Progress and challenges on battery waste management : a critical review

Rarotra, Saptak; Sahu, Satyabrata; Kumar, Pawan; Kim, Ki-Hyun; Tsang, Yiu Fai; Kumar, Vikas; Kumar, Parveen; Srinivasan, Madhavi; Veksha, Andrei; Lisak, Grzegorz

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Progress and Challenges on Battery Waste Management: A Critical Review --Manuscript Draft--

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Abstract:	The use of batteries in the electronics, automobile, and chemical industries is growing rapidly worldwide. The portability, high energy density, and low maintenance needs of batteries eliminates the need for transportation or reticulation of power. However, battery technologies suffer from a limited life span, which results in a need for frequent replacement. The generation of large quantities of battery waste has created a need for an effective management strategy to safely treat and recover valuable resources

	<p>used in battery manufacturing. This review covers current issues in battery waste management, including a description of the advantages, limitations, challenges, and economical feasibility of various treatment technologies. Future perspectives are also discussed to encourage research on imminent environmental issues associated with batteries.</p>
Author Comments:	<p>To 13th Feb. 2020 The Editor Chemistry Select</p> <p>Subject: Submission of response titled "Progress and Challenges on Battery Waste Management: A Critical Review"</p> <p>Ref: batt.202000002 for Batteries & Supercaps - [EMID:16e0c50bdc407759]</p> <p>Dear Editor,</p> <p>Thank you for your valuable comments and suggestions on the language and structure of our manuscript. We have modified the manuscript accordingly, and corrections have been made to comply with each comment raised by the reviewers. All issues regarding the revision of our ms are now listed below point by point in yellow marking.</p> <p>Reviewers' comments:</p> <p>Reviewer I</p> <p>We thank the referee for providing the insightful comments, which helped in improving the quality of the manuscript significantly. Followings are the corrections made in the revised manuscript to incorporate all the changes suggested/advised by the referee, with a point-wise response.</p> <p>Comment 1: Introduction: "Examples of power supply systems include (a) battery energy storage,.....(d) lead-acid batteries, (g) lithium-ion batteries"..... What is the difference between (a) and (d), (g)?</p> <p>Response: In the present-day scenario, Lead -acid batteries and lithium batteries are the main source of energy storage. As there is not much difference in the basic principle and uses of both the batteries. However, lead -acid batteries and lithium batteries are the most common battery types but they have a different working chemistry. As their names imply, lithium-ion batteries are made with the metal lithium, while lead-acid batteries are made with lead. With the differences in chemistry, there are some major differences in performance and cost.</p> <p>There are many key differences between lead-acid and lithium batteries</p> <p>1. Cycle life/Depth of discharge</p> <p>Cycle life is also a function of depth of discharge i.e. total capacity use before recharging a battery. Discharge depth refers to the overall capacity of the battery which is used before recharging the battery. Deeper discharges put more stress on the battery, which shortens its cycle life. The cycle life and higher usable capacity of lithium batteries is more than the Lead batteries.</p> <p>2. Efficiency</p> <p>Lithium batteries are more efficient than lead -acid batteries which also suggests that lithium batteries charge faster as compared to lead -acid batteries. Typically lithium batteries are more than 95% efficient as compared to lead-acid batteries which are 80-85% efficient depending on the model and condition.</p> <p>3. Charge Rate</p> <p>As the efficiency of lithium batteries is higher, it also comes with the higher charge rate. Lithium batteries can store a higher amperage, which resources faster refilling as compared to lead-acid.</p> <p>4. Energy Density</p> <p>The energy density of lithium batteries is much higher than lead-acid, meaning they fit more storage capacity into less space.</p> <p>Comment 2: - Figure 1 is outdated. It shows the technical maturity from 2008.</p>

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Additional Information:	
Question	Response
Do you agree to comply with the legal and ethical responsibilities outlined in the journal's Notice to Authors?	Yes
Has a previous version of this manuscript been submitted to this journal?	No; No

Is this manuscript, or part of it, currently under consideration elsewhere?	No; No
Is this manuscript, or part of it, published, posted, or in press? This includes content posted on preprint servers (preprint guidelines) or published as part of a thesis.	No; No
Please provide us with information about the history of your manuscript, including previous submissions, transfers, or prior versions:	<p>To 15th January 2020 The Editor Batteries & Supercaps</p> <p>Subject: Submission of response titled "Progress and Challenges on Battery Waste Management: A Critical Review"</p> <p>Ref: batt.202000002 for Batteries & Supercaps - [EMID:16e0c50bdc407759]</p> <p>Dear Editor,</p> <p>Thank you for your valuable comments and suggestions on the language and structure of our manuscript. We have modified the manuscript accordingly, and corrections have been made to comply with each comment raised by the reviewers. All issues regarding the revision of our ms are now listed below point by point in yellow marking.</p> <p>Reviewers' comments: Reviewer I</p> <p>We thank the referee for providing the insightful comments, which helped in improving the quality of the manuscript significantly. Followings are the corrections made in the revised manuscript to incorporate all the changes suggested/advised by the referee, with a point-wise response.</p> <p>Comment 1: Introduction: "Examples of power supply systems include (a) battery energy storage,.....(d) lead-acid batteries, (g) lithium-ion batteries".... What is the difference between (a) and (d), (g)?</p> <p>Response: In the present-day scenario, Lead -acid batteries and lithium batteries are the main source of energy storage. As there is not much difference in the basic principle and uses of both the batteries. However, lead -acid batteries and lithium batteries are the most common battery types but they have a different working chemistry. As their names imply, lithium-ion batteries are made with the metal lithium, while lead-acid batteries are made with lead. With the differences in chemistry, there are some major differences in performance and cost.</p> <p>There are many key differences between lead-acid and lithium batteries</p> <p>1. Cycle life/Depth of discharge</p> <p>Cycle life is also a function of depth of discharge i.e. total capacity use before recharging a battery. Discharge depth refers to the overall capacity of the battery which is used before recharging the battery. Deeper discharges put more stress on the battery, which shortens its cycle life. The cycle life and higher usable capacity of lithium batteries is more than the Lead batteries.</p>

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The Editor

Batteries & Supercaps

Subject: Submission of response titled "Progress and Challenges on Battery Waste Management: A Critical Review"

Ref: batt.202000002 for Batteries & Supercaps - [EMID:16e0c50bdc407759]

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Does the research described in this manuscript include animal experiments or human subjects or tissue samples from human subjects?	No; No
Do you or any of your co-authors have a conflict of interest to declare?	No; No

REVIEW

Progress and Challenges on Battery Waste Management: A Critical Review

Saptak Rarotra,^{a,f,†} Satyabrata Sahu,^{a,†} Pawan Kumar,^{a,†} Ki-Hyun Kim,^{b,1} Yiu Fai Tsang,^c Vikas Kumar,^d
Parveen Kumar,^d Madhavi Srinivasan,^e Andrei Veksha,^f Grzegorz Lisak^{f,g,2}

REVIEW

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Abstract: The use of batteries in the electronics, automobile, and chemical industries is growing rapidly worldwide. The portability, high energy density, and low maintenance needs of batteries eliminates the need for transportation or reticulation of power. However, battery technologies suffer from a limited life span, which results in a need for frequent replacement. The generation of large quantities of battery waste has created a need for an effective management strategy to safely treat and recover valuable resources used in battery manufacturing. This review covers current issues in battery waste management, including a description of the advantages, limitations, challenges, and economical feasibility of various treatment technologies. Future perspectives are also discussed to encourage research on imminent environmental issues associated with batteries.

1. Introduction

Electronic devices play an important role in industrial and academic activities as well as professional and personal development. The devices can be classified into two main groups, i.e., wired and wireless, both of which require a continuous power supply. [1,2] Portable power supplies in the form of batteries are extremely popular due to their practical features, including low maintenance and ease of transportation.

Examples of power supply systems include: a) battery energy storage (BES), b) pumped hydroelectric storage system (PHS), c) compressed air energy storage (CAES), d) lead-acid batteries, e) nickel-cadmium (NiCad) batteries, f) network-attached storage (NAS), g) lithium-ion (Li-ion) batteries, h) metal-air batteries, and i) vanadium-redox flow batteries (Figure 1). Among these systems, BES and PHS are the most mature and the most popular options worldwide [3,4,5] owing to their high energy-storage capability, ease of use, and high-frequency regulation.[6,7] According to a report from Bloomberg New Energy Finance, demand for and production of batteries are increasing daily due to high energy demand (Figure 2).[8] The US, UK, France, Japan, South Korea, Australia, China, Germany, and India are expected to be the leading producers of batteries by 2040. [3,4,5] Grand View

Research Inc. (2016) [9] and Recharge (2018) [10] report that the global market for batteries was worth approximately 62 billion USD in 2014, with a particularly high demand from automotive applications. Likewise, the demand for lead-acid and Li-ion batteries by the transportation, uninterruptible power supply, and telecommunication industries is expected to continue to grow (Figure 3). [9,10]

The US Environmental Protection Agency (EPA) [11] reported that the US disposes of more than 180,000 tons of battery waste, including more than 86,000 tons of alkaline batteries and 14,000 tons of rechargeable batteries, each year. [10-12] In China, 570,000 tons of battery waste were generated in 2013. As a result, large volumes of battery waste are causing serious health and environmental concerns. [13-16] Battery waste management involves treatment processes such as landfilling, thermochemical treatment, and waste reduction through the application of physical and chemical recycling. Spent batteries should be recycled to address the scarcity of resources and minimize pollution. [17-21] In this paper, the composition of batteries and current waste management solutions are discussed. Various types of batteries are described followed by a discussion of the elementary principles of battery waste management. The final section addresses the challenges and economic feasibility of various battery-waste management and concludes with an overview of future perspectives.

Biographical Sketch.

((Author Portrait))

REVIEW

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((Author Portrait))

2. Types of batteries

Batteries can be classified into chemical, physical, and biological varieties (Figure 4). Chemical batteries can be further classified into primary and secondary types. Primary batteries are disposable, non-rechargeable, and characterized by low initial costs, replaceability, and suitability for portable applications, but a high life-cycle cost.[22] Examples of primary batteries are, alkaline, Zn-C, Li-ion, and manganese dry cells. Alkaline batteries can be classified according to their metallic composition, as shown in Table 1. Batteries can also be classified by size and design, i.e., AA, AAA, C, and D. [23]

For example, the negative terminal in alkaline and Zn-C batteries consists largely of metallic zinc, and the positive terminal is composed of manganese (IV) oxide. Previously, small amounts of mercuric oxide were used to suppress the formation of internal gases that otherwise can lead to leakage and/or a short shelf life. Metallic zinc is converted to zinc oxide through the loss of electrons during the discharge process. Elemental mercury is generated from mercuric oxide through the acquisition of electrons. To prevent the evolution of hydrogen, only small quantities of mercuric oxide were introduced into the cell. However, due to environmental concerns, the use of mercury in batteries was prohibited in the US under 1996 legislation. According to the United States Environmental Protection Agency, metallic zinc is toxic to aquatic life. [25] However, in spent batteries elemental zinc is converted into zinc oxide, which is a less toxic and more stable compound.[26,27] Manganese (III-IV) oxide poses no potential environmental risks, although the dust generated by incinerating spent alkaline batteries reportedly poses human health threats .[26-30] Secondary (rechargeable) batteries (i.e., NiCad, nickel metal hydride [NiMH], lead-acid, and Li-ion products) reportedly have relatively high initial costs and low life-cycle costs.[28-30] NiCad batteries consist of nickel-oxide hydroxide and metallic cadmium as positive and negative electrodes, respectively. While both metals can cause health and environmental risks, cadmium is the more toxic of the two. Exposure to cadmium compounds produces a wide variety of acute and chronic effects in humans, leading to a build-up of cadmium in the kidneys. This accumulation can cause kidney diseases while increasing the risk of lung cancer. [27,31] Owing to the hazardous nature of cadmium, NiCad batteries have been replaced by less-toxic NiMH batteries, which contain alloys of hydrogen-adsorbing rare earth elements instead of cadmium. In contrast, lead-acid batteries remain common in the telecommunications and automobile industries, modular data centers, and electrical grids (as backup power). All lead compounds are considered hazardous to human health due to

their negative effects on the nervous system, kidney, and other major organs. [32-34]

Li-ion batteries are the preferred technology in the global battery market for electric vehicles and household appliances. [35-37] These batteries contain cobalt, nickel, iron, aluminum, or manganese species as positive electrodes, and graphite, carbon, or copper as negative electrodes. Exposure to these metals is associated with health and environmental problems. [37-40] More information on batteries and their progress can be obtained elsewhere.[41]

Due to growing environmental concerns, various reports have been published on recycling, reuse, and overall utilization of batteries [19, 42,43], with the main research focusing on finding low-cost solutions and environmentally friendly technologies. The next section discusses waste management solutions and recycling, reuse, and utilization of batteries.

3. Waste management solutions for spent batteries

Several solutions have been implemented to manage battery waste (Figure 6). Fundamentally, battery waste management can be divided into waste reduction, landfilling, and thermal treatment. [44] Certain pre-treatment methods are also recommended for battery waste management, such as manual pre-treatment (at the laboratory scale) and mechanical pre-treatment (at the industrial scale). The latter options comprise various sub-categories: dismantling and classification, crushing, sieving, separation, and recycling. [44] Resource recovery processes have been classified into hydrometallurgy and pyrometallurgy.

3.1. Waste reduction

Waste reduction (or prevention) is the most economic and environmentally friendly of all waste management strategies. The minimization of both raw resources and the quantity of treatable waste can be achieved through better product design and improved process management. Moreover, waste reduction can be achieved more efficiently by recycling spent batteries instead of manufacturing new ones. Most lead-acid batteries are already manufactured by recycling materials from spent batteries and other sources of lead. [45]

3.2. Landfilling

Landfilling involves dumping waste into secured land masses that have low groundwater levels. Typically, two different approaches are used: (i) confine the waste to a small area, and (ii) compact the waste to reduce volume. [46,47] A standard weighing mechanism is generally applied to measure the waste materials upon arrival at a landfill. The landfilling of household (alkaline and Zn-C) batteries reportedly poses no substantial risk (SEMB; November 2001) [48], and a similar conclusion was drawn by the US EPA and National Electrical Manufacturers Association (NEMA, June 2002) [49]. As a result, these batteries are not considered hazardous waste for landfilling. [46,47] However, landfilling is unsuitable for NiCad and NiMH products, as leaching of heavy metals can contaminate groundwater. [50] Landfilling also suffers from major disadvantages in the form of energy consumption for transporting and collecting waste. [51]

REVIEW

3.3. Thermal treatment

Thermal processing (incineration, gasification, or pyrolysis) is applied in the treatment of municipal and industrial solid waste, which can contain battery waste. The temperatures involved in incineration and gasification range between 980 °C and 2000 °C. During incineration, the original volume of the waste is reduced by about 80–90%. [52,53] Current incinerators and gasifiers offer safe and environmentally sound disposal of highly contaminated and harmful waste from chemical and processing operations. Carbon dioxide, carbon monoxide (CO), dioxins, solid particulates, and heavy metals are byproducts of thermal processing. The degree of pollution resulting from thermochemical conversion of waste varies according to the nature of the waste and the treatment infrastructure. As alkaline batteries are frequently incinerated, the emissions and ash resulting from their incineration, which contain potassium hydroxide and manganese, are extremely dangerous. [54]

3.4. Manual pre-treatment

Manual pre-treatment of battery waste at the laboratory scale usually involves a simple procedure in which individual spent cells of a battery are discharged and dismantled by hand. After dismantling, various separation methods can be employed according to the properties of the collectors and binders. [55,56] Mechanical separation includes crushing and screening to separate current collectors and active materials, solvents and calcination can remove adhesive binders, and active materials can be separated through the dissolution of current collectors. These pre-treatment steps are depicted in Figure 5. [57]

3.5. Mechanical pre-treatment of battery waste: dismantling, crushing, sieving, and separation

At present, manual dismantlement of spent batteries is conducted by specialized personnel as different manufacturers employ different pack architectures. [58] Mechanical pre-treatment is nonetheless a more favorable option for industrial applications. After the crushing, the metallic fraction passes through a sieving or screening process to help separate and concentrate the fractions. The different components are separated based on their thermal properties, surface wettability, electromagnetic behavior, density, and magnetic and electric characteristics. [59]

3.6. Recycling and reuse

From the 4,000 tons of used batteries, 1100 tons of heavy metals and 200 tons of toxic electrolytes were produced in 2005. [60,61] Discarding spent battery waste that includes untreated heavy metals into a landfill at the end of a battery's useful life can pollute groundwater and soil. Recycling of battery waste is therefore a useful prospective option for sustainable waste management. Recycling is the most valuable among the known waste management techniques because it reduces waste volume. In 2018, in the US and EU, approximately 42% of spent batteries were recycled (Recharge, 2018). Several hydrometallurgical and pyrometallurgical processes that can recover valuable metal components from batteries have been introduced [58,59,62,63] In Table 2, pyrometallurgical and hydrometallurgical recovery

processes are summarized. However, few cost-benefit analyses of battery waste management technologies have been conducted.

3.6.1. Hydrometallurgy

Recycling in hydrometallurgy consists of several steps. [64,65] A representative flow diagram for hydrometallurgy is supplied in Figure 7. [64]. The major processes in the hydrometallurgical method are leaching, electrowinning, and melting and casting. Leaching agents commonly used in the leaching process include organic and inorganic acids and ammonia-ammonium salts. This technique is applicable to alkaline, ZN-C, NiMH, and Li-ion batteries. [64,65] Different types of materials had been employed as leaching reagents to extract metals from spent batteries (Table 4), including reducing agents such as Na₂SO₃ [66], H₂O₂ [65,67–69], ascorbic acid [70,71] and glucose. [72] The main factors that affect the leaching process are reaction time, temperature, and concentrations of the leaching and reducing agents. The leaching of spent Li-ion batteries has been investigated using different acidic leaching agents, such as HCl, HNO₃, and H₂SO₄, without a reducing agent. [65,73] The leaching of Co³⁺ from cathodic terminals is difficult to induce, as Co³⁺ is converted to Co²⁺. Among the leaching agents, HCl provides the best combination of efficiency and purity (Table 2). The optimal condition for leaching is 4 mol. L⁻¹ HCl, 90 °C, 18 h, and 50 g L⁻¹ S/L ratio. When HCl is used in leaching LiCoO₂-like raw materials, the proposed chemical reaction was as follows [65,74]

In Equation (1), Cl₂ gas is generated during the leaching process, which can pose a health risk. In response, H₂SO₄ has been proposed instead of HCl to leach raw LiCoO₂ [65,69,75]. Researchers earlier had reported treating a LiCoO₂ cathode with H₂SO₄, HNO₃, and HCl at optimized conditions: H₂SO₄/2 M HCl/2 M HNO₃ at 30 °C for 2 h. [69] The resulting pulp density was 75 g L⁻¹. H₂SO₄ was chosen because it was suitable for the dissolution of cobalt. HCl and HNO₃ precipitated at high concentrations can decrease leaching efficiency. A combination of H₂O₂ (as a reducing agent) and H₂SO₄ (as a leaching reagent) efficiently increased the cobalt recovery rate from 30% to 97%. [69] Approximately 98% of the cobalt was extracted from the leachate using 20% Cyanex 272 at a pH of 4.8. [69] A concentrated cobalt solution was evaporated to produce solid CoSO₄ with a purity of greater than 98%. The recovery rates of cobalt and lithium were 97% and 99.99%, respectively, through reactions reported by [69]

The leaching of spent ZnO-MnO₂ powder obtained from the electrode was studied by dissolving it with H₂SO₄ as a leaching agent and using C₆H₈O₆, C₆H₈O₇, and C₂H₂O₄ as reducing agents. [71] Zinc can be dissolved completely in H₂SO₄. However, the leaching rate of manganese was approximately 60% due to the existence of manganese (IV) in spent battery waste. Reducing agents were introduced to increase the leaching efficiency. The resulting reaction was:

REVIEW

Citric acid: $9\text{MnO}_2 + 9\text{H}_2\text{SO}_4 + \text{C}_6\text{H}_8\text{O}_7 \rightarrow 9\text{MnSO}_4 + 13\text{H}_2\text{O} + 6\text{CO}_2$ (6)

Oxalic acid: $\text{MnO}_2 + \text{H}_2\text{SO}_4 + \text{C}_2\text{H}_2\text{O}_4 \rightarrow \text{MnSO}_4 + 2\text{H}_2\text{O} + 2\text{CO}_2$ (7)

Among all the reducing agents, $\text{C}_6\text{H}_8\text{O}_6$ demonstrated the greatest leaching efficiency. Applying the optimal conditions of 0.5 mol L⁻¹ H_2SO_4 , 20 mL g⁻¹, 25 °C, 2 h, and 10 g L⁻¹, $\text{C}_6\text{H}_8\text{O}_6$ yielded an efficiency of up to 98% for metal ions. [71] In contrast, the recovery rates for zinc and manganese were 91% and 94%, respectively. Achieving efficient leaching using inorganic acids is relatively straightforward. Because inorganic acids produce wastewater and harmful gases such as Cl_2 , [71,75] environmentally friendly organic acids can be used at the leaching stage. When the leaching effect of H_2O_2 as a reducing agent and $\text{C}_4\text{H}_6\text{O}_4$ as a leaching agent on lithium-nickel-manganese-cobalt oxide cathodes was studied, the optimal conditions were 2 M $\text{C}_4\text{H}_6\text{O}_4$, 4% H_2O_2 , 30 min, 70 °C, and 17 g L⁻¹ pulp density.[68] The leaching efficiencies of manganese, lithium, cobalt, and nickel were 99.31%, 99.07%, 98.64%, and 99.31%, respectively. [68] The corresponding reactions were:

3.6.2 Pyrometallurgy

A typical pyrometallurgical process consists of several steps, including desulfurization, smelting, and refining. [64] This process can be used to treat both the electrodes and the electrolyte of spent battery waste. A representative flow diagram for pyrometallurgy is illustrated in Figure 8 [64]. Lead-acid and Li-ion batteries are preferably recycled by this technique to recover cadmium, lithium, and cobalt compounds. [76-81]

When the recovery of cadmium from spent NiCad batteries was previously investigated, vacuum metallurgy separation and magnetic separation to recover cadmium was reported under the following optimized conditions: 749 °C, 1.5 h, and 1 wt% of carbon powder.[76] More than 99.2% of the cadmium and 98.0% of the ferromagnetic materials were recovered at 60 rpm. Although the proposed process was able to yield high-value products, large amounts of energy were consumed. Likewise, a recovery process for a Li-ion battery employing evaporation (vacuum and gas) at higher temperatures (i.e., > 1400 °C) was proposed (Trager et al., 2015), as was a novel method for valuable metals recovery in an argon atmosphere at low temperatures followed by a water-leaching process.[81] By adjusting the solid/liquid ratio to 100 g L⁻¹ for the leaching time of 2 h, a concentration of lithium in the leachate solution of 4.36 g L⁻¹ was possible. More recently, Farzana et al. suggested a thermal treatment method for Zn-C batteries at 900 °C in an argon atmosphere and a horizontal quartz tube furnace. Finally, zinc was applied for the synthesis of ZnO nanoparticles.[82]

Although pyrometallurgy involves a simple recovery operation, it is not environmentally friendly due to its low overall recovery rate, the generation of secondary pollution, and high energy consumption (Table 3). [76,77,80,83 84] Consumption of strong acids in hydrometallurgy leads to additional emission of gases

(e.g., Cl_2 and CO_2), which is a shortcoming that needs to be addressed.[85]

4. Challenges associated with BWMT

The first difficulty in the management of spent battery wastes is that their in-flow rates are still not classified by the waste management industry. [86-89] As a result, a large number of spent batteries end up in landfills, causing negative economic, health, and environmental impacts.

The immediate challenges in battery waste management are collection, safe transportation, and storage of spent batteries.[23] Proper guidelines are required to safely discharge active batteries prior to their transportation to collection centers. Incompletely discharged or partially charged batteries can cause fires or short circuits when electrodes come into contact with casings. The immersion of spent battery waste in an aqueous solution can mitigate the threats posed by incomplete battery discharge, lowering battery temperature during the discharge process.[57] Lastly, the targeted segregation of batteries must be carried out according to chemical composition. [23,57,89] During processing, various chemical compositions are mixed in solution or powder form. The presence of impurities during the metal recovery phase can complicate the refining process. Each manufacturer must provide a separate document in the form of a data sheet for each recovered chemical. This approach can make segregation easier and more cost-effective. [23,57]

Another challenge is the safe dismantling of batteries. Several technologies are available. Workers in often unorganized sectors dismantle batteries by hand without taking any precautions to prevent exposure to volatile electrolytes. They usually tear batteries apart to recover the casing, copper, aluminum foil, and printed circuit boards while treating cathode and anode black powder as waste. The powders are sent to landfills or nearby stagnant water or open lands. [23,57,89,90]

Chemical and other industries usually have technologies to process metals, but the processing of the black mass of cathodes and anodes remains a challenge and is often exported to other countries for further processing. Commercialization is a challenge. [90] but the adoption trends for such technologies indicates that high leaching and acceptable metal recovery rates can offer cost-effective solutions for recycling and recovery of battery waste. [91] The final and most important challenge is developing an environmentally friendly technology for the recycling, recovery, and reuse of recovered battery metals. Conventional hydrometallurgy is applicable to harsh acidic or basic conditions, offering attractive leaching and recovery rates. [92-94] However, these processes can result in hazardous fumes in the working environment and require large amounts of water and neutralizing

REVIEW

solutions to treat the acid waste used in hydrometallurgy. This increases the operating cost of sewage treatment plants and wastes of resources. Government agencies such as the Environmental Foundation for Africa and European Environment Agency are focusing on mild acidic options and closed-loop processes for metal leaching and recovery. The health and environmental risks should be minimized while resource recovery is maximized. Human interference and manual processes should be avoided to minimize health concerns. Industries should also propose and develop solutions for the automation of the process involved. This approach may increase process costs and involve the hiring of additional human resources, but reduce associated liabilities in terms of moral, social, and financial grounds.

5. Future scope and conclusion

Battery waste has become a serious environmental concern that demands thoughtful solutions at a global scale. The volume of battery waste is increasing rapidly due to increasing use of electronic devices. Battery waste contains a variety of toxic substances that can contaminate the environment and threaten human health. Numerous studies confirm that toxic chemicals such as heavy metals continuously contaminate the environment. A research gap has arisen between academia and industries working in the field of battery recycling, and recycling technologies are often restricted to the bench scale. In many countries, governments are partnering with industries and academia (<https://waste-management-world.com/a/calling-academia>) to address this problem. As a result, the recycling and recovery of metals from Li-ion batteries has been extensively explored. However, many technologies remain impractical at commercial scales. Researchers should collaborate with chemical industries to develop novel technologies that can be scaled up without imposing high costs and environment burdens.

Figure 1. Technology Readiness of Energy Storage Technologies (R. Baxter Energy Storage Financing: A Roadmap for Accelerating Market Growth, 2016)

Figure 2. Global cumulative storage deployments (2016-2030) (BNEF, US), "Battery Market Size, Share, Industry Research Report, 2024," [Online], Available: <http://www.grandviewresearch.com/industry-analysis/battery-market>

Figure 3. North America battery revenue 2013-2024 (Grand View Research Inc., US)

Figure 4. Classification of batteries (Glascok, Winfield, Wu, Charlotte, Yu, Au Loong, 2012, Globalization Monitor.)

REVIEW

Figure 5. Pre-treatment processes and technologies of LIBs from perspectives of industrial scale and lab scale (L. Li et al. 2010, Zhang et al., 2018)

Figure 6. Battery waste management strategies

Figure 7. A representative flowsheet for hydrometallurgical processing of spent LABs. (Z. Sun et al. Waste Management, 64, 2017, 190-201.)

Table 1. Metallic composition of batteries (%).

A. Alkaline Batteries								
Sl. No.	Mn	Zn	C	O	S	Fe	Ni	Reference
1)		35	15				0.5	0.05
2)		32.06	27.62	17.35	22.92	0.02	0.01	

B. Zn-C Batteries						
Sl. No.	Zn	Mn	Fe	Co	Cl	Reference
1)	18.39	34.96	3.64	3.39	16.19	Farzana et al., 2018 [82]

C. NiCad Batteries								
Sl. No.	Cd	Ni	Fe	Co	Zn	Li	Cu	Reference
1)	23.2	16.4	35.0	1.1	0.5	0.1	0.3	Huang et al., 2009 [76]
2)	33.17	24.32	12.92					Rudnik et al., 2007 [97]

D. Lead-acid Batteries								
Sl. No.	Pb	S	Fe	Na	Ca	Al	Sb	Reference
1)	72.90	4.69	0.02	0.33	0.16	0.05	0.07	Li et al., 2019[98]
2)	68.67	7.87	0.015				0.029	Ma et al., 2015[79]

E. Li-ion Batteries							
Sl.no	Co	Li	Al	Cu	Fe	Ni	Reference
1)	15.51	2.27	3.43	9.54	19.31		Wang et al., 2009 [99]

Figure 8. A representative flowsheet of spent LABs recycling using pyrometallurgy. (Z. Sun et al.; Waste Management, 64, 2017, 190-201.)

REVIEW

2)	16	2	3	10	19		Li et al., 2009 [100]
3)	16.5	2	4.1	7.1			Lain et al., 2001[101]
4)	29.49	3.14	8.02	16.48		0.02	Dorella et al., 2007 [58]
5)	20.48	11.50	9.94			0.08	Zeng et al., 2008 [103]
6)	27.5	14.5	14	24.5			Lee et al., 2002 [102]
7)	22.31	2.74	9.78	7.47		0.40	Li et al., 2009 [100]
8)	20	2.4	1.2	2.4	0.3	0.8	Dutta et al., 2018 [69]
9)	23	4	1	1	0.3	11	Trager et al., 2015 [80]
10)	26.77	3.34	5.95	1.24	3.76	0.34	Chen et al., 2011 [67]

Table 2. Techniques of recycling and recovery of metals from spent batteries.

Sl. No.	Techniques	Spent batteries	Leaching reagent	Recovered product	Recovery rate (%)	Purity (%)	Reference
1	Leaching, Liquid-liquid extraction	Zn-MnO ₂ Alkaline	HCl	ZnO		99	Deep et al., 2011 [19]
2	Leaching, electro-winning	Alkaline	H ₂ SO ₄	Zn, MnO ₂		99.8	De Souza et al., 2004[96]
3	Hydrogen reducti	Alkaline		Zn	Zn-99.8		Ebin et al.,

	on assisted pyrolysis	and Zn-C					2017[104]
4	Leaching, precipitation separation	Alkaline	H ₂ SO ₄	MnSO ₄ . H ₂ O, ZnSO ₄ . 6H ₂ O	Mn-99, Zn-99	-	Morcali et al., 2015 [66]
5	Leaching, precipitation separation	Alkaline	HCl	ZnO	> 95		Deep et al., 2016[95]
6	Leaching, evaporation, calcination	Alkaline	(NH ₄) ₂ CO ₃	ZnO			Lopez et al., 2017 [105]
7	Leaching, precipitation	Alkaline	H ₂ SO ₄ , NaOH	Zn	92-94	> 99.5	Sadeghi et al., 2016 [106]
8	Leaching, Solvent extraction	Zn-C, NiCad	HCl	ZnO, CdO	Zn-99, Cd-99		Singh et al., 2017 [107]
9	Reductive leaching, precipitation, calcination	Zn-MnO ₂	H ₂ SO ₄	ZnO, MnO ₂	Zn-91, Mn-94		Chen et al., 2017 [71]
10	Thermal route, separation	Zn-C		ZnO			Farzana et al., 2018 [82]
11	Vacuum separation, inert gas condensation	Zn-Mn		ZnO	Zn-99.68	99	Xiang et al., 2015 [83]
12	Vacuum metallurgy separation, magnet	NiCad		Cd	Cd-99.2, Fe-99.2, Ni-96.1,	99.98	Huang et al., 2009 [76]

9

REVIEW

30	Leaching, primary purification, solvent extraction, precipitation	Li-ion	H ₂ SO ₄	CoCO ₃		95	Pagnanelli et al., 2015 [119]
31	Leaching, precipitation	Li-ion	HCl	Co ₂ O ₃ ·3H ₂ O Ni(OH) ₂	Co-100 Ni-99	90.25 96.36	Joulie et al., 2013 [73]
32	Leaching, separation, precipitation	Li-ion	CH ₃ COOH	Li ₂ CO ₃		99.93	Gao et al., 2018 [120]
33	Leaching, selective precipitation	Li-ion	H ₂ SO ₄	Li ₂ CO ₃ Bis(dimethylglyoxime)-Ni CoC ₂ O ₄ ·2H ₂ O	Ni-98.7, Mn-97.1, Co-98.0, Li-81.0	99.18 97.81 97.47	Chen et al., 2015 [116-118]
34	Leaching, precipitation	Li-ion	C ₄ H ₆ O ₅	Li ₂ CO ₃	Li-100, Co-99.87	99.5	Meng et al., 2017 [72]
35	Leaching, solvent extraction, precipitation	Li-ion	H ₂ SO ₄	CoC ₂ O ₄		99.9	Chen et al., 2011 [67]
36	Leaching, selective precipitation	Li-ion	H ₃ PO ₄	CoC ₂ O ₄ ·2H ₂ O Li ₃ PO ₄	Li-88, Co-99	98.3 97.8	Pinna et al., 2016 [121]
37	Leaching, extraction separation, crystallization	Li-ion	H ₂ SO ₄	CoSO ₄	Co-97 Li-99.99	98	Dutta et al., 2018 [69]
38	Leaching, precipitation	Li-ion	H ₃ PO ₄	Co ₃ (PO ₄) ₂	Co-99, Li-99	97.1	Chen et al., 2017 [71]
39	Leaching	Li-ion	C ₄ H ₆ O ₆	C ₄ H ₄ O ₆ Co C ₄ H ₄ O ₆ Li ₂			He et al.,

	extraction			C ₄ H ₄ O ₆ Ni C ₄ H ₄ O ₆ Mn			2017 [68]
40	Leaching, adsorption separation	Li-ion	NH ₃ ·H ₂ O- NH ₄ HCO ₃	Li ₂ CO ₃ NiSO ₄ CoSO ₄	Li-81.2, Ni-96.4, Co-96.3		Wang et al., 2017 [87]

Table 3. Comparison of various recycling processes for batteries waste management.

Sl. No.	Extraction Processes	Advantages	Disadvantages	References
1.	Hydrometallurgy	Low energy requirement, high purity, minimal air emission	High chemical reagents consumption, long recovery process	Dutta et al., 2018 [69]; Tanong et al., 2016 [85]
2.	Pyrometallurgy	Great capacity, simple operation	High energy consumption, low metal recovery rate	Huang et al., 2009 [76]; Trager et al., 2015 [80]; Wang et al., 2017 [87]

Table 4. List of various material used as leaching agents.

Sl. No.	Class	Materials	References
1.	Inorganic acids	HCl	Yang et al., 2003 [108]; Yang et al., 2014 [109]; Deep et al., 2016 [95]; Petranikova et al., 2019 [110];
		H ₂ SO ₄	De Souza et al., 2004 [96]; Rudnik et al., 2007 [97]; Morcali et al., 2015 [66]; Sadeghi et al., 2016 [106]; Chen et al., 2017 [71]; Porvali et al., 2018 [94]
		H ₃ PO ₄	Chen et al., 2017 [71]; Pinna et al., 2016 [121]
2.	Alkaline medium	NaOH	Sadeghi et al., 2016 [106]
3.	Organic acids	CH ₃ COOH	Gao et al., 2018 [120]
		C ₄ H ₆ O ₆	He et al., 2016 [68]
		C ₂ H ₅ NO ₂	Nayak et al., 2016 [70]

REVIEW

		C ₄ H ₆ O ₅	Li et al., 2010 [123]; Meng et al., 2017 [72]
		C ₆ H ₅ O ₇	Li et al., 2013 [124]
4.	Ammonium salts	NH ₃ ·H ₂ O-NH ₄ HCO ₃	Wang et al., 2017 [87]

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REVIEW

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