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Circular Management of End-of-Life Lithium-Ion Batteries in Ghana: Risks, Recycling Technologies and Sustainable Pathways

Frank Agyekum [a, #], Affah Augustine Akwochonga [b], Caleb Appiah [c], Daniel Asafori Adu-Boadu [d], Thaddaeus Oklu [e], Emmanuel Nii Otoo Tetteh [f]

[a] Jubaili Agrotech Limited, Department of Quality Control, Kumasi, Ghana
[b] Shamrock Quarry and Concrete Limited, Department of Production, Accra, Ghana
[c] Platinum International School, Department of Science, Kumasi, Ghana
[d] Kwame Nkrumah University of Science and Technology, Department of Physics, Kumasi, Ghana
[e] University of Mines and Technology, Department of Minerals Engineering, Tarkwa, Ghana
[f] 37 Military Hospital, Department of Microbiology, Accra, Ghana

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ABSTRACT

Ghana is at a critical stage in its energy transition. The growing use of lithium-ion batteries in mobile electronics, solar energy systems, and emerging electric mobility is creating a new waste stream within an already strained e-waste management system. Available national estimates indicate substantial growth in Ghana's e-waste stream, although the quantities attributable specifically to lithium-ion batteries remain poorly resolved. This review provides a Ghana-specific assessment of lithium-ion battery applications, environmental and safety risks, recycling technologies, and circular management opportunities. Three principal lithium-ion battery recycling routes (pyrometallurgy, hydrometallurgy, and direct recycling) together with hybrid approaches and emerging bioelectrochemical methods, are evaluated in terms of their technical and economic suitability for Ghana. A practical seven-stage circular-management pathway is proposed, integrating safe collection and aggregation, transportation, battery identification and state-of-health assessment, with a decision point directing suitable batteries toward second-life deployment and unsuitable batteries toward controlled recycling, material recovery, and reintegration within Ghana's existing legal framework. The review also identifies the need for better battery data, technical capacity, testing facilities, producer responsibility, and regional recycling partnerships to support Ghana's energy transition.

1. Introduction

Lithium-ion batteries (LIBs) have become important energy-storage devices because they combine high energy density, good cycling performance, relatively high operating voltage, and low self-discharge with a wide range of applications (Goodenough and Park, 2013; Nitta et al., 2015). These characteristics have made LIBs

Corresponding author: frankgyekum@gmail.com

important energy-storage technologies for portable electronics, electric vehicles, and stationary electricity storage, including applications involving renewable energy systems (Goodenough and Park, 2013; Nitta et al., 2015). Their relevance to Ghana's energy transition is also increasing as the country advances electric mobility and renewable-energy development. The same expansion is creating a growing end-of-life management problem because battery packs eventually lose the performance required for their original applications. For Ghana, the issue is closely connected to the country's expanding market for electronic equipment and its broader e-waste stream. Baldé et al. (2024) estimated that Ghana generated approximately 72 kt of e-waste in 2022. This estimate provides an internationally reported benchmark for Ghana's e-waste generation for that year.

Across Western Africa, the report did not document a formal collection and recycling rate in its regional statistics (Baldé et al., 2024). These figures describe the wider e-waste system rather than LIBs specifically, but they indicate the scale of the waste-management environment into which spent batteries are entering. LIBs require particular attention because they combine material value with hazards that are not typical of many other e-waste fractions. A damaged lithium-ion cell may retain residual electrical energy. Mechanical damage, such as crushing or puncturing, thermal abuse, or internal short-circuiting, can initiate thermal runaway (Chen et al., 2021; McKerracher et al., 2021). Battery electrolytes also contain organic solvents and lithium salts that require controlled handling. Consequently, a national approach to spent LIBs must address both resource recovery and safety. The International Labour Organisation (ILO) identifies e-waste as one of the fastest-growing waste streams globally and emphasizes the challenges associated with its hazardous composition, complex management requirements, and inadequate regulatory enforcement (Lundgren, 2012). In 2022, only 22.3 % of the global e-waste stream was documented as formally collected and recycled, leaving a substantial proportion outside documented formal management systems (Baldé et al., 2024). Global e-waste generation is projected to reach approximately 82 Mt by 2030 if current trends continue (Serpe et al., 2025). Within this rapidly expanding e-waste stream, the growing use of batteries in portable electronics, electric vehicles, and stationary energy-storage systems is creating an increasingly important battery-waste management challenge (Smith and Behdad, 2025). This review synthesizes the available evidence on LIB applications and end-of-life management relevant to Ghana. It focuses on the environmental implications of poor handling, the technologies available for recovering valuable battery materials, and a practical circular-management pathway that could be adapted to Ghana's existing e-waste framework.

2. Methodology

This review adopted a structured narrative approach to examine the end-of-life management of LIBs in Ghana. Literature searches were conducted in Scopus, Google Scholar, and Web of Science, with the last search performed on 31 July 2026. The main publication period considered was from January 2005 to July 2026. This period was selected to capture developments in LIB applications, second-life use, recycling and material recovery technologies, as well as changes in Ghana's e-waste management and regulatory context. Earlier publications were retained when they provided essential historical information or foundational evidence relevant to Ghana's e-waste sector or to established battery-management principles.

Search terms included "lithium-ion batteries," "spent lithium-ion batteries," "battery waste," "battery recycling," "second-life batteries," "material recovery," "circular economy," "e-waste management," "Ghana," and "Africa." These terms were combined in different ways, including "spent lithium-ion batteries" AND recycling, "lithium-ion battery waste" AND "circular economy," and ("battery waste" OR "lithium-ion batteries") AND (Ghana OR Africa). Searches were adapted to the terminology and coverage of each database.

Sources were selected according to their relevance to the review's objectives, the credibility of the issuing journal or institution, and the availability of sufficient information for interpretation. Peer-reviewed research articles were considered alongside Ghanaian policy and regulatory documents, institutional reports, and technical guidance relevant to LIB applications, environmental and occupational risks, second-life assessment, recycling, material recovery, and circular management. Ghana-specific sources were prioritized when available, while international studies were used to explain technologies and management practices that could inform the Ghanaian context. Sources that were unrelated to the review objectives, lacked sufficient bibliographic information, or contained claims that could not be adequately verified were excluded from the synthesis. Source selection was based on thematic relevance and the usefulness of the available evidence; it was not intended to be a systematic review or meta-analysis.

The evidence was organized into six themes: (i) current and emerging LIB applications in Ghana; (ii) the national e-waste management context; (iii) environmental,

occupational, and safety risks associated with spent LIBs; (iv) second-life assessment and repurposing; (v) recycling and material recovery technologies; and (vi) circular-management and policy options relevant to Ghana. Recycling routes were compared in terms of their principal processing steps, material recovery potential, resource and energy requirements, operational complexity, and practical relevance to Ghana. The proposed circular-management pathway was developed by integrating collection, transport, assessment, reuse, treatment, recovery, and reintegration stages identified in the reviewed literature and considering their applicability to Ghana's regulatory and infrastructure context. No primary experimental measurements or human-participant data were collected for this review.

3. LIBs in Ghana: Applications, E-Waste Trends, Second-Life Use and Recycling Technologies

3.1. LIB Applications

In Ghana, an important application of LIB technology is energy storage for solar photovoltaic (PV) systems. Battery storage allows electricity generated during periods of strong solar radiation to be stored and used when solar generation is low or unavailable, thereby improving the usefulness and reliability of solar systems (Opoku et al., 2020). Studies of renewable energy systems in Ghana have identified battery storage as a useful option for balancing variable renewable generation and meeting electricity demand outside periods of solar production (Acakpovi et al., 2020; Opoku et al., 2020). The deployment of lithium-ion battery storage is also emerging in Ghana. For example, a solar PV mini-grid commissioned at Onaa in the Ashanti Region incorporated lithium-ion batteries to store electricity generated by the photovoltaic system (Kwame Nkrumah University of Science and Technology, 2025). Such systems are particularly relevant to communities with limited access to reliable grid electricity because they can make renewable electricity available beyond daylight hours (Opoku et al., 2020; Kwame Nkrumah University of Science and Technology, 2025).

LIBs are becoming increasingly important to Ghana's transport sector as the country advances its transition toward electric mobility. Ghana's National Electric Vehicle Policy provides a framework for promoting electric-vehicle adoption and developing the supporting ecosystem, including charging infrastructure, battery recycling and end-of-life management (Ministry of Transport, 2023). The Energy Commission has also engaged stakeholders in developing regulations for electric vehicle charging infrastructure and battery swap systems in Ghana. The proposed framework seeks to establish minimum technical and safety standards, as well as registration, licensing and certification requirements for different aspects of the EV charging and battery swapping value chain (Gumah, 2026). An example of this development is the solar-powered electric-vehicle charging facility established by the Energy Commission in Accra. The facility combines solar photovoltaic generation with a lithium-ion battery storage system, demonstrating how renewable electricity and battery storage can be integrated to support electric mobility (Energy Commission, 2025). Battery swapping systems may be particularly beneficial for commercial electric two-wheelers, especially in delivery services, because they allow discharged batteries to be replaced with fully charged ones, reducing the time riders spend waiting for battery replenishment compared with conventional plug-in charging (Feng and Lu, 2022). Beyond the use of imported battery systems, Ghana has opportunities to develop capabilities across the battery value chain, including research, material development, battery-pack production, and recycling. Research in Ghana has demonstrated the potential of locally sourced manganese ore as a precursor for producing nanostructured manganese oxide for lithium-ion battery anodes (Mohammed et al., 2021). This research highlights opportunities to add value to Ghana's mineral resources through the development of battery-related materials. Furthermore, initiatives to promote the local processing of manganese into higher-value products underscore the importance of strengthening collaboration among universities, research institutions and industry (Apeatua Addo, 2024).

These activities could help connect Ghana's mineral resources and scientific expertise with emerging battery technologies. However, the deployment of second-life lithium-ion batteries for solar photovoltaic energy storage in Ghana faces several challenges. These include the high initial cost of solar energy systems, limited technical capacity for testing and evaluating used batteries, the absence of dedicated testing laboratories and standards for second-life battery certification, regulatory uncertainties surrounding the importation and reuse of used batteries, and concerns about their safe handling and end-of-life management (Painuly et al., 2024). Addressing these challenges will require investment in technical capacity, testing infrastructure, appropriate regulatory arrangements, and effective battery-management systems. As Ghana considers the deployment of second-life lithium-ion batteries for solar photovoltaic energy storage, strengthening technical capacity, battery testing, safety assessment, appropriate

standards, and end-of-life management will be important for ensuring their safe and effective use (Painuly et al., 2024). LIB technology has significant potential to support Ghana's renewable energy and electric mobility objectives. Continued investment in research and development, technical training, appropriate standards, battery testing and certification, local assembly, and effective regulatory frameworks would strengthen Ghana's capacity to participate in the expanding battery value chain. In addition, developing effective systems for battery collection, reuse, recycling, and end-of-life management would help maximize the economic benefits of battery deployment while minimizing associated environmental and safety risks (Ministry of Transport, 2023; Painuly et al., 2024).

3.2. Ghana's E-Waste Management Context

Ghana faces challenges in managing waste electrical and electronic equipment (WEEE), particularly because substantial quantities are handled by informal collection and recycling networks. Amoyaw-Osei et al. (2011) estimated that approximately 171 kt of WEEE entered the informal recycling sector in 2009. This flow comprised approximately 96 kt collected directly from consumers, 5 kt from communal collection, 48 kt obtained through repairers and 22 kt of imported waste (Amoyaw-Osei et al., 2011). The assessment separately estimated that approximately 109 kt of WEEE reached the end of its useful life in Ghana in the same year (Amoyaw-Osei et al., 2011). These estimates describe distinct material flows. Consequently, the 171 kt estimate should not be interpreted as total domestically generated e-waste. More recently, Ghana's EPA, through its 2024 National E-Waste Inventory Report, reported an estimated 650 kt of e-waste generation in 2023, equivalent to 19.24 kg per capita (Oppong-Ansah, 2025). This estimate indicates the substantial scale of national e-waste generation. However, the difference between 171 kt in 2009 and 650 kt in 2023 cannot be interpreted directly as a growth rate because the former measures material entering informal recycling, including imported waste, while the latter is reported as total e-waste generation. The EPA inventory was developed through a national data-collection exercise. In September 2023, the EPA described plans for enumerators to visit households, offices, and institutions to collect information on electrical and electronic equipment and associated waste, using questionnaires and a defined sampling framework (Obeng, 2023). Several factors could contribute to differences between estimates, including the equipment categories covered, the treatment of imported used or discarded electrical and electronic equipment, the underlying data sources, and the estimation procedures applied.

Owusu-Sekyere and Aladago (2023) estimated that about 40.3 % of residual fractions from five common informal processing routes were ultimately landfilled or openly burned. The fate of residues varied by equipment type, with information and communication technology, cathode-ray tube (CRT), and small appliance streams showing different loss patterns, which matters for circularity interventions (Owusu-Sekyere and Aladago, 2023). The Old Fadama (Agbogbloshie) e-waste site in Accra provides an important case study of informal processing. Detailed material-flow measurements estimated an annual throughput of 13.09-17.094 kt, with a mean of approximately 15.092 kt. However, these estimates should not be generalized to Ghana's entire e-waste sector, which includes other collection points, repair hubs, scrap markets, dismantling areas and disposal sites, including Dagomba Line in Kumasi (Daum et al., 2017; Owusu-Sekyere et al., 2022).

3.3. Environmental and Health Risks

The environmental consequences of uncontrolled e-waste processing in Ghana have been demonstrated through measurements of metals and organic contaminants in soil, sediment, water, and other environmental media. Studies undertaken at Agbogbloshie have reported substantial enrichment of potentially toxic elements, including lead (Pb), copper (Cu), cadmium (Cd), chromium (Cr), nickel (Ni), arsenic (As), antimony (Sb), and zinc (Zn) (Daum et al., 2017; Amponsah et al., 2023; Dodd et al., 2023). At burning sites, mean concentrations were 218 mg/kg As, 65 mg/kg Cd, 182 mg/kg Cr, 15,841 mg/kg Cu, 145 mg/kg Ni, 6,106 mg/kg Pb, 552 mg/kg Sb, and 16,065 mg/kg Zn (Dodd et al., 2023). Concentrations at dismantling locations were also substantially elevated, although generally lower than those observed at burning locations for several elements (Dodd et al., 2023). These findings demonstrate the importance of combustion activities as a pathway for the redistribution and concentration of metal contaminants.

Mercury contamination has also been documented at Ghanaian e-waste recycling locations beyond Accra. Ghana lacks established national soil-quality criteria for mercury, and previous studies have therefore used international guidelines to contextualize mercury concentrations in Ghanaian soils (Ansah et al., 2022; Asamoah et al., 2025). European countries apply different soil mercury limits. Carlon et al. (2007) reported screening values of 0.5 mg/kg in Finland and 20 mg/kg in Germany. In Denmark, the soil-quality limit is 1 mg/kg, while 3 mg/kg is the cut-off value for restricted

use (Carlon et al., 2007). De Vries et al. (2005) reported a lower ecotoxicological criterion of 0.1 mg/kg to protect soil organisms. A study comparing Agbogbloshie in Accra with the Dagomba Line recycling site in Kumasi found mercury concentrations in soil ranging from 0.01 to 4.36 mg/kg at Agbogbloshie and 0.11 to 7.57 mg/kg at Dagomba Line, with the highest concentrations occurring at dismantling locations (Amponsah et al., 2023). Although the calculated human-health risks in that study did not indicate potential adverse effects under the exposure assumptions used, the authors concluded that informal e-waste recycling could contaminate surface soils with mercury irrespective of the scale of the operation (Amponsah et al., 2023). This illustrates that environmental risks in national e-waste management are not limited to large, internationally recognized scrapyards but can also occur at smaller and informal waste-handling sites. Contamination can also extend beyond the immediate processing areas. Investigations of informal e-waste recycling in Ghana have identified heavy metals, polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), chlorinated benzenes and polycyclic aromatic hydrocarbons (PAHs) in soil and groundwater associated with different processing activities (Owusu-Sekyere et al., 2024). Manual dismantling of cathode-ray tube and ICT equipment was identified as an important source of heavy-metal contamination (Owusu-Sekyere et al., 2024). Earlier studies likewise documented contamination of the Odaw River and Korle Lagoon by metals associated with e-waste processing, highlighting the potential for contaminants generated at processing sites to move into connected aquatic systems (Daum et al., 2017). Such transport is particularly significant in Accra because intense rainfall and surface runoff can facilitate the movement of contaminated particles and residues from processing areas toward drainage channels, rivers and lagoons.

The atmospheric exposure pathway is another major concern. Open burning of insulated cables and other e-waste components is commonly used to recover copper and other valuable materials. Combustion can release particulate matter, heavy metals, and hazardous organic compounds, including PAHs and halogenated combustion products (Daum et al., 2017). Studies conducted around Agbogbloshie have reported elevated concentrations of metals and persistent organic contaminants associated with e-waste processing and burning (Daum et al., 2017). Consequently, the environmental impacts of informal recycling extend beyond solid waste residues to interconnected exposure pathways involving air, soil, water, and food.

The human health implications of these exposures have also received considerable attention. Research on e-waste workers in Ghana has reported elevated exposure to several metals and organic contaminants, while studies of environmental samples have shown that pollutants generated during dismantling and burning can become accessible to surrounding populations (Daum et al., 2017). Research using bioaccessibility measurements has indicated that metals at Agbogbloshie burning and dismantling sites could pose substantial potential health risks through incidental ingestion of contaminated soil (Dodd et al., 2023). The authors reported particularly high concentrations of Cu, Pb and Zn at burning locations and concluded that the contamination and associated risk were sufficiently elevated to warrant environmental and public health concern (Dodd et al., 2023). These findings reinforce the need to move beyond simply measuring total contaminant concentrations and to consider bioavailability, exposure pathways, and actual human health risk when evaluating e-waste sites. An important and increasingly relevant component of Ghana's e-waste stream is battery-containing electronic equipment, particularly LIBs.

3.4. LIB-Specific Risks

LIBs are widely used in mobile phones, laptops, tablets, cameras, power tools and other portable electronics, meaning that their end-of-life management is intrinsically connected to the broader WEEE system. The increasing electrification of transportation and deployment of battery-based renewable-energy storage are expected to further increase the relevance of lithium-containing waste streams (Harper et al., 2019; Torchyan and Schuster, 2022). However, the precise contribution of LIBs to Ghana’s e-waste stream remains difficult to quantify in the absence of comprehensive inventory data (Amoyaw-Osei et al., 2011; Forti et al., 2020).

The management of e-waste containing LIBs requires particular attention because, unlike many conventional WEEE fractions, batteries can undergo thermal runaway, cause fires, and present chemical hazards when damaged, crushed, short-circuited or improperly stored. Ghana-specific guidance on the reuse of end-of-life LIBs emphasizes the need for appropriate identification, handling, testing and storage procedures (Torchyan and Schuster, 2022). Ghana's e-waste management guidelines similarly recognize batteries as components requiring controlled removal and special handling before subsequent treatment operations (Environmental Protection Agency, 2018). These requirements are particularly important in informal recycling environments dismantling may involve manual tools and where damaged batteries can be mixed with other

metallic or plastic fractions.

Ghana has progressively strengthened its regulatory framework for e-waste management through dedicated legislation, obligations for producers and importers, eco-levy mechanisms and provisions for environmentally sound collection and recycling. Ghana's Hazardous and Electronic Waste Control and Management Act, 2016 (Act 917), together with its implementing regulations, established an earlier legal framework for e-waste management. This framework was subsequently incorporated into the Environmental Protection Act, 2025 (Act 1124), which provides the current legislative basis for the control, management and disposal of hazardous waste and electrical and electronic waste in Ghana (Republic of Ghana, 2016, 2025).

From a resource-recovery perspective, Ghana's e-waste contains substantial quantities of potentially valuable materials. Conventional WEEE contains copper, aluminum, iron, precious metals and other elements, while batteries introduce additional strategic materials such as lithium, cobalt, nickel, manganese, copper and graphite depending on battery chemistry (Torchyan and Schuster, 2022; Dodd et al., 2023). A proportion of material value is lost through inefficient separation, combustion and uncontrolled disposal. Material-flow analysis has demonstrated that substantial fractions of processed e-waste are lost to landfilling and burning (Owusu-Sekyere et al., 2022; Owusu-Sekyere and Aladago, 2023). Improving collection and separation could therefore simultaneously reduce environmental contamination and increase the recovery of secondary raw materials.

One major limitation in Ghana is the scarcity of detailed, continuously updated data on the composition, quantity and spatial distribution of specific e-waste fractions. Although national inventories provide important estimates of total e-waste generation, there remains a need for more detailed information on batteries, printed circuit boards, plastics, cables, displays and other technologically important fractions. The absence of reliable material-flow data makes it difficult to determine the economic feasibility of specialized recycling facilities and to design appropriate collection and treatment capacities (Owusu-Sekyere et al., 2022; Owusu-Sekyere and Aladago, 2023). Material-flow analysis has therefore been identified as an important tool for improving WEEE management because it can quantify inputs, outputs, material losses and the destinations of different fractions (Cucchiella et al., 2015).

The informal sector should not be excluded from future formal e-waste systems. Informal workers already possess substantial practical knowledge of collection, dismantling, sorting and material trading, and they provide services that formal systems have historically struggled to deliver at sufficient scale (Grant and Oteng-Ababio, 2012; Owusu-Sekyere and Aladago, 2023). Recent research argues for approaches that incorporate informal actors into safer and more regulated recycling systems rather than treating them solely as an obstacle to formalization (Owusu-Sekyere and Aladago, 2023).

Ghana's e-waste challenge has transitioned from a localized waste-management problem into a broader resource, environmental-health and circular-economy challenge. The available evidence demonstrates rapidly increasing e-waste generation, a dominant informal recycling sector, substantial losses of material fractions and measurable contamination of soil and other environmental compartments (Dodd et al., 2023; Owusu-Sekyere and Aladago, 2023; Owusu-Sekyere et al., 2024).

3.5. Second-Life Use of Lithium-Ion Batteries

Second-life use refers to redeploying LIBs that no longer meet the performance requirements of their first application, typically electric vehicles (EVs), into less demanding stationary applications. Although EV retirement criteria are often set at around 70-80 % of nominal capacity, many packs still retain considerable usable capacity and energy at that point. The actual remaining performance is highly variable and depends on cathode chemistry, depth-of-discharge history, temperature exposure, charge rates, and calendar age (Salek et al., 2024; Wett et al., 2024). Potential second-life applications explored in Ghana and similar contexts include solar home systems, solar mini-grid storage, backup for telecom base stations, and support for EV charging stations. Moving a battery from first to second life cannot be based on capacity alone. A robust assessment should combine physical inspection for swelling, cracks, corrosion, electrolyte leakage or damaged terminals; electrical screening for remaining capacity, internal resistance, open-circuit voltage deviation and self-discharge, and diagnostic indicators such as state of health (SoH) derived from capacity tests, impedance spectroscopy, and voltage response under load (Amuta and Kowal, 2023; Michelini et al., 2023; Song et al., 2024). A key challenge is information asymmetry. Retired batteries, especially those entering Ghana through used electronics or vehicles, often lack reliable first-life data from a battery management system. Without operating history, SoH estimation becomes more uncertain, and batteries with similar capacities may have very different degradation mechanisms and safety margins (Kampker et al., 2023). Safety screening must

therefore precede any reuse decision. Cells showing signs of lithium plating, abnormal heating, high impedance growth or physical damage should be routed directly to recycling. For those that qualify, repurposing requires reconfiguration into new modules with a suitable battery management system, thermal management and safety certification for the intended second-life application (Kampker et al., 2023; Salek et al., 2024). Life-cycle assessments show that second-life benefits are context-dependent. The net carbon and economic advantages are influenced by battery remaining lifetime in the second application, round-trip efficiency, the carbon intensity of the electricity it displaces, and logistics costs (Dong et al., 2023).

3.6. Recycling Technologies

Growth in EVs, portable electronics and stationary storage is increasing the global volume of spent LIBs. These batteries contain valuable materials such as lithium, cobalt, nickel, manganese, copper, aluminum and graphite that can be recovered to reduce dependence on primary resources. As summarized in Figure 1, lithium-ion battery recycling involves three main routes: pyrometallurgy, hydrometallurgy and direct recycling. Mechanical pretreatment is an important stage in many LIB recycling routes and may involve battery discharging, dismantling, electrolyte recovery, crushing, and physical separation of electrode materials. These operations facilitate subsequent material recovery through metallurgical processes. In addition, hybrid processing strategies and emerging electrochemical methods are being investigated to improve material recovery efficiency and reduce the environmental impacts associated with conventional recycling approaches (Tembo et al., 2024; Gao et al., 2025; Ma et al., 2025).

Pyrometallurgy uses high-temperature furnaces to melt battery materials and concentrate cobalt, nickel and copper into a metallic alloy phase. It tolerates mixed feedstocks and is already operated at industrial scale, but it is energy intensive, requires gas treatment, and lithium and graphite are often lost to slag unless additional hydrometallurgical steps are added (Georgi-Maschler et al., 2012; Yang et al., 2017; Zhong et al., 2019; Makuza et al., 2021; Roy et al., 2021). For Ghana, deploying a dedicated large smelter is unlikely to be economically justified in the near term without regional aggregation of feedstock.

Hydrometallurgy relies on aqueous chemistry to selectively dissolve target metals. The usual sequence involves discharge, dismantling, crushing and physical separation to produce black mass, followed by leaching in an acid or alkaline lixiviant. Both mineral acids (e.g., sulfuric, hydrochloric) and organic acids (e.g., citric, malic, oxalic) have been studied, often with a reducing

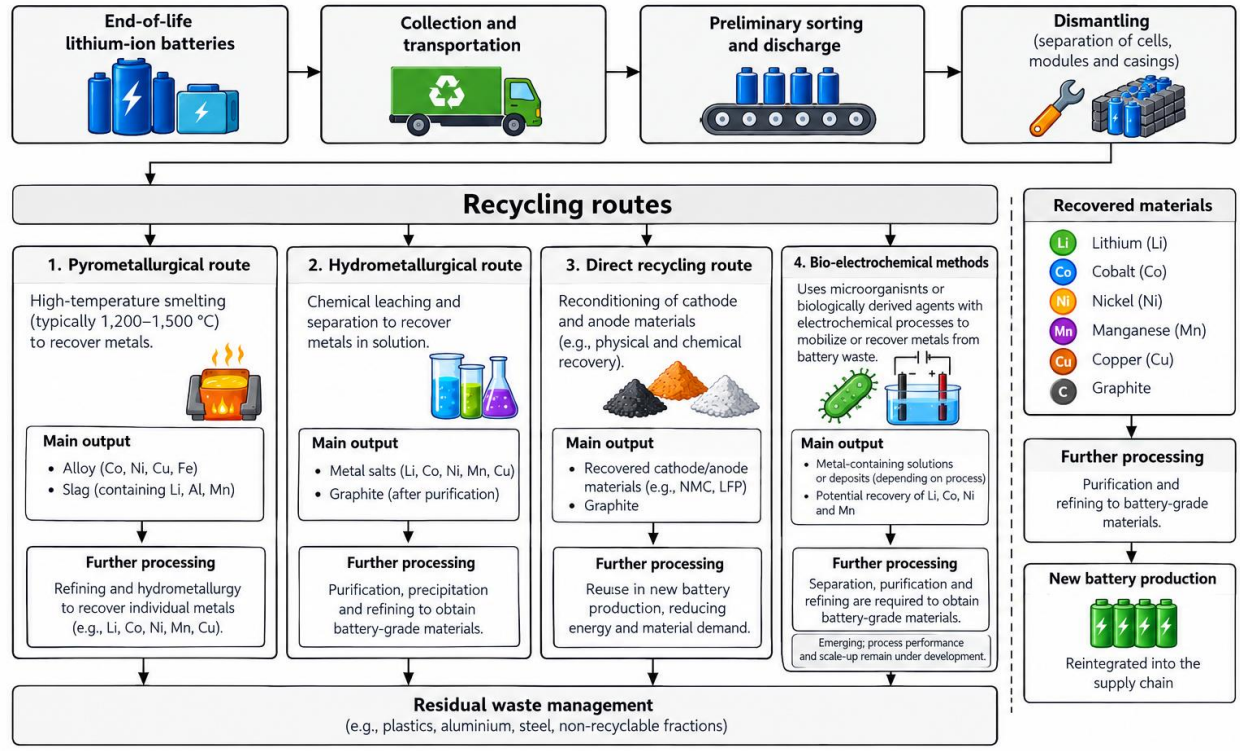

Figure 1. Classification of battery recycling methods. *Source: Authors' illustration*

agent such as hydrogen peroxide to enhance dissolution of cobalt and manganese (Xu et al., 2008; Lv et al., 2018; Yao et al., 2018; Jung et al., 2021). The resulting pregnant leach solution is then purified by a combination of precipitation, solvent extraction, ion exchange or crystallization to separate lithium, cobalt, nickel and manganese into battery-grade products (Xu et al., 2008; Lv et al., 2018; Jung et al., 2021). Hydrometallurgy can achieve high recovery rates and product purity at lower temperatures than pyrometallurgy, but performance depends on reagent consumption, control of impurities and treatment of secondary effluents. Recent research has therefore focused on improving leaching selectivity, using alternative leaching agents, and developing processes that recover and reuse valuable materials and process solutions (Cerrillo-Gonzalez et al., 2024; Wu et al., 2024). Direct recycling aims to preserve the crystal structure of cathode materials rather than breaking them down to elemental form. The process includes safe discharge, separation of electrodes from current collectors, removal of binder and electrolyte residues, and a relithiation step to restore lithium content and electrochemical activity (Cao et al., 2024; Huang et al., 2024; Lan et al., 2024; Zhou et al., 2024). Regeneration routes include solid-state sintering, hydrothermal treatment, molten salt, and chemical or electrochemical relithiation. By avoiding full chemical breakdown, direct recycling can reduce energy and reagent use, but it requires well-sorted feedstock by chemistry and careful quality control to meet battery-grade specifications (Huang et al., 2024; Zhou et al., 2024).

Bioelectrochemical recycling uses microbial fuel-cell systems to facilitate metal release and recovery from spent lithium-ion battery cathodes. Huang et al. (2021) demonstrated a three-stage microbial fuel-cell system for recovering lithium and cobalt from $LiCoO_2$ cathode material. Under optimized laboratory conditions, approximately 45 % of the lithium and 93 % of the cobalt were released during the leaching stage, while a subsequent subsystem achieved 96 % cobalt recovery. More recently, Baniasadi et al. (2025) combined indirect bioleaching with electrowinning and precipitation to recover metals from spent battery black mass. These studies demonstrate the potential of biological and electrochemical integration, although further work is required to establish its economic feasibility and scalability for industrial recycling.

4. A Circular Management Pathway for Spent LIBs in Ghana

A circular management framework for LIBs in Ghana should integrate controlled collection, safe handling, battery assessment, second-life deployment and material recovery within a coordinated end-of-life management system. Its implementation would require cooperation among environmental regulators, local authorities, battery importers and distributors, waste-management operators, recycling facilities, research institutions and informal-sector workers. Ghana's Environmental Protection Act, 2025 (Act 1124), provides a current legislative basis for environmental protection and the management of hazardous and electronic waste, while the Electrical and Electronic Waste Management Fund provides a financing mechanism for e-waste management activities (Republic of Ghana, 2025; Electrical and Electronic Waste Management Fund, n.d.). The Environmental Protection Authority should provide environmental oversight, establish and enforce applicable requirements for battery collection, storage, transportation, treatment, and disposal, and monitor compliance by authorized operators. The Ministry of Environment, Science and Technology should support policy coordination, while the Electrical and Electronic Waste Management Fund could, where eligible under its mandate, support collection infrastructure, worker training, recycling facilities, and public education. Metropolitan, municipal, and district assemblies (MMDAs) should facilitate local collection points, community awareness, and coordination with authorized waste-management operators. These responsibilities would connect national policy with local implementation and help prevent spent LIBs from entering mixed-waste streams or being dismantled under unsafe conditions.

The proposed framework recommends that battery importers, distributors, renewable-energy companies and other organizations placing LIB-containing products on the Ghanaian market participate in take-back arrangements, consumer information programs and the safe transfer of end-of-life batteries to authorized collection facilities. The specific obligations and implementation mechanisms would need to be established or clarified through the applicable regulatory and producer-responsibility arrangements. Collection and transport operators should maintain records of battery origin, condition and destination and use suitable packaging, segregation, and storage procedures. Competent technical operators should assess collected batteries to determine whether they remain suitable for repair, refurbishment or second-life applications, such as stationary energy storage, or should proceed directly to recycling. Any second-life deployment should be preceded by appropriate electrical, thermal, and functional assessment, with clear requirements for installation, monitoring, and eventual retirement.

The informal sector should be incorporated into the

framework rather than treated solely as a source of non-compliance. Informal collectors and dismantlers already participate in Ghana's wider e-waste recovery chain, and their local networks may help identify and collect discarded batteries that formal systems do not readily reach. The proposed framework should therefore provide practical routes for informal workers to register or affiliate with recognized collection systems, receive training in battery hazard recognition and emergency response, access suitable protective equipment, and receive transparent payment for batteries delivered to approved collection points. Workers should not be encouraged to dismantle, crush, puncture, burn, or manually recover materials from damaged LIBs without appropriate facilities, training, and controls. Instead, trained workers could undertake designated collection, identification and transfer activities, while hazardous battery opening, cell processing and material extraction should be restricted to appropriately equipped and authorized facilities. This approach would preserve the useful collection capacity of the informal sector while reducing occupational exposure, fire hazards and uncontrolled releases. At the processing stage, authorized recyclers should prioritize material-recovery routes appropriate to the chemistry and condition of the batteries received. Hydrometallurgical or other suitable recovery technologies may be used where technically and economically viable, with controls for reagent use, wastewater, emissions and residual wastes. Research institutions and universities could support battery characterization, recycling-process development, life-cycle assessment and evaluation of recovered-material quality. The framework should also include traceability from collection to final treatment, reporting of recovered materials, and monitoring of worker safety and environmental performance. Its implementation should be supported by clear institutional responsibilities, sustainable financing, appropriate technical standards and reliable data on collection rates, battery chemistry, second-life performance, and material recovery.

Drawing on established battery recycling and circular-economy practices, this review proposes an integrated circular-management pathway for spent LIBs in Ghana, as shown in Figure 2. The framework is adapted to the

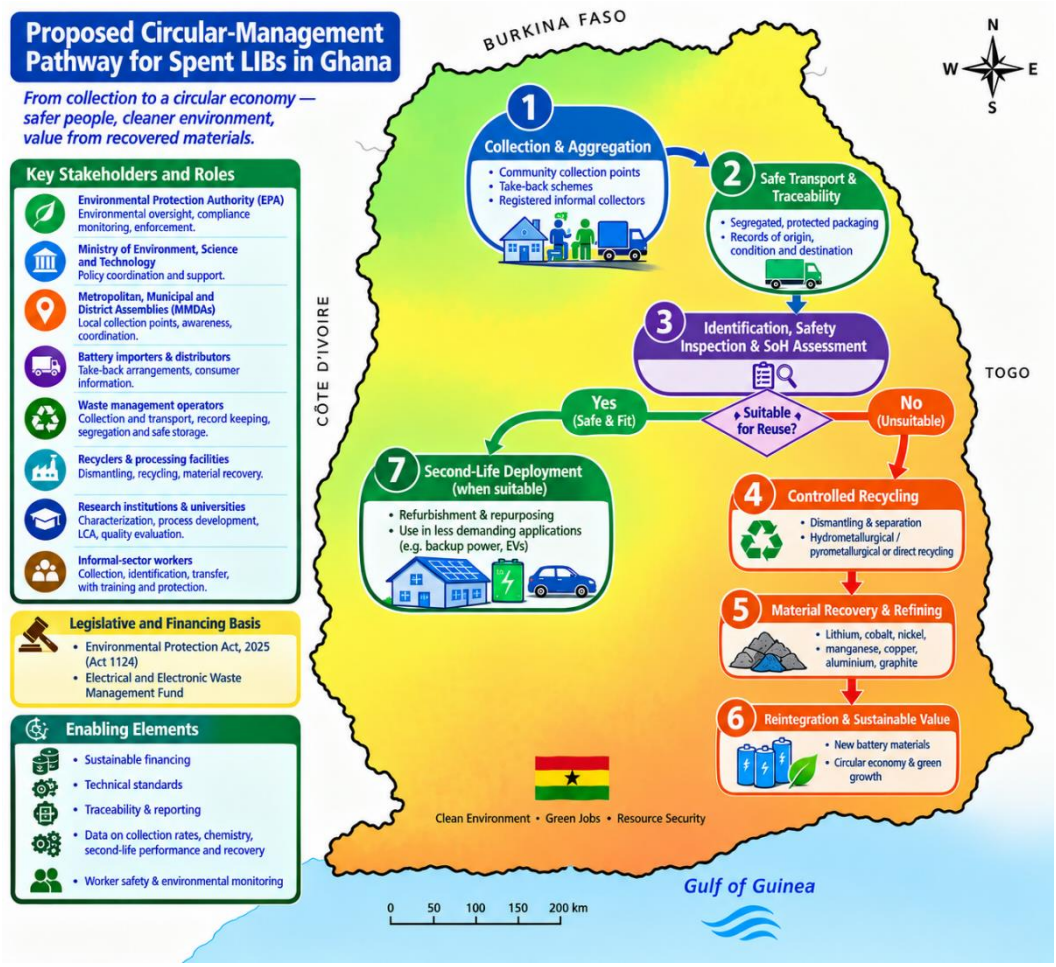

Figure 2. Proposed seven-stage circular-management pathway for spent LIBs. Authors' synthesis based on the reviewed literature

Ghanaian context by considering collection and aggregation, safe transport and traceability, identification, safety inspection and SoH assessment, second-life applications, controlled recycling, material recovery and refining, and reintegration of recovered materials into the battery value chain. A key feature of the proposed framework is the decision point following identification, safety inspection, and SoH assessment. Batteries that retain adequate capacity and acceptable safety characteristics may be considered for second-life applications where their remaining performance is appropriate for the intended use (Patel et al., 2024; Vignesh et al., 2024). SoH assessment is particularly important because battery degradation is not uniform, and decisions regarding reuse should consider factors such as remaining capacity, internal resistance, degradation history, battery chemistry, and intended application (Vignesh et al., 2024). Batteries that are damaged, unstable, excessively degraded, or unsuitable for repurposing should instead be directed to controlled recycling rather than being placed in secondary-use markets (Patel et al., 2024; Vignesh et al., 2024). For batteries selected for recycling, mechanical pretreatment can be used to dismantle and separate the battery into fractions suitable for subsequent recovery processes (Li et al., 2024). Depending on the battery chemistry and the desired products, the resulting materials can then undergo hydrometallurgical, pyrometallurgical, or direct-recycling processes to recover useful battery constituents (Biswal et al., 2024; Li et al., 2024). Hydrometallurgical processing can recover valuable elements through leaching and subsequent separation and purification, whereas pyrometallurgical processing relies on high-temperature treatment. Direct recycling seeks to preserve and regenerate electrode materials rather than completely reducing them to their constituent elements (Biswal et al., 2024). The ultimate objective of the proposed pathway is to return recovered materials to productive use within a circular economy. Depending on the battery chemistry and recycling technology employed, recoverable materials may include lithium, cobalt, nickel, manganese, copper, aluminum, and graphite (Li et al., 2024). These recovered materials can be converted into purified chemical products or other secondary raw materials for use in battery manufacturing and other industrial applications (Li et al., 2024). Such an approach can reduce dependence on virgin raw materials, limit the environmental burden associated with inappropriate battery disposal, and improve resource efficiency (Biswal et al., 2024).

5. Economic and Research Opportunities

A formal LIB management sector could create employment in collection, logistics, sorting, diagnostics, dismantling, recycling, laboratory analysis, equipment maintenance and environmental monitoring. It could also support new services for battery testing, refurbishment and second-life deployment. Universities and research institutions in Ghana can contribute through battery characterization, hydrometallurgical research, electrode regeneration, process optimization, environmental assessment and life-cycle analysis. Collaboration with industry would allow laboratory findings to be evaluated using actual local battery waste rather than only laboratory-synthesized materials. Regional cooperation is also important. If domestic battery quantities are initially insufficient for a large recycling plant, Ghana could develop collection and pretreatment capacity while partnering with regional or international processors for downstream refining. This approach could reduce the financial barrier to entry while preventing valuable battery materials from being lost in uncontrolled waste streams.

6. Policy Priorities, Research Gaps and Future Prospects

Ghana lacks disaggregated data on spent LIBs; national e-waste totals cannot serve as proxies for battery quantity, chemistry or location, necessitating a dedicated battery-flow assessment. Near-term policy priorities should include extended producer and importer responsibility, dedicated collection points, standards for safe transport and storage, worker training, battery identification and fire-safety protocols, and defined routing for damaged batteries, with technical support for formal centers. Research should focus on local battery composition, techno-economic and environmental evaluation of recovery routes, second-life performance, and the feasibility of regional recycling partnerships. Pilot studies and life-cycle assessments should guide investment before large-scale infrastructure is built, with the long-term goal of a circular system in which spent LIBs are safely collected, assessed for reuse, recycled when needed, and returned as secondary materials to supply chains.

7. Conclusions

LIBs are becoming increasingly important in Ghana's consumer electronics, renewable energy, telecommunications, and emerging electric-mobility sectors. Their growing use will increase the need for effective end-of-life management. The challenge differs from conventional e-waste because spent LIBs combine valuable materials with electrical, fire and chemical hazards. Ghana already has an institutional foundation

for electronic-waste management, but a more specialized battery pathway is needed. The most practical approach is not to rely on a single recycling technology but to establish a staged system that combines safe collection, chemistry identification, battery assessment, second-life use, mechanical preparation, and appropriate downstream recycling. The proposed pathway provides a framework that can be developed within Ghana's existing e-waste-management system. Establishing this pathway could reduce environmental and occupational risks while creating opportunities for secondary-resource recovery, research, employment, and circular-economy development.

Artificial Intelligence Tools

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) exclusively to generate and visually refine of Figure 2. The tool assisted in developing the infographic illustrating the proposed circular-management pathway for spent lithium-ion batteries in Ghana, including the graphical representation of the seven operational stages and their alternative process connections. The authors reviewed and revised the AI-generated illustration, verified its technical consistency with the proposed framework, and take full responsibility for the accuracy and final content of the figure.

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Cirkularno upravljanje litijum-jonskim baterijama na kraju životnog veka u Gani: rizici, tehnologije reciklaže i održivi pristupi

Frank Agyekum [a, #], Affah Augustine Akwochonga [b], Caleb Appiah [c], Daniel Asafori Adu-Boadu [d], Thaddaeus Oklu [e], Emmanuel Nii Otoo Tetteh [f]

[a] Jubaili Agrotech Limited, Odeljenje za kontrolu kvaliteta, Kumasi, Gana
[b] Shamrock Quarry and Concrete Limited, Odeljenje za proizvodnju, Akra, Gana
[c] Platinum International School, Odeljenje za prirodne nauke, Kumasi, Gana
[d] Univerzitet nauke i tehnologije Kwame Nkrumah, Katedra za fiziku, Kumasi, Gana
[e] Univerzitet za rudarstvo i tehnologiju, Katedra za mineralno inženjerstvo, Tarkva, Gana
[f] Vojna bolnica 37, Odeljenje za mikrobiologiju, Akra, Gana

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Litijum-jonske baterije
Upravljanje otpadom od električne i elektronske opreme
Cirkularna ekonomija
Reciklaža baterija
Baterije za drugu upotrebu

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I Z V O D

Gana se nalazi u ključnoj fazi energetske tranzicije. Sve veća upotreba litijum-jonskih baterija u prenosivim elektronskim uređajima, sistemima za korišćenje solarne energije i sektoru elektromobilnosti koji je u razvoju dovodi do nastanka nove kategorije otpada u okviru već opterećenog sistema upravljanja otpadom od električne i elektronske opreme. Dostupne procene na nacionalnom nivou ukazuju na značajan porast količine ovog otpada u Gani, iako količine koje potiču isključivo od litijum-jonskih baterija još uvek nisu dovoljno precizno utvrđene. U ovom preglednom radu analizirani su primena litijum-jonskih baterija u Gani, rizici po životnu sredinu i bezbednost, tehnologije reciklaže i mogućnosti za uspostavljanje cirkularnog sistema upravljanja ovim baterijama. Tri osnovna postupka reciklaže litijum-jonskih baterija (pirometalurški i hidrometalurški postupci i direktna reciklaža), zajedno sa kombinovanim postupcima i novim bioelektrohemijskim metodama, ocenjena su sa stanovišta njihove tehničke i ekonomske primenljivosti u Gani. Predložen je praktičan model cirkularnog upravljanja koji obuhvata sedam faza i integriše bezbedno sakupljanje i objedinjavanje sakupljenih baterija, transport, identifikaciju baterija i procenu njihovog stanja (SoH), uz donošenje odluke o daljem postupanju. Baterije koje ispunjavaju odgovarajuće uslove usmeravaju se ka drugoj upotrebi, odnosno korišćenju za druge namene nakon završetka prvobitne funkcije, dok se baterije koje ne ispunjavaju te uslove upućuju na kontrolisanu reciklažu, izdvajanje korisnih materijala i njihovo ponovno uključivanje u proizvodne tokove, u skladu sa postojećim pravnim okvirom Gane. U radu je takođe ukazano na potrebu za unapređenjem dostupnosti podataka o baterijama, razvojem tehničkih kapaciteta i infrastrukture za ispitivanje, jačanjem odgovornosti proizvođača i uspostavljanjem regionalnih partnerstava u oblasti reciklaže, radi pružanja podrške energetskoj tranziciji Gane.