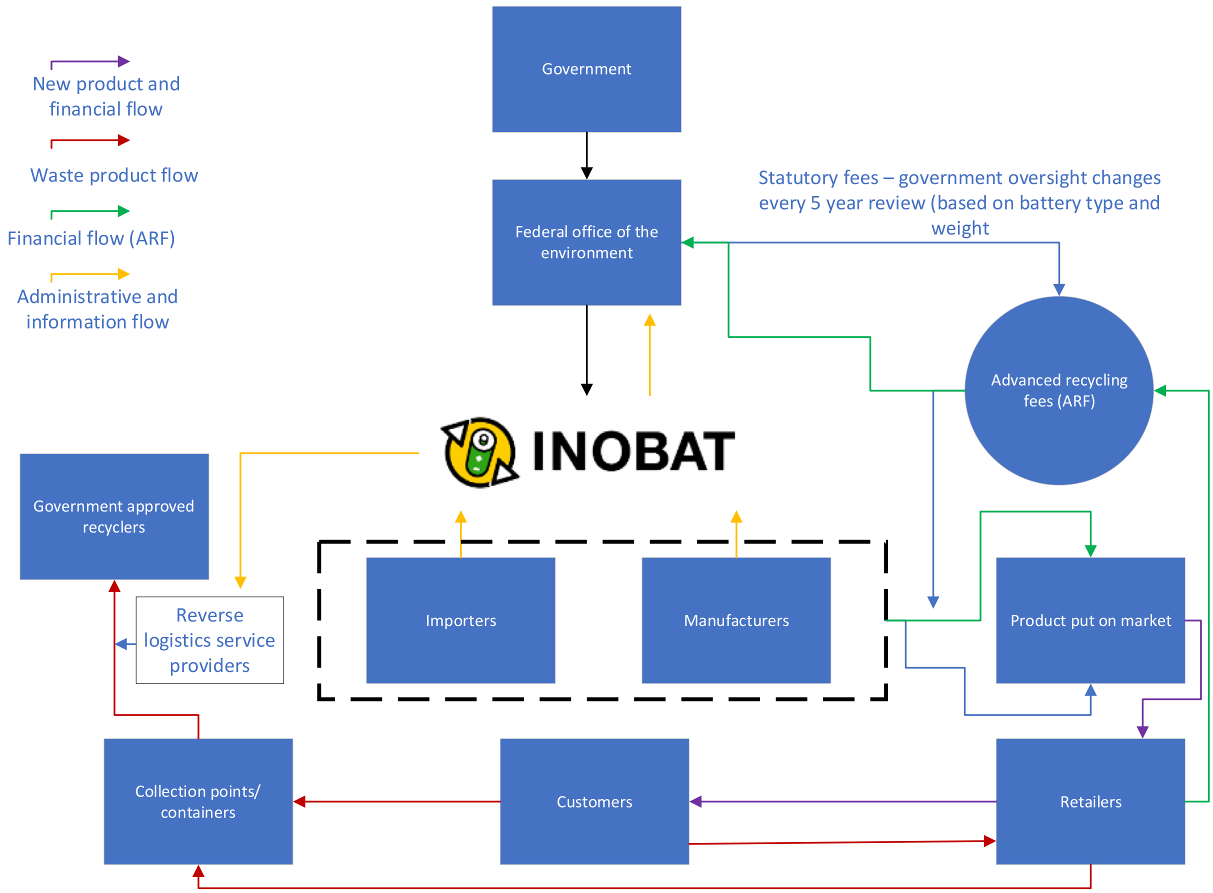

Fig. 7. INOBAT's waste battery waste management system in Switzerland.
Source: Adapted from [76].

3.1.2. *Case study 1 – INOBAT, Switzerland*

Switzerland's waste battery collection and recycling system has a long history of government-led regulation. In 1986, the first legal take-back requirements were established, followed by voluntary producer financing in 1991. By April 2001, the Chemical Risk Reduction Ordinance (ORRChem) mandated fees for portable batteries. The ORRChem ordinance also restricts certain substances or substance families due to associated health and environmental risks. In February 2011, the ordinance was revised to align with the EU Batteries Directive 2006/66/EC [75]. Fig. 7 illustrates the interconnected activities and key stakeholders within the INOBAT system.

Producers and importers in Switzerland are required to pay advanced recycling fees (ARF) to INOBAT, the collective organization (i.e., one of the Producer Responsibility Organizations (PROs)) responsible for waste battery management. They must also report the volume of batteries they place on the market. The fees, set by the Federal Office for the Environment (FOEN), amount to Swiss Franc (CHF) 3.20 (EUR 2.11) per kg for portable batteries and CHF 1 (EUR 0.66) per unit for lead batteries. Acting on behalf of FOEN, INOBAT has maintained a collection rate of 65% to 70% for waste batteries since the late 1990s. The price INOBAT pays to BATREC—the country's sole recycler, which utilizes pyrometallurgical processes for all battery types—is legislated at CHF 4400 (EUR 3520) per tonne. Battery retailers are obligated to accept waste batteries from consumers for transfer to INOBAT, while local authorities have no collection obligations [76].

Switzerland has over 11,000 collection points managed by retailers and municipalities (in the case of voluntary collection points). Each year, approximately 165 million batteries are sold in Switzerland, with customers paying the ARF upon purchase. The current recycling rate for waste batteries through INOBAT exceeds 70% [75]. The subsequent waste treatment process is also critical, underscoring the importance of environmentally sound recycling practices for managing battery waste.

3.1.3. *Case study 2 – BEBAT, Belgium*

The first voluntary agreement between the battery industry and the Belgian government began in 1988–1990. In 1993, an eco-tax was introduced with specific collection targets, and by 1995, BEBAT was established as a non-profit organization, starting operations in January 1996. Bebat has established and organized collection points for waste batteries, achieving a collection rate of approximately 49% by 2012. Providing a comprehensive take-back solution, BEBAT supports battery producers and manufacturers as a PRO, ensuring compliance with reporting, financial, and regulatory requirements on behalf of the government.

BEBAT collaborates directly with government-approved recyclers to facilitate efficient recovery of materials such as nickel, carbon, steel, titanium, cobalt, lead, and plastics. It also plays a vital role in encouraging public participation in the waste battery collection system. Importers and manufacturers must pay environmental and administrative fees to access BEBAT's services. Additionally, producers are required to pay a tax of EUR 0.5 per battery placed on the market unless they meet a collection rate of 45% from 2010 and 50% from 2012, either through a collective or individual system [10,75,77,78]. Effective sorting is crucial for achieving high recycling efficiency within the BEBAT system [10]. Fig. 8 illustrates the management and operational structure, along with the sorting process employed by BEBAT.

3.2. *Technology options*

In this section, various recycling technologies are highlighted based on battery chemistries. According to the new EU Battery Regulation,

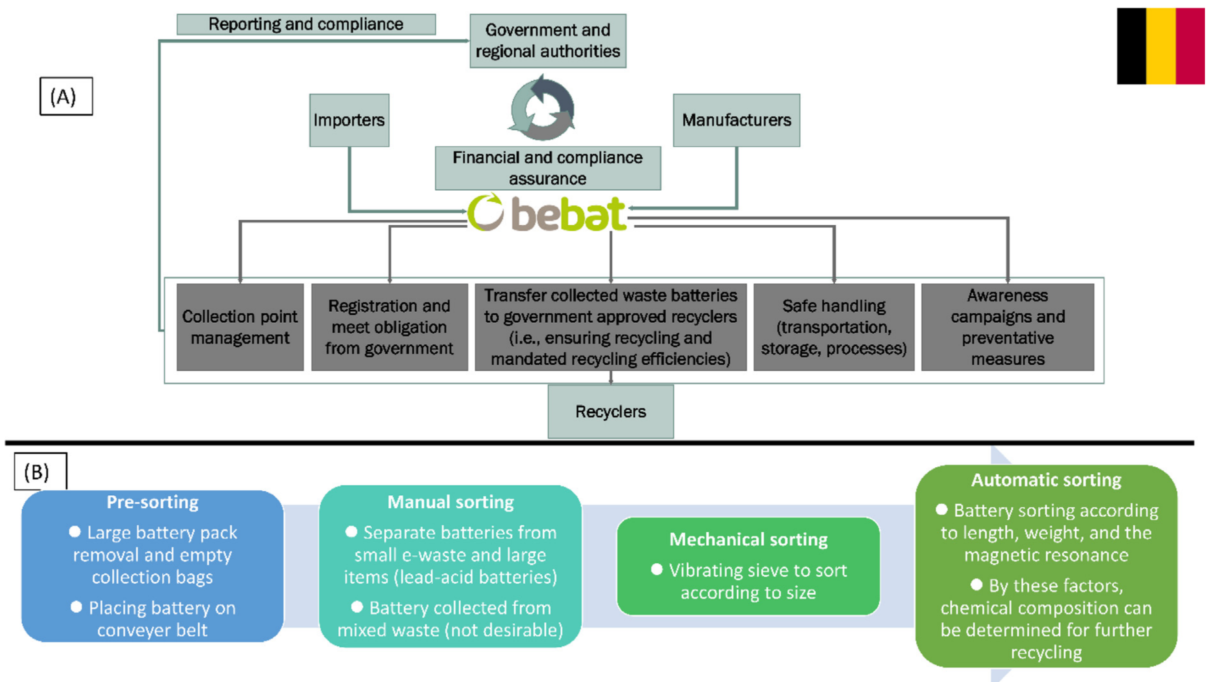

Fig. 8. (A) BEBAT's take-back system and (B) sorting technique utilized by BEBAT [10,75,77,78].

Table 2
Chemistry-specific battery recycling techniques and prospect of recycled material use, adopted from BEBAT [10].

Battery chemistry	Materials for recycling	Recycling process	Application of recycled materials in other industries
Alkaline and carbon–zinc	Zn, Iron, Mg, plastics	Carbothermic process for recovering high-value zinc/zinc oxide (Zn/ZnO) powder, catalysts-based total oxidation of hydrocarbons (acid treatment)	Iron for a variety of applications zinc for roofs, windows, pipes and fences chemical products for the galvanic industry slug for road construction fuel for cement factories (Recyfuel – plastics & paper)
Button cells	Hg (that must be distilled) according to law. The reminder is recycled.	Pyrolysis	Raw materials for several industries
Nickel-cadmium	Iron, cadmium (NiCd) and nickel	Chemical recycling of cadmium, pyro-and hydrometallurgical processes	Recycled materials used in the production of nickel-cadmium batteries and production of ferronickel
Nickel metal hydride	Iron, nickel and cobalt content	Hydrothermal, NMP dissolving, bioleaching treatment, acid leaching	Battery remanufacturing
Lead–acid batteries	Lead (Pb). Removal of battery acid is the first step.	Hydrometallurgical and pyrometallurgical processes	Lead recovery is the main product that can be used for manufacturing of lead–acid batteries or protection in radiotherapy sessions or when taking X-rays. Plastic parts serve as a fuel along with cokes as a fuel.
Lithium (generally categorized as Lithium primary and lithium rechargeable)	Iron, cobalt, copper, nickel and aluminum.	Mechanical treatment, pyrometallurgy, or hydrometallurgy	The metals are again used as raw materials for various industries

batteries are categorized into the following types: (1) starting–lighting–ignition (SLI) or automotive batteries, such as LABs used in ICE, (2) EV batteries, (3) portable batteries weighing 5 kg or less, (4) industrial batteries, and (5) light means of transport batteries, typically used in two- or three-wheeled vehicles and weighing 25 kg or less. Chemistry-specific recycling techniques for these battery types are outlined in Table 2.

A range of recycling technologies is currently available or under development for waste battery recycling. Major recycling methods include hydrometallurgy, pyrometallurgy, bio-metallurgy (also known as biotechnology), and direct recycling. Details on some of the technologies widely utilized by commercial recyclers globally are provided in the following subsection. Research and development (R&D) opportunities related to these technologies are discussed in Section 3.2.2. Fig. 9 illustrates the various recycling technologies applied to major waste battery streams, such as LIBs.

3.2.1. Commercial-scale battery recycling technologies

Table 3 provides an overview of commercial-scale recycling companies operating worldwide, along with relevant details such as their geographical distribution, recycling technologies employed, recycling capacities, material recovery efficiencies, types of batteries processed, in-house technological innovations, and other pertinent information.

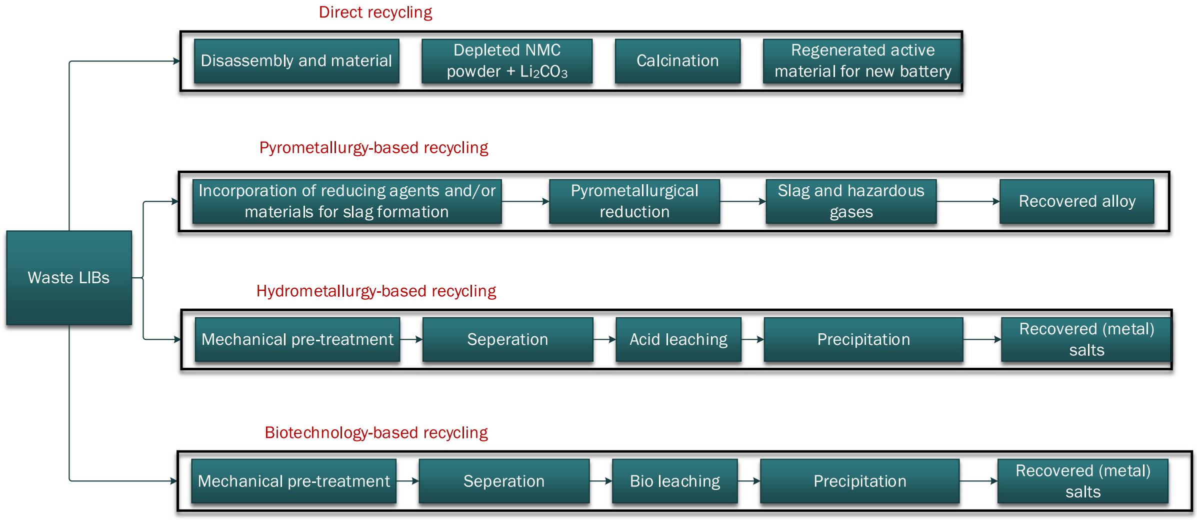

Fig. 9. Various waste LIBs recycling technologies.
Source: Adopted from [79].

A diverse range of companies worldwide are engaged in battery recycling, with notable contributions from Belgium, Germany, South Korea, Japan, China, Finland, the USA, India, Switzerland, and other countries. Germany and China, in particular, host numerous large-scale recycling facilities and lead the global battery recycling market.

Umicore, Accurec, Nickelhütte Aue, GEM, and Glencore are some of the companies utilizing both hydrometallurgical (chemical leaching) and pyrometallurgical (high-temperature smelting) recycling technologies. Companies like Accurec, SungEel HiTech, and Envirostream employ mechanical recycling techniques such as shredding, disassembly, and pretreatment in their processes. Specialized in early-stage material preparation, Envirostream and Guanghua Sci-Tech emphasize that preprocessing is a critical aspect of effective recycling. Companies like Umicore, Brunp, and Redux combine pyrometallurgical and hydrometallurgical processes to enhance material recovery rates for a diverse range of materials.

In terms of technological innovation, some companies are adopting novel approaches. For example, Duesenfeld focuses on life-cycle assessment (LCA) to ensure environmentally friendly battery recycling processes, while Li-Cycle has introduced its patented Spoke & Hub Technologies™ to optimize recycling. Accurec, one of the first LIB recyclers in Europe, combines multiple recycling technologies, including thermal and mechanical processes.

The recycling capacities of companies vary significantly across regions. In China, large-scale battery recycling plants like those operated by GEM (300,000 tons/year) and Brunp (120,000 tons/year) are among the highest-capacity facilities globally, aimed at processing substantial volumes of waste LIBs. In comparison, mid-sized facilities such as Nickelhütte Aue (7000 tons/year) in Germany and Umicore (7000 tons/year) in Belgium also handle large quantities of waste batteries, though their processing capacities are smaller than those of their Chinese counterparts.

Some companies are actively planning to expand their capacities in response to the growing demand for recycling technologies. For example, Li-Cycle in the USA and Fortum have indicated potential for scaling up. Brunp has ambitious plans to expand its capacity to over 1 million tons/year, while companies like Envirostream, Attero, and Fenix are also preparing for significant capacity increases in the coming years.

For materials like cobalt, lithium, and nickel, recovery rates typically range from 90% to over 99%. Companies like Brunp Recycling and Glencore have achieved recycling efficiencies exceeding 99% by utilizing advanced technologies. Others, such as Accurec and SNAM, report recovery efficiencies between 69% and 95%, which are still relatively high given the complexities of battery design and composition. Both high-value materials (e.g., Co, Ni, and Li) and secondary metals (e.g., Cu, Al, and Fe) are recovered by various companies. Additionally, some companies focus on toxic material management, including mercury recovery, as demonstrated by Batrec Industrie AG and SNAM. Fig. 10 illustrates the comparative recycling process of Ascend Elements alongside the pyrometallurgy-based recycling process used by Batrec Industrie AG in Switzerland.

All companies listed in Table 3 recycle LIBs, given their widespread use in EVs, consumer electronics, and energy storage systems. Additionally, European recyclers like Accurec, Nickelhütte Aue, and Ecobat (Australia) extensively handle other battery types, including Nickel-Cadmium (Ni-Cd), Nickel-Metal Hydride (Ni-MH), and LABs. This highlights the necessity and importance of recycling a wide range of battery chemistries.

3.2.2. *Progress and future opportunities in research and development (R&D) for waste battery recycling*

In academic literature, numerous research articles have been published on waste battery recycling technologies, with a significant focus on waste LIBs. Fig. 11 highlights critical recycling technologies and techniques, along with their associated challenges for widespread industrial-scale applications. From a system-level perspective, Salehi, Maroufi [152] reported that over 90% of rare earth elements (REEs) contained in batteries are discarded annually in landfills, representing a loss of valuable resources and creating opportunities for urban mining. Globally, only 5% of waste LIBs are recycled [153].

The complexity of diverse battery chemistries and their unsegregated mixture in the waste stream poses challenges for valuable material recovery, necessitating advanced separation technologies [154]. Despite the progress in recycling technologies, there remains significant room for improvement. For example, Yi, Zhou [155] and Niu, Xiao and Xu [156] noted that current recycling processes often overlook graphite recovery, even though it is abundant in waste LIBs. Additionally, LFP batteries, commonly used in EVs, may emit significant toxic gases when processed via pyrometallurgical methods [157]. Kumar [157] also identified that due to high chemical consumption, hydrometallurgical recycling of LFP batteries is relatively expensive.

4. Discussion and a roadmap for sustainable circular waste battery management in Saudi Arabia

Based on the in-depth analysis of the current status of waste battery management and recycling in Saudi Arabia, as well as global

Table 3
Summary of commercial-scale waste battery recycling technologies utilized by companies across the world (Source: Authors' own compilation based on various references).

Name of the company	Country	Recycling technology	Capacity of the plant (tons/year)	Recovery rate	Type of battery recycle	Material recovery	Other information/comments	References
Umicore	Belgium	Pyrometallurgy + Hydrometallurgy	7000	Over 95%	LIBs (lithium-ion rechargeable battery) from EVs and batteries from portable applications	Co, Ni, Cu, Fe, Li	The company implement closing loop process.	[82], [83], [84]
Accurec	Germany	Thermal + Mechanical + Pyro + Hydro	3000–4000	Li_2CO_3 recovery of 90%	Ni-Cd batteries; from nickel-metal hydride batteries, LIBs from electric vehicles, electronic devices, e-scooters and e-bikes.	Lithium carbonate and a NMC alloy	The initial throughput of the plant was 4,000 tons of spent batteries, and the company claimed to be the first lithium recycling plant in Europe.	[82], [85], [86]
Nickelhütte Aue	Germany	Thermal + Pyro + Hydro	7000	95%	LIBs from EVs, Ni-MH batteries	Metal salts (Ni–Co–Mn)	The company also recycles other materials, including converters, fuel cells, transformers, industrial catalysts from chemical plants, and switch gears. Including batteries, the total amount handled by the company reaches 90,000 tons per year.	[82], [87], [88]
SungEel HiTech	South Korea	Mechanical + (Thermal +) Hydro	8000	95% (recycling rate)	Lithium secondary battery and scrap	Ni, Co, Li and other form battery power (e.g., cobalt sulfate, nickel sulfate, lithium carbonate, manganese sulfate, electrolytic nickel, electrolytic copper)	The company is expanding its capacity to 24,000 tons per year, primarily focusing on secondary lithium battery sources such as those from EVs, mobile phones, IT devices, e-mobility, energy storage systems, power tools, and manufacturing scraps. Collection and pretreatment processes are conducted alongside hydro center-based recycling.	[82], [89], [90]
Kyoei Seiko	Japan	Pyrometallurgy	>1000	Unknown	Button battery, small Rechargeable Batteries	Unknown	–	[82], [91], [92]
Dowa	Japan	Thermal + Pyro + Hydro	6500	Unknown	LIBs	Fe, Al, Co–Ni mixtures, and other metals	In 2021, after receiving a new license, the company was authorized to increase its capacity six-fold, achieving a monthly recycling capacity of 100 tons of treatable batteries. A fixed-bed furnace will be utilized specifically for recycling EV lithium-ion batteries (LIBs).	[93], [82],

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Table 3 (*continued*).

Name of the company	Country	Recycling technology	Capacity of the plant (tons/year)	Recovery rate	Type of battery recycle	Material recovery	Other information/comments	References
Brunp Recycling Technologies	China	Thermal + Mechanical + Hydro	120,000	99.6% for nickel, cobalt and manganese, and 91% for lithium, copper recovery 89%, iron 90%, Aluminum 92%.	Various type of batteries containing lithium iron phosphate, lithium nickel cobalt manganese oxide, lithium cobalt oxide and lithium-rich manganese-based material.	Ni, Co, Mn, Li	Baum, Bird [94] noted that the company employs a pyro/hydro combination recycling technology. By 2025, the company's capacity is expected to increase to 100,000 tons per year. Core activities include battery disassembly, metallurgical recovery, material synthesis, and resource development, with a primary focus on waste traction batteries. Additionally, over 300,000 tons of recycling capacity is currently under construction, and more than 1 million tons of capacity is in the planning stages.	[82], [94], [95], [96]
GEM	China	Mechanical + Hydro	300,000	90% of lithium and extract Ni from materials that contains less than 0.1% of the metal.	scrapped lithium batteries from EVs (i.e., in first half of 2020, 12,000 EV batteries were recycled).	Ni, Co, Li, tungsten (W) and carbide	The recycled materials are supplied to Samsung SDI and Ecopro Co Ltd. The company also recycles e-waste, having processed 16 million tons of e-waste from 2013 to 2019, as well as scrap automobile parts. Internationally recognized for its collection and recycling of waste residue and wastewater, the company operates 16 circular industrial hubs.	[82], [97], [98]
Huayou Cobalt	China	Mechanical + Hydro	65 000	cobalt, nickel and manganese — 98.5% and Li — 90%	Battery packs (lithium ion batteries)	Co, Ni, Mn, Li	The company recently partnered with the German recycler Tozero to develop a European recycling facility with a capacity of 90,000 tons per year.	[99], [82], [100]
Ganzhou Highpower	China	Mechanical + Pyro + Hydro	10 000	Unknown	lithium ion and nickel-metal hydride (Ni-MH) rechargeable batteries	Nickel sulfate, cobaltous sulfate, cobalt chloride, lithium carbonate	Battery scrap is converted into metal salts, with pyrometallurgical steps utilized during the pre-treatment process. The company operates a closed-loop system for material recycling, implementing an echelon utilization scheme throughout the recycling process.	[82], [101]

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Table 3 (*continued*).

Name of the company	Country	Recycling technology	Capacity of the plant (tons/year)	Recovery rate	Type of battery recycle	Material recovery	Other information/comments	References
SNAM	France	Thermal + Pyro + Hydro	10,000	69% (up to 93% recycling effectiveness)	Portable batteries	Al, Co, Cu, Fe, Ni	The company partners with several automobile manufacturers in Europe and produces metals, ingots, and chips as commercial products. In addition to recycling, it offers collection and logistics services as well as battery condition diagnostics. Metal purification is achieved through hydrometallurgical processes, while metal recovery is performed using pyrometallurgical methods. Previously, Reiner Sojka, Qiaoyan Pan and Billmann [82], described the company as operating at pilot scale (<1000 tons/year). However, with the recent increase in capacity, it is now considered an industrial-scale operation.	[82], [102]
Euro Dieuze Industrie (E.D.I.)	France	Mechanical (aqueous shred) + hydrometallurgy	Over 6000	Up to 80%	Mixed batteries (e.g., Alkaline and zinc carbon, Ni-Cd, Primary and secondary lithium), EV batteries	Ni, Cd, Fe (steel)	The recycling process involves sorting, shredding, component separation, and hydrometallurgy. The company operates two separate lines: (1) an alkaline and Ni-Cd shredding process and (2) a lithium shredding process. EDI is a subsidiary of SARP Industries, France. The recovered materials are used in the production of alloys and chemical salts.	[103], [82], [104]
AkkuSer	Finland	Pyrometallurgy + Hydrometallurgy	4000	50% of the battery materials are recycled for reuse	High-grade Co-Li batteries, Ni-MH battery, Alkaline battery, Low-grade Co-Li batteries, lead–acid batteries, lithium primary batteries, and batteries derived from e-waste)	Zn, Fe from alkaline batteries; Ni, Co from Ni-MH battery, Co, Cu from high-grade cobalt Li-ion batteries.	The technology, known as the Dry-Technology method, does not use water, chemicals, or heat, resulting in zero emissions. For alkaline batteries, the process involves mechanical crushing followed by magnetic and mechanical separation. Metal refineries are then used to recover metals. Power tools, electric bicycles, and other electric mobility devices are the primary sources of low-grade cobalt lithium-ion batteries.	[82], [85], [105], [94]
Redux	Germany	Thermal + Mechanical + hydrometallurgy	10 000	>95%	LIBs from various sources such as smartphones, propel electric cars and bicycles, power tools	Al, Fe, Al/Cu mixture and active mass, Co, Li, Ni, and Mn	The recycling process includes discharging, disassembly, pre-treatment, and mechanical processing. According to [94], the plant has a capacity of 50,000 tons per year.	[94], [82], [106], [107]

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Table 3 (*continued*).

Name of the company	Country	Recycling technology	Capacity of the plant (tons/year)	Recovery rate	Type of battery recycle	Material recovery	Other information/comments	References
Duesenfeld	Germany	Mechanical + Hydro	<1,000	91%	LIBs from EVs	Solvent of the electrolyte, the graphite and the Li	The company extensively employs life cycle assessment (LCA) methodology to demonstrate the eco-friendliness of its recycling process.	[82], [108]
Ecobat (previously Promesa)	Germany	Mechanical (aqueous shred) + unknown	<1,000	95% of a scrap battery for reuse. Recycled lead has 99.9% purity.	LIBs from EVs and LABs	Pb, Al, Cu, steel (Fe), plastics	The company operates a lead production facility with 11 smelting units capable of processing 840,000 tons of lead per year, achieving a recovery rate of 99% for repurposed lead. It also has an advanced diagnostics and engineering center for testing EV batteries. In addition to collection and dismantling services, the company offers traceability services and operates 65,000 collection points.	[82], [92], [108], [109], [110]
TES-AMM (formerly Recupyl SAS)	France	Mechanical (inert gas) + Hydro	110	90% recovery rates. Cobalt and lithium recovered with 99% purity	alkaline, zinc-carbon, and lithium-ion batteries, EV batteries	lithium carbonate, lithium phosphate, steel (Fe), Cu, Mn and Co	The company offers shipping, logistics, and environmental compliance services, with a strong emphasis on battery reuse through module assessment and low-energy processes. A primary focus of the company is on advancing circular economy principles.	[82], [92], [111], [112]
Retriev	USA	Mechanical (aqueous shred) + Hydro	4500	98% (recover and regenerate cathode-grade material from spent LIBs)	LIBs	Lithium carbonate, metal oxides, steel (Fe), Cu, and Co	The output of the Toxco process produces metallic oxides and lithium carbonate cakes that can be directly utilized as downcycled materials in the metal industry.	[82], [85]
Erlos	Germany	Mechanical + reconditioning (Direct recycling)	3000	–	LIBs	Fe, Al, Cu, graphite and cathode active materials for new cells	The company processes 2,000 tons of materials per year. In addition to waste batteries, it also recycles plastics and battery storage systems.	[82], [113], [114]
ABT	USA	Mechanical + hydrometallurgy	20 000	More than 90%	LIBs	Li in the form of lithium hydroxide, Ni in the form of nickel sulfate and Co in the form of cobalt sulfate, Mn in the form of manganese sulfate, steel (Fe), plastics, Cu, Al	The company emphasizes environmentally sustainable processes, a closed-loop supply chain, and material circularity. It employs automated de-manufacturing technology.	[94], [115], [116]

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Table 3 (*continued*).

Name of the company	Country	Recycling technology	Capacity of the plant (tons/year)	Recovery rate	Type of battery recycle	Material recovery	Other information/comments	References
Envirostream	Australia	Preprocessing	3000	More than 95%	LIBs, alkaline, Li-ion, nickel metal hydride, lead acid and nickel cadmium, LABs, batteries associated with mobile phones and e-cigarettes/vapes and other types of e-waste	Fe, Cu, Al, mixed metal compound	The company implements circular economy principles and has a partnership with LG Energy. The conference emphasizes safe handling and reliable collection practices. In the current financial year, the company aims to divert 2,779 EV batteries from landfills. Additionally, waste generated from Ni-Cd batteries is transferred to specialized cadmium processors, while waste from lead–acid batteries is sent to lead–acid processors.	[94], [117], [118]
Sumitomo/Sony	Japan	Pyrometallurgical + hydrometallurgical	150	98% in Japan and 85.2% overseas.	lithium-ion secondary batteries	Cobalt oxide and a Co–Ni–Fe alloy.	During the recycling process, aluminum, lithium, and graphite are lost.	[94], [119], [44]
JX Nippon Mining	Japan	Pyrometallurgy + Hydrometallurgy	5000	25 percent by 2030, 50 percent by 2040	LIBs	Cu	The company emphasizes circular economy principles and the United Nations Sustainable Development Goals (SDGs).	[94], [120]
Posco Hy Clean Metal	Korea	Unknown	12 000	97.5%	LIBs (black power)	Cathode materials such as Li, Ni and Co	The company has opened a plant named PLSC, which supplies black powder from scrap and used batteries. From waste EV lithium-ion batteries (LIBs), the company can produce 12,000 tonnes of nickel, 4,000 tonnes of cobalt sulfate, and 2,500 tonnes of lithium carbonate.	[94], [121], [122], [123]
Guanghua Sci-Tech	China	Preprocessing + Hydrometallurgy	12 000	unknown	LIBs	Lithium carbonate, and other metal salts.	The company emphasizes cascade battery utilization.	[94], [124]
Quzhou Huayou	China	Pyrometallurgy	40 000	lithium metal recovery rate is over 90%, cobalt, nickel and manganese — 98.5	LIBs	Ni, Co, Mn, Li	The company implements an integrated treatment process and is a subsidiary of Huayou Cobalt. It has developed a joint project with Japan's Ohno to establish a closed-loop system.	[94], [125]
Taisen	China	Hydro	6000	Unknown	LIBs (from cell phone battery, laptop battery and EVs)	Lithium carbonate battery grades, Cobalt sulfate and Nickel sulfate	The company operates production lines for battery dismantling, sorting, crushing, and separation. It has a handling capacity of 37,200 tonnes of scrap lithium-ion batteries.	[94], [126]

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Table 3 (*continued*).

Name of the company	Country	Recycling technology	Capacity of the plant (tons/year)	Recovery rate	Type of battery recycle	Material recovery	Other information/comments	References
Northvolt	Norway	hydrometallurgy	12000 (tons of battery packs/year)	up to 95% of the metals	LIBs, Sodium-ion, Lithium-metal.	Ni, Mn and Co	The recycling process employs crushing, shredding, filtering, and dismantling techniques. Aluminum, copper, and plastic recovered from waste battery processing are processed by a third-party company. The company aims to recycle 125,000 tons of battery materials per year and is capable of producing cathode materials from 100% recycled materials. The company utilizes systems such as the Voltpack Core and the Voltpack Mobile System.	[94], [127]
Glencore	Switzerland	Pyrometallurgy + Hydrometallurgy	3000	over 99% for LAB and 98% for LIB.	LIBs	Cu, Au, silver (Ag), platinum (Pt), palladium (Pd), and other metals from such electronics	The plant's annual processing capacity will be 250,000 tons of LABs and 47,000 tons of LIBs. E-waste will be one of the primary target waste streams.	[94], [128], [129]
Fenix	UK	Hydrometallurgy	10 000	90%	LIBs (from portable electronic devices), alkaline batteries and wet and dry NiCad batteries.	Not specified.	The company plans to increase its capacity to 20,000 tons per year. This initiative is a joint effort between the University of Birmingham and the circular economy research-led company Ever Resource, funded by Innovate UK, the national innovation agency. The facility will serve as a mixed-chemistry battery recycling plant.	[94], [130], [131], [132]
Li-Cycle	Canada	Hydrometallurgy	5000	95%	LIBs	Ni, and Co, lithium carbonate	The company has implemented its patent-protected Spoke & Hub Technologies™ to provide consumer-centric solutions for waste LIBs. It envisions increasing its capacity to 35,000 tons per year.	[94], [133]
Li-Cycle	USA	Hydrometallurgy	25 000	95%	All types of lithium-ion batteries	Ni, Co, and lithium carbonate	In the USA, the company operates three plants located in Arizona, New York, and Alabama. It envisions increasing its pre-processing capacity to 100,000 tons of LIBs equivalent for the Spoke system, while targeting post-processing capacity for the Hubs of 85,000 to 105,000 tons of black mass, which can yield up to 25,000 tons of lithium carbonate per year.	[94], [134]

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Table 3 (*continued*).

Name of the company	Country	Recycling technology	Capacity of the plant (tons/year)	Recovery rate	Type of battery recycle	Material recovery	Other information/comments	References
Ascend Elements (Previously Battery Resourcers)	USA	Hydrometallurgy	30 000	Up to 98%	LIBs from EVs	NMC precursor materials (e.g., Co, Mn, Ni, Li)	The recycled materials demonstrate a 50% longer cycle life and 88% higher capacity compared to conventional materials. Additionally, cathode materials are up to 50% less costly, with up to 90% lower carbon emissions produced during their manufacturing. The company utilizes the Hydro-to-Cathode® direct precursor synthesis process and the Hydro-to-Anode® process for graphite recovery and purification.	[94], [135], [136], [80]
Batrec Industrie AG	Switzerland	Pyrometallurgy (thermal treatment)	3200	60% to over 70%	Alkaline, Zn-air, Zn-C batteries as well as button batteries, Lithium batteries (e.g., $LiMnO_2$) or Li-ion batteries (Phones, E-bikes, electric vehicles, electric tools).	Ferromanganese, mercury (Hg), iron (Fe), Mn, zinc (Zn) and mercury (Hg)	The company also accepts nickel-metal hydride (NiMH) accumulators. In the recycling process, both wet and dry off-gas treatment methods are employed. The company specializes in the management of toxic metallic mercury from button cell batteries, converting pollutants into a harmless form. While nickel-cadmium and lead batteries are sorted by the company, they are not recycled.	[94], [137], [81], [138]
Attero	India	Mech + hydro	15 000	Extraction efficiency 98%	nickel–manganese–cobalt, lithium cobalt oxide, lithium-ion manganese oxide, lithium titanate and lithium iron phosphate-based batteries	Co, lithium carbonate, graphite, Ni and manganese dioxide	The company plans to enhance its capacity to 20,000 tons per year and currently processes 144,000 tons of e-waste annually. It aims to increase its processing capacity for LIBs and e-waste recycling to 300,000 tons per year and 1 million tons per year, respectively. Additionally, the company plans to develop plants in Poland and the USA, each with a capacity of 100,000 tons per year.	[92], [139]
Batx	India	Mechanical (Black mass) + Chemical (hydrometallurgical) process	5000	Unknown	LIBs	Li, Ni, Co and Mn from Black Mass	The company can produce high-grade plastic, aluminum, copper, and stainless steel suitable for manufacturing. It is particularly focused on achieving net zero waste and net zero emissions. The reverse logistics operation utilizes a HUB (for any geographical location) and SPOKE (ensuring safe transportation to recycling and manufacturing facilities) model.	[92], [139]

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Table 3 (*continued*).

Name of the company	Country	Recycling technology	Capacity of the plant (tons/year)	Recovery rate	Type of battery recycle	Material recovery	Other information/comments	References
Exigo	India	Mech + hydro	10 000	96%	Lithium Iron Phosphate (LFP), NMC, Lithium Cobalt Oxide (LCO), Lithium Titanium Oxide (LTO), Zinc Manganese oxide (ZMO), (Ni-MH)	Battery grade graphite (purity >98%), Lithium Carbonate (purity >95%), Nickel sulfate (purity >95%), Manganese Oxide (purity >95%), Cobalt sulfate (purity >95%), Graphene (purity >98%).	The company plans to enhance its capacity by an additional 10,000 tons per year. It operates five state-of-the-art facilities that implement a zero-waste and zero-pollution policy, integrating circular economy principles, sustainable manufacturing, and a low-carbon supply chain.	[92], [140]
Fortum	Finland	Mech + hydro	3,000	80% of the battery, 95% of the valuable metals from black mass	LIBs from EVs and industrial-sized batteries	Plastics, Al, Cu, and black mass via mechanical processing and Ni, Co, Mn and Li-based products via the pyrometallurgical process.	The company offers low-CO_2 recycling solutions and provides recycling services to battery manufacturers, focusing on hazardous waste management and addressing challenging waste streams.	[92], [141]
Kobar	Korea	Mech + hydro	1000	Unknown	Unknown	Unknown	Unknown	[92]
Li-Circle	India	Mechanical (Black mass	1000	Unknown	Telecom batteries, grid storage batteries, and renewable energy storage batteries, 2-wheeler batteries, 3-wheeler batteries, car batteries and bus batteries, cell phone lithium-ion batteries, laptop lithium-ion batteries, and other e-devices.	Unknown	The company plans to expand its capacity to 25,000 tons per year.	[92], [142]
Primobius	Germany	Hydrometallurgi-cal	2500 (the company has developed joint recycling plant with Mercedes-Benz)	Up to 96% battery mass	consumer electronic batteries (devices with LCO cathodes), and nickel-rich EV and stationary storage battery chemistries NMC cathodes	Co, Ni, Li, Cu, Fe, Al, carbon, plastics and Mn	The company plans to introduce a plant with a capacity of 18,250 tons per year. Additionally, it operates a mechanical shredding plant with a capacity of 10 tons per day.	[92], [143]
SMCC	USA	Mech + hydro	5000	Unknown	LIBs	Co and Li	–	[92], [144], [145]
Tata Chemicals	India	Hydrometallurgi-cal	500 (planned)	Unknown	LIBs	Li, Co, Ni and Mn (99% plus purity)	Circular economy is one of the core principles implemented by the company.	[92]
Telerecycle	China	Mech + hydro	<1,000	Unknown	LIBs, Ni-MH, Ni-Cd, carbon alkaline, new energy vehicle power batteries, Ni-Cd, LABs	Unknown	–	[92], [146]
Valdi (previously ERAMET)	France	Pyrometallurgical	20,000	More than 90% of the strategic metals (nickel, cobalt, lithium)	LIBs from EVs	Mn, Ni, Li, Co and mineral sands	The plant's capacity will be increased to 50,000 tonnes of battery modules per year.	[92], [147], [94],

(*continued on next page*)

Table 3 (*continued*).

Name of the company	Country	Recycling technology	Capacity of the plant (tons/year)	Recovery rate	Type of battery recycle	Material recovery	Other information/comments	References
Ziptrax	India	Mech + hydro	350	Unknown	LIBs	Unknown	The company plans to introduce a plant with a capacity of 5,000 tons per year.	[92]
EcoBatt	Australia	State-of the art technology (no more details found)	30 000	Unknown	Industrial, Automotive & Portable (e.g., alkaline, Button cells, Lead Batteries Lithium Ion, Lithium Ion Polymer, $LiSO_2$, Lithium $LiPO_4$, $LiMnO_2$, Lithium Primary, Ni-Cd, Ni-MH, Zinc Air, Zinc Carbon)	Hg, Pb, Ag, Ni, Co, Fe, Li and plastic	They have integrated sorting and recycling facilities that leverage pre-existing widespread collection points.	[148], [149]
Kyburz	Switzerland	Direct battery recycling	4000 cells (at initial stage)	95%	LIBs (e.g., $LiFePO_4$ batteries)	Li salt	In 2022, the company produced its first battery from recycled materials. It is planning to increase its capacity to recycle 24,000 battery cells per year.	[150], [151].

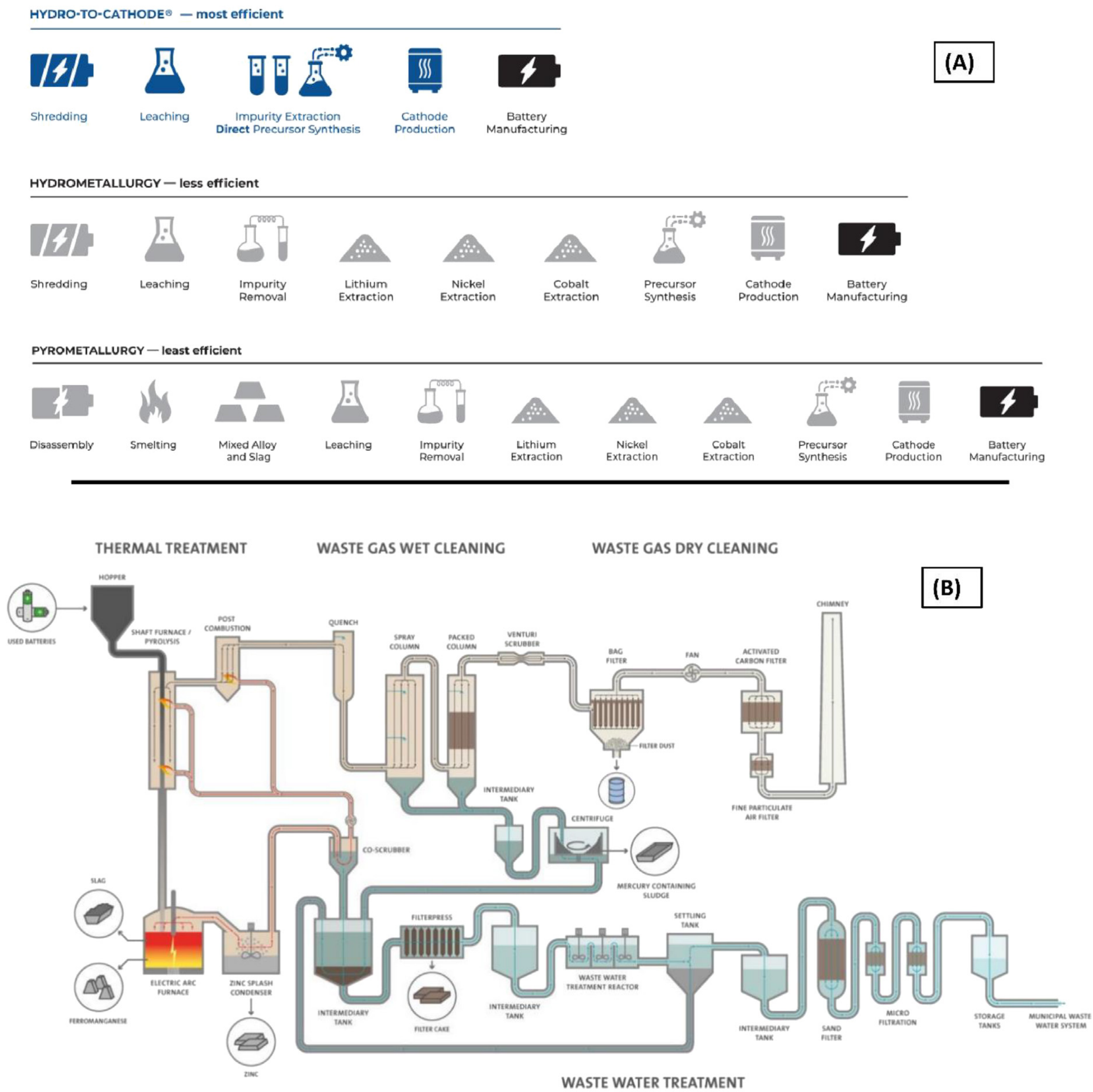

Fig. 10. (A) Various steps associated with the recycling technologies [80] and (B) Pyrometallurgical process by BATREC-INOBAT Swiss system [81].

technological advancements and management strategies from the EU battery regulation and presented case studies, this section provides a roadmap for sustainable waste battery management and recycling in Saudi Arabia. Fig. 12 illustrates the roadmap across key components.

4.1. Regulatory and policy framework

As outlined in Section 2.2, significant gaps exist in addressing waste battery-related guidelines within the Saudi Arabian context. Insights from the best practices, as discussed in Section 3.1, can serve as a foundation for developing management strategies that emphasize the importance of a robust regulatory and policy framework. By adopting principles from the EU Battery Regulation, Saudi Arabia should establish a mandatory EPR mechanism that holds producers and importers accountable for the entire lifecycle of batteries, including their collection, recycling, and safe disposal.

To support such a policy, the government should introduce key performance indicators (KPIs) such as mandatory reporting of CO_2 footprint assessments during battery production, the incorporation of recycled content in new battery manufacturing, and compliance monitoring. This holistic approach would alleviate the burden on local municipal authorities while incentivizing environmentally friendly product design. Additionally, a government-led EPR system should include achievable recycling targets, such as a 50% collection and recycling rate within the next five years, coupled with penalties for non-compliance by participating organizations. This approach has been effectively implemented in advanced countries, such as Australia, under the National Television and Computer Recycling Scheme (NTCRS), where co-regulatory arrangements (CRAs) face penalties for failing to meet set targets [178].

Currently, the Saudi government has set ambitious waste management goals, aiming to recycle up to 95% of all waste types by 2040 [179]. Another source indicates plans to divert 90% of waste from landfills by recycling 40%, composting 31%, incinerating 16%, and addressing the remaining 3% through other methods [180]. However, specific and well-defined targets for the collection and recycling of waste batteries, as well as e-waste containing batteries, are necessary.

Recycling technologies and techniques	Challenges
Hydrometallurgical recycling	1. **High Costs:** The process involves the use of chemicals, which increases operational costs (Bae and Kim, 2021). 2. **Environmental Impact:** The use of acids, bases, and solvents leads to secondary waste, including harmful gases and liquid waste, which harm the environment (Bae and Kim, 2021; Al-Asheh et al., 2024). 3. **Process Efficiency:** There is a need for further experimental work to fully verify the effectiveness of hydrometallurgy in industrial applications (Al-Asheh et al., 2024).
Pyrometallurgical recycling	1. **High Energy Consumption:** The process requires significant energy input, making it environmentally and economically costly (Bae and Kim, 2021; Zhou et al., 2021). 2. **Environmental Pollution:** It generates harmful emissions and by-products, which are detrimental to the environment (Bae and Kim, 2021). 3. **Selective Recovery Issues:** Pyrometallurgical methods are not selective, meaning they may not efficiently recover specific valuable materials like lithium (Zhou et al., 2020).
Direct Regeneration	1. **Scalability:** Direct regeneration techniques need to be optimized and scaled up for industrial applications (Li, P. et al., 2024; Pavlovskii et al., 2022). 2. **Material Compatibility:** Varying battery chemistries (e.g., NCM, LFP) pose challenges for direct recycling, as each chemistry requires different treatment methods (Pavlovskii et al., 2022). 3. **Impurity Removal:** Removing impurities while regenerating the electrode materials is critical for maintaining high-quality recycled materials (Zhou et al., 2021).
Bioleaching (Biological methods)	1. **Lower Efficiency:** Biological methods like bioleaching are less efficient compared to hydrometallurgical and pyrometallurgical processes, making them less viable for large-scale use (Rautela et al., 2023). 2. **Longer Processing Time:** Bioleaching is slower, which limits its competitiveness compared to faster chemical-based recycling methods (Roy et al., 2021). 3. **Optimization Needs:** Factors like temperature, pH, and microorganism effectiveness need further optimization to improve process efficiency (Naseri et al., 2022).
Supercritical Fluid (SCF) technology	1. **Industrial Application:** SCF technology is still in the research phase and requires further development before it can be implemented on an industrial scale (Cattaneo et al., 2024). 2. **High Costs:** The equipment and processes for SCF technology can be expensive, limiting its widespread adoption (Cattaneo et al., 2024).
Direct Lithium Extraction via Intercalation Materials	1. **Scaling Up:** Intercalation materials have been demonstrated at smaller scales but require further investigation to be used in large-scale applications (Wang and Koenig Jr., 2024).
Relithiation and Defect Restoration	1. **Complexity of Relithiation:** Replenishing lithium and restoring defects in cathode materials can be technically complex and needs further research to enhance efficiency (Lu et al., 2022).
Deep Eutectic Solvents (DESs)	1. **Slow Reaction Rates:** The leaching efficiency of DESs can be lower than conventional solvents, leading to slower processing times (Li, Yilin et al., 2024). 2. **Scalability Issues:** While DESs are promising, more research is needed to scale them up for industrial applications (Wang, Z. et al., 2022). 3. **Challenges with Reusability:** Maintaining the reusability of DESs without compromising the quality of metal extraction is a key challenge (Wang, Z. et al., 2022).
Corona-Electrostatic Separation	1. **Recovery of Non-Metallic Fractions:** The recovery rate for non-metallic fractions is lower, which may reduce the overall efficiency of the process (Calin et al., 2021).
Froth Flotation	1. **Effectiveness in Organic Binders:** The presence of organic binders in LIBs can reduce the efficiency of flotation by making it difficult to separate anode and cathode materials (Nazari et al., 2024). 2. **Pretreatment Needs:** Effective flotation requires prior removal of organic binders through pretreatment, adding complexity and cost to the process (Nazari et al., 2024).
Electrodialysis	1. **Energy Consumption:** Integrating electrodialysis into LIB recycling requires optimization to reduce energy use and enhance process efficiency (Cerrillo-Gonzalez et al., 2024).
Ultrasound-Assisted Recycling	1. **Industrial Application Challenges:** While ultrasound-assisted recycling shows promise, scaling it for industrial applications remains a challenge due to process complexity (Tong et al., 2023).
Synergistic Pyrolysis	1. **Optimization for Efficiency:** Although it offers environmental benefits, optimizing synergistic pyrolysis for industrial use is necessary to make the process more efficient and scalable (Pan and Shen, 2023). 2. **Industrial Scalability:** This method has potential but faces significant challenges in scaling up to industrial levels (Pan and Shen, 2023).
Membrane-Integrated hybrid approach	1. **Technological Integration:** Further research is needed to integrate membrane technology with traditional recycling methods and ensure its industrial scalability (Pan and Shen, 2023).
Salt-Thermal Recycling Method	1. **Process Optimization:** The salt-thermal method requires fine-tuning to maximize material recovery and minimize environmental impacts (Qu et al., 2023). 2. **Scalability:** This method is still evolving and needs further development to be implemented on an industrial scale (Qu et al., 2023).
Bio-Metallurgical Approaches	1. **Efficiency and Speed:** Bio-metallurgical processes are slower than conventional methods and need optimization to increase their efficiency (He et al., 2023). 2. **Microbe Effectiveness:** The effectiveness of microorganisms in metal recovery needs more research to improve the yield of these methods (He et al., 2023).

Fig. 11. Summary of various recycling technologies and techniques for waste battery.
References: Bae and Kim [158], Al-Asheh, Aidan [159], Zhou, Li [160], Zhou, Yang [154], Li, Liu [161], Pavlovskii, Pushnitsa [162], Rautela, Yadav and Kumar [163], Roy, Cao and Madhavi [164], Naseri, Pourhossein [165], Cattaneo, D'Aprile [166], Li, Sun [167], Wang, Li [168], Calin, Catinean [169], Nazari, Vakylabad [170], Cerrillo-Gonzalez, Villen-Guzman [171], Tong, Ren [172], Pan and Shen [173], Qu, Zhang [174], He, Jin [175], Wang and Koenig Jr. [176], Lu, Peng and Zhang [177].

Given the complexity and resource-intensive nature of battery recycling, it is essential to set realistic targets through consultation with industry stakeholders as an initial step in this direction.

The regulatory framework should also focus on restricting hazardous substances in batteries and mandating environmentally friendly recycling practices to minimize health risks. Drawing from Switzerland's ORRChem ordinance, Saudi Arabia could implement strategies and restrictions to limit hazardous substances in batteries, thereby reducing associated risks. Together with SASO and industry stakeholders, comprehensive guidelines should be developed for all battery types, including LABs, LIBs, Ni-MH, and Ni-Cd. The absence of clear definitions for suppliers and a lack of material-specific targets in current regulatory guidelines could pose significant challenges to the effective implementation of a waste battery recycling framework.

Although EPR-based systems are widely applied in OECD countries, their applicability in Saudi Arabia remains largely unexplored, particularly in light of informal sectors and widespread landfilling practices. SASO and other key government stakeholders should focus on developing an industry-wide implementation strategy that integrates the e-waste sector to promote sustainable waste management practices.

Currently, SASO does not provide specific guidelines for different types of waste batteries, instead treating all batteries—regardless of size or chemistry—the same, with the exception of those used in military, medical, and space equipment. In most cases, SASO refers to international standards for waste battery management. Internationally, there is also a gap in developing harmonized guidelines and regulations tailored to specific battery types, such as LIBs. While SASO assigns

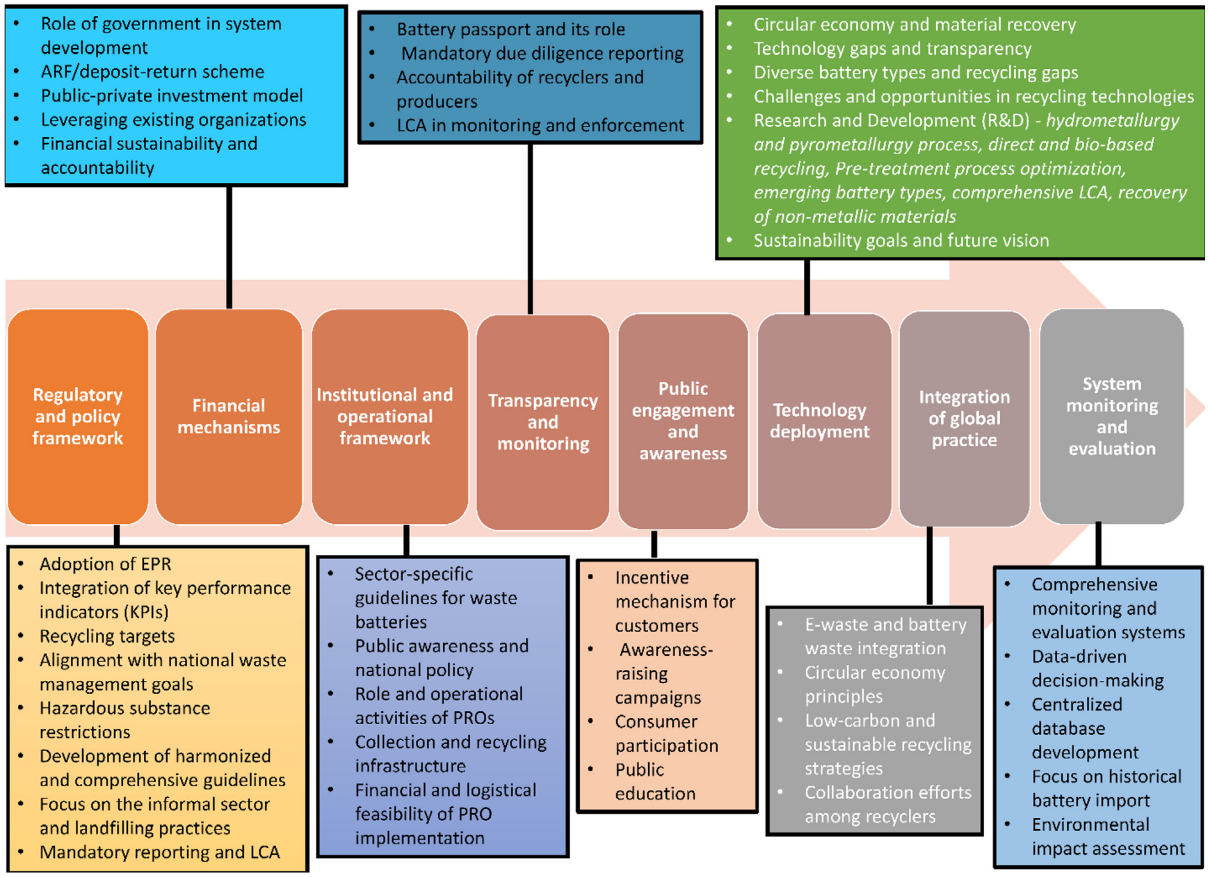

Fig. 12. Roadmap for sustainable circular waste battery management and recycling in Saudi Arabia.

significant responsibilities to suppliers, the definition of "supplier" remains unclear in the technical documents [67]. Furthermore, suppliers are responsible for labeling, providing recycling guidelines, and sharing recycling information, which becomes impractical when batteries are imported from overseas. The technical document implies that specific guidelines and mandatory responsibilities are directed at local manufacturers for managing waste batteries. SASO has an opportunity to issue policy guidelines for importers and local manufacturers under the EPR scheme. SASO's technical guidelines should also include specific requirements for local recyclers concerning recycling processes and mandatory reporting, using scientific assessment techniques like LCA. This should extend to battery manufacturers to ensure commitment to environmental sustainability and public health, which are key mandates of SASO.

4.2. Financial mechanisms

From the two case studies presented in Sections 3.1.1 and 3.1.2, it is evident that an effective waste battery recycling system relies not only on state-of-the-art recycling technologies but also on the coordination and integration of various other elements including the role of consumers, the establishment of collection points, the financial structure of the system (such as ARF from consumers and payments by manufacturers for registration and system operation under EPR), and the recycling processes managed by formal government-approved recyclers. The government plays a critical role by mandating registration for producers, manufacturers, and importers to prevent free-riding and by facilitating the establishment of collection points. Following the example of Switzerland's INOBAT system, Saudi Arabia could introduce an ARF, where consumers pay a fee at the time of battery purchase. This fee would be utilized to fund the collection, recycling infrastructure, and operational processes. The financial sustainability of the system can be ensured through transparent reporting and a clearly defined fee structure, managed by a dedicated organization such as the SIRC.

In both the systems, PRO operate on behalf of manufacturers and importers, assigning reverse logistics activities to specialized companies. A similar approach could be proposed for Saudi Arabia, with the development of a PRO that coordinates with government entities like SASO and SIRC to establish guidelines for the Saudi PRO. The PIF could partially fund the development of recycling infrastructure, while the PRO would assign responsibilities to manufacturers and importers, who would contribute financial resources to support system activities.

To support the development of collection and recycling infrastructure, co-financing mechanisms involving the PIF and private entities should be established under a public–private partnership (PPP) investment model. Additionally, there should be financial and operational support for approved and formal recycling facilities, ensuring transparency in fee structures and overall system accountability. The National Environmental Recycling Company (Tadweer), currently involved in e-waste recycling, could expand its operations to include waste battery recycling by partnering with leading recycling companies from Europe, the USA, and China, as outlined in Table 3.

4.3. Institutional and operational framework

Oil and gas manufacturing companies, electricity generation companies, consumer electronics manufacturers, and importers should be targeted with specific instructions and guidelines for managing waste batteries, given the high usage levels in these sectors. It is understood that generally, the oil producing companies use LIBs as power sources for various downhole tools in operations such as drilling, measurement, testing, wireline, and well intervention [181]. It can be inferred that similar battery-powered activities might occur within Saudi Aramco, which is one of the largest oil producing companies in the world. Assessing battery usage patterns, waste generation and direct waste analysis should be prioritized for the company. This characterization could be facilitated through collaborative research projects with universities.

Implementing robust EPR legislation across sectors and industries, would require detailed operational activities including monitoring, enforcement, and collaboration among stakeholders, as well as the development of collection and treatment infrastructure [182]. SASO should register manufacturers and importers, providing them with guidelines to ensure compliance with standards related to consumer electronics and waste batteries. Additionally, a national-level policy focused on consumer awareness and a comprehensive framework for waste battery management and recycling are essential for effectively managing e-waste.

A formal recycling system requires a steady supply of waste collected through various channels. The BEBAT system demonstrates that a high number of collection points is a critical success factor, as it significantly increases the volume of waste batteries collected, which in turn supports recycling efforts. INOBAT system has more than 11,000 collection points for waste batteries. Manual and automated sorting processes are essential to ensure the purity of materials recovered during recycling. Thus, network of convenient and accessible collection points is one of the key success factors of the system.

As a PRO, BEBAT engages in key operational activities such as financial and compliance reporting, organizing awareness-raising campaigns, and promoting source separation of different types of waste batteries. Further assessment is required in terms of financial and logistical feasibility implementing PRO as part of the operational framework under EPR in Saudi Arabia's context. EPR mechanism and reporting obligations should be ensured by PRO. By collaborating with recyclers, PRO would ensure environmentally sound and economically efficient material recovery. PRO must engage with SASO, PIF and SIRC for better efficiency and transparent system development. Following the BEBAT and INOBAT, Saudi Arabia should develop PRO system to management operational aspects of waste battery collection and recycling. The main activities of the PRO will be to ensure compliance with regulations, collect fees from producers and importers and collaborate with government supported recyclers who performs environmentally sound recycling process.

4.4. Transparency and monitoring

The battery passport is a unique addition to the new EU battery regulation, though its implementation is scheduled for 2027. Saudi Arabia could leverage this opportunity by partnering with EU counterparts to develop a similar passport or an integrated platform. Such a platform could provide valuable information about manufacturers, importers, and materials used in battery design. Implementing mandatory due diligence reporting and a monitoring framework for manufacturers would also be beneficial, supporting supply chain sustainability by tracking metrics such as CO_2 emissions, performance, and durability parameters. The battery passport would facilitate recycling and reuse efforts while providing transparency throughout the supply chain. It would create opportunities to hold recyclers and producers accountable for the performance, durability, and materials used in both products and recovered materials after recycling. Monitoring and enforcement of mandatory reporting using LCA could be introduced for both waste management and battery manufacturing companies.

4.5. Technology deployment

The circular economy approach in waste battery management and recycling emphasizes material circularity and resource efficiency. By adopting this approach, Saudi Arabia can significantly enhance its sustainability efforts while addressing its reliance on imported raw materials. Saudi Arabia has very limited proven reserves of critical minerals required for LIB manufacturing, such as lithium, cobalt, nickel, manganese, and graphite. Recovering these resources from waste battery streams offers a valuable opportunity for material recovery and supports the development of domestic battery manufacturing capabilities.

Currently, limited attention has been given to advancing recycling technologies and raising awareness among recyclers in Saudi Arabia. Identifying and assessing technologies suitable for the country's unique context is imperative. The SIRC should disclose the technologies it plans to implement or currently utilizes. This transparency would enable the development of techno-economic-environmental options for future infrastructure and foster greater stakeholder collaboration.

While recycling technologies for LIBs are receiving considerable focus, other battery types, such as Ni-Cd, Ni-MH, and LABs, are not being prioritized. Household portable batteries, although smaller in volume, constitute a significant source of both hazardous and high-value waste and should be included within the broader battery supply chain. Recycling companies, which often prioritize LIBs, should establish specialized units to handle these other battery types effectively. Addressing this gap would improve the overall efficiency of the waste battery management system.

The current maturity of recycling technologies presents both opportunities and challenges. Widely used methods such as hydrometallurgy and pyrometallurgy are effective for material recovery on a large scale but are associated with significant environmental and cost challenges. For industrial-scale applications, more sustainable alternatives such as direct reaeration and bioleaching show promise. Emerging techniques, including supercritical fluid and deep eutectic solvents, offer tremendous potential for future applications but require further optimization to enhance their efficiency and scalability. Other innovative methods, such as corona-electrostatic separation and froth flotation, have garnered attention among researchers but remain less comprehensive in terms of material recovery compared to established methods like hydrometallurgy and pyrometallurgy.

By focusing on advancing recycling technologies, Saudi Arabia can foster material recovery, reduce its dependence on virgin materials, and support a circular economy. Combining state-of-the-art techniques with a clear assessment of their techno-economic and environmental impacts will ensure the development of a sustainable and efficient waste battery management system tailored to the country's needs.

Several technology-specific R&D activities are recommended for future exploration:

- **Hydrometallurgical and pyrometallurgical processes:** Despite their widespread deployment, future research should assess the environmental footprint of these processes, with a focus on energy consumption and hazardous waste generation. Research should aim to reduce toxic chemical use and enhance process efficiency. LCA can be utilized to identify environmental hotspots, exploring bio-based catalysts and chemicals to minimize waste generation impacts. Investigating the cost-effectiveness of chemical reuse, as well as low-energy and renewable energy technologies, is essential.
- **Direct recycling technologies:** Further evaluation of the performance and industrial scalability of direct recycling techniques is needed, particularly for reducing waste and energy use while preserving component integrity. Research should investigate the applicability of direct recycling for material recovery from LFP and NMC batteries, which are widely used in EVs.
- **Bio-based recycling technologies:** Progress in bio-based recycling remains limited. Research is needed at both lab and commercial scales to explore its potential as an alternative to hydrometallurgy and pyrometallurgy. Supercritical fluid technology and deep eutectic solvents have shown promise in lab-scale studies; further research is necessary to evaluate the cost-effectiveness of these green recycling techniques for industrial scalability.

- **Recovery of non-metallic materials:** While high-value material recovery remains a primary focus, significant opportunities exist in recovering graphite, binders (e.g., polyvinylidene fluoride (PVDF)), and electrolytes. Researchers should address the challenges of separating and recovering these materials using non-destructive methods.
- **Pre-treatment process optimization:** The effectiveness and efficiency of recycling systems are heavily influenced by pre-treatment steps such as discharge, dismantling, and crushing. Research into automated pre-treatment processes could enhance efficiency in large-scale operations, as suggested by Li, Li and Zhang [183] and Sommerville, Shaw-Stewart [184].
- **Comprehensive lifecycle assessment:** There is a need for more comprehensive LCAs to understand the environmental impacts of various recycling methods. Future studies should focus on LCA for battery design and recycling processes. Additionally, research should explore circular hydrometallurgy concepts to create less waste in closed-loop recycling systems.
- **Emerging battery types:** As solid-state and sodium-ion batteries gain traction in large-scale energy storage, research into recycling methods for these new battery types should draw on experiences from LIB recycling. Further exploration is required for separation and material recovery techniques in mixed battery waste streams. Artificial intelligence (AI)-driven image processing, currently applied to plastic and municipal solid waste sorting, could be adapted for this purpose.

4.6. Public engagement and awareness

Public engagement and awareness-raising campaigns are critical for effective battery disposal and recycling, as seen from BEBAT's operational activities. These efforts, particularly in educating consumers, lead to higher collection rates and improved recycling efficiencies. Globally, numerous examples highlight the presence of behavior-intention gaps among consumers regarding recycling, which can be significantly mediated through targeted awareness campaigns [185].

Consumer engagement is paramount for higher recycling rates in the context of circular economy, as evident from the research of Guo and Huang [186]. The BEBAT system successfully integrated consumers, collection points, and awareness campaigns to create a highly efficient waste battery management framework.

In Saudi Arabia, however, the lack of adequate infrastructure to motivate consumers to participate in collection and recycling systems remains a significant challenge. A nationwide public education campaign should be launched once the collection infrastructure is established. Such a campaign should focus on proper disposal practices, the environmental impact of improper disposal, and the economic benefits of recycling [73]. Additionally, as an alternative to an ARF, refundable deposits for returned spent batteries could be introduced to incentivize consumers and encourage appropriate disposal practices.

4.7. Integration with global practices

E-waste has been identified as a major source of waste batteries by volume in Saudi Arabia, and large-scale waste generation from EVs is expected to contribute significantly to the waste stream in the near future. Currently, there are no specific regulations or policies addressing e-waste in the country. However, existing waste management regulations could be extended to cover this waste type. E-waste is classified as special waste under the national waste management policy, offering an opportunity to integrate the collection and recycling infrastructure for both battery waste and e-waste through a unified collection and recycling scheme.

Global recycling leaders such as Umicore, Brunp, and GEM emphasize the importance of closed-loop supply chains and the implementation of circular economy principles. These strategies focus on the reuse of recycled materials in battery manufacturing, reducing reliance on virgin resources, and lowering carbon intensity. Additionally, companies like Envirostream, Attero, and Fortum have adopted low-carbon or zero-emission strategies, reflecting a growing commitment to environmental sustainability in battery recycling processes.

Collaborative efforts among recyclers also provide valuable insights for Saudi Arabia. For instance, SungEel HiTech is expanding its capacity by partnering with local collection points and pre-treatment facilities. Similarly, Fenix and Brunp are advancing circular economy principles and enhancing recycling efficiencies through research partnerships with Innovate UK and Eramet. GEM has also collaborated with Samsung SDI and Ecopro to improve material recovery, enabling the direct utilization of recovered materials in new battery manufacturing processes.

Drawing on the experiences of INOBAT and BEBAT, Saudi Arabia can contextualize financial, logistical, and cultural aspects to develop circular economy-focused strategies. These strategies would promote the reuse of recovered materials in battery manufacturing and reduce reliance on virgin resources, as recycled materials have been shown to have lower carbon intensity (as illustrated in Fig. 1).

In the Saudi context, several key requirements must be addressed to achieve these goals. First, a robust logistical framework must be developed to overcome challenges posed by the country's large geographic area and diverse spatial distribution of cities. Second, circular economy-focused closed-loop supply chains should be established to ensure the reuse of materials in new battery production. Finally, partnerships with global leaders from the EU, USA, and China for the development of collection and recycling infrastructure would be highly beneficial. These collaborations would enable Saudi Arabia to integrate best practices and innovation from international stakeholders into its waste battery management system.

4.8. System monitoring and evaluation

There is a need to develop a comprehensive monitoring and evaluation system for the effective battery waste management in Saudi Arabia. Data-driven decision-making should be a cornerstone of this framework, enabling the continuous assessment of system performance. Developing a centralized database to monitor waste battery flows, recycling rates, and environmental impacts would significantly enhance the efficiency and effectiveness of the management system. Such a database would facilitate evidence-based policy decisions and strategic planning.

In addition to performance monitoring, special focus should be given to battery types which are imported historically in Saudi Arabia; for example, manganese oxide-based batteries. It is important to investigate waste generation from these batteries, particularly in terms of manganese flow into the country and the proportion of waste ending up in landfills. Additionally, zinc-air, lithium primary cells, and other primary batteries are also imported in significant quantities. Estimating waste generation for these battery chemistries should be a priority for understanding and managing their environmental impact.

5. Future research directions

Based on the topics discussed, this study proposes several critical future research directions that will be valuable for researchers in the field.

- A nationwide mapping of battery manufacturers and suppliers involved in the battery supply chain, including EoL processors and recyclers, should be conducted in Saudi Arabia. This mapping should also assess the technical capabilities of suppliers in developing recycling guidelines, drawing on core principles such as EPR, product stewardship, and circular economy concepts. Additionally, this mapping could provide valuable insights into the transboundary movement of waste batteries, as there is currently no data on the types and volumes of waste batteries transferred overseas for further processing. In this context, material flow analysis (MFA), in consultation with stakeholders, could be a strategic tool.

- Developing estimation models for various waste battery types should be a top priority. In countries with significant EV adoption, researchers have recently focused on estimating waste generation, particularly for LIBs. However, in the context of Saudi Arabia, lead–acid batteries and batteries from other sources, such as consumer electronics, should be prioritized. As EV penetration in the transportation sector grows, it will be essential to estimate future waste generation from EV-related LIBs. This could involve using methodologies like dynamic MFA and a Weibull distribution-based approach. Additionally, a systematic assessment of waste LABs from vehicles should be conducted.
- Product design and battery manufacturing processes should be evaluated through a LCA to understand the potential environmental impacts of current battery manufacturing technologies and to gain insights into EoL processing.
- Although pyrometallurgy is an energy-intensive process, the use of renewable energy for recycling should be further investigated from a comparative LCA perspective. Given water scarcity and the challenges associated with wastewater treatment in hydrometallurgy, additional assessment is needed to evaluate the suitability of this process within the context of Saudi Arabia.
- Understanding consumer behavior regarding perceptions, awareness, and practices around waste battery recycling and disposal is essential for developing a data-driven policy and decision-making framework. Following this assessment, various statistical models can be created to analyze the complex interactions of behavioral factors across different socio-economic dimensions that influence waste battery collection and recycling.
- From a policy and regulatory perspective, the involvement of the informal sector in EoL e-waste treatment should be considered. Although limited research has been conducted on this topic within the context of Saudi Arabia, particularly for waste batteries, it is likely that similar dynamics exist in battery recycling. Future research should explore the prospects, barriers, and opportunities related to EPR implementation for waste batteries and e-waste. The recycling practices of the informal sector are not well-documented and should be investigated through field observations. Additionally, there is a need to estimate the future generation of waste batteries and e-waste.
- Investigating the environmental impacts of waste battery landfilling presents an open research opportunity in the context of Saudi Arabia, where most waste batteries are disposed of in landfills. Since e-waste disposal in landfills is also a common practice, it warrants thorough examination to understand the associated environmental risks.
- Investigating stakeholder perceptions of waste battery management and recycling could yield valuable insights and inform the development of policy and regulatory frameworks.
- In addition to recycling techniques, research should also focus on collection and reverse logistics. Designing a reverse logistics network for collection and recycling facilities presents a significant research opportunity. Key models, such as location–allocation and capacity planning, can be applied in this context using mathematical modeling approaches like mixed-integer programming (MIP) and mixed-integer linear programming (MILP).
- A techno-economic analysis should be conducted to evaluate various commercial-scale recycling technologies, specifically tailored to the context of waste battery generation in Saudi Arabia.

6. Conclusion

This research presents the first systematic investigation into the current state of waste battery management and recycling in Saudi Arabia. Drawing on experiences from European regulations and management strategies, particularly the case studies of two leading Producer Responsibility Organizations (PROs) and technologies developed by 49 global recycling companies, this study proposes a roadmap for Saudi Arabia to establish a sustainable and circular battery waste management system. The roadmap also highlights several research and development opportunities to support this transition. There is an urgent need to develop a comprehensive policy and regulatory framework for the battery sector as an industrial segment, aiming to mitigate economic losses and severe environmental impacts. The development of mechanisms such as Extended Producer Responsibility (EPR) and operators like PROs could significantly enhance the implementation of well-defined and standardized waste battery management guidelines, particularly those focusing on hazardous substances. Integrating Life Cycle Assessment (LCA) methods into both battery manufacturing and recycling processes would provide a comprehensive evaluation of the environmental impacts across the production chain and material recovery stages. In alignment with Saudi Vision 2030 and the national mission of achieving a sustainable, closed-loop supply chain, stakeholder collaboration, However, the development of waste battery collection and recycling infrastructure remains a key challenge for Saudi Arabia. Addressing this challenge is essential before motivating consumers to appropriately dispose of spent batteries and implementing financial mechanisms such as Advanced Recycling Fees (ARF) and/or a deposit-refund system. Technologies such as hydrometallurgical, pyrometallurgical, and their combinations, along with emerging approaches like direct reaeration, bioleaching, and innovative techniques such as supercritical fluids, deep eutectic solvents, corona-electrostatic separation, and froth flotation, should be further explored. Data-centric monitoring and evaluation systems, combined with a battery passport approach, should also be prioritized. Additionally, the inclusion of e-waste and widely used battery types (e.g., lithium-ion batteries, lead–acid batteries, and various household batteries) is critical to developing a comprehensive waste battery management framework. The future research directions highlighted in this study will play a pivotal role in advancing the field within the Saudi context.

In alignment with Saudi Vision 2030 and the national mission to achieve a sustainable, closed-loop supply chain, stakeholder collaboration should be emphasized. Such measures will help prevent the diversion of valuable resources to landfills. A nationwide assessment of battery waste—including sources, destinations, local processing capabilities, transboundary movements, and other relevant factors—is urgently needed.

CRediT authorship contribution statement

Md Tasbirul Islam: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Amjad Ali:** Supervision, Project administration, Funding acquisition. **Sikandar Abdul Qadir:** Writing – review & editing, Visualization. **Muhammad Shahid:** Writing – review & editing.

Declaration of competing 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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