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Review

Recycling technologies, policies, prospects, and challenges for spent batteries

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SUMMARY

The recycling of spent batteries is an important concern in resource conservation and environmental protection, while it is facing challenges such as insufficient recycling channels, high costs, and technical difficulties. To address these issues, a review of the recycling of spent batteries, emphasizing the importance and potential value of recycling is conducted. Besides, the recycling policies and strategies implemented in representative countries are summarized, providing legal and policy support for the recycling industry. Moreover, a comprehensive classification and comparison of recycling technologies identify the characteristics and current status of different approaches. The integrated recycling technology provides a better recycling performance with zero-pollution recycling of spent battery. Biorecycling technology is expected to gain a broad development prospect in the future owing to the superiority of energy-saving and environmental protection, high recycling efficiency, via microbial degradation, enzymatic degradation, etc. Consequently, as for the existing recycling challenges of waste batteries, developing new recycling technology and perfecting its recycling system is an indispensable guarantee for the sustainable development of waste battery. Meanwhile, theoretical support is offered for the recycling of spent batteries.

INTRODUCTION

Energy saving and emission control is a hot topic because of the shortage of natural resources and the continuous augmentation of greenhouse gases.[1] So, sustainable energy sources, solar energy,[2] tidal energy,[3] biomass,[4] power battery[5] and other emerging energy sources are available and a zero-carbon target is proposed.[6] Actually, the major contributor of greenhouse gas emissions, i.e., fuel combustion or engines, is gradually replaced by battery-driven.[7] Currently, there exist many types of power batteries, i.e., lead-acid, Ni-Cd, lithium-ion batteries (LIBs), and $LiFePO_4$ batteries,[8] etc. Also, the development of power battery technology is maturing, which leads to the prevalence of electric vehicles (EVs) in the near future.[9] Meanwhile, it causes an increased demand for raw materials for power cells. Therefore, spent batteries and valuable metal substances should be fully recycled to prevent a shortage of raw materials,[10] as presented in Figure 1.

Spent batteries primarily consist of abundant substances, i.e., Al, Cu, Fe, Mn, Co, Ni, etc., which not only result in environmental pollution but also pose risks to human life and health.[12] Therefore, the recycling of spent batteries holds significant importance, and extensive research has been conducted on the recycling of spent batteries. Kang et al.[13] conducted comprehensive studies and employed standardized leaching tests, life cycle impact assessment, and hazard assessment models to evaluate the environmental hazards caused by used lithium batteries. The research indicates that Co, Cu, Ni, and Ti are responsible for causing environmental impacts. Besides, Yan et al.[14] proposed a two-step crushing method, and demonstrated its superior crushing efficiency and environmental friendliness compared to single tear crushing and single hammer crushing techniques. In a similar vein, Shin et al.[15] developed a froth flotation technology for active material separation, showcasing its ability to retain a significant portion of electrochemical activity in the recovered positive active material. This technology can be readily implemented in a direct recovery process. Li et al.[16] introduced a novel pyrometallurgical process known as low-temperature alkali pool smelting, which effectively recovers Pb from spent lactic acid bacteria. Liu et al.[17] adopted the interval plant-wide hierarchical optimization methodology for uncertainty optimization of hydrometallurgical plant-wide processes to reduce economic losses. Liivand et al.[18] proposed a pioneering approach to drive the green transition by utilizing graphite recovered from spent batteries. Furthermore, Kastanaki et al.[19] suggested a circular economy business model to regulate the remanufacture, reuse, and recycling of spent LIBs. Gu et al.[5] introduced a government incentive and punishment model to impact battery market recycling rates. Various recycling technologies are depicted, i.e., physical recycling, direct recycling, pyrometallurgical, and hydrometallurgy recycling methods, which promote the green transformation. Hence, the waste battery recycling industry holds significant potential for application and development.

The recycling of waste batteries faces several challenges, including the establishment of effective recycling channels, high recycling costs, and technical complexities. To tackle these obstacles and present an efficient and green recycling process for spent batteries, a review of

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https://doi.org/10.1016/j.isci.2023.108072

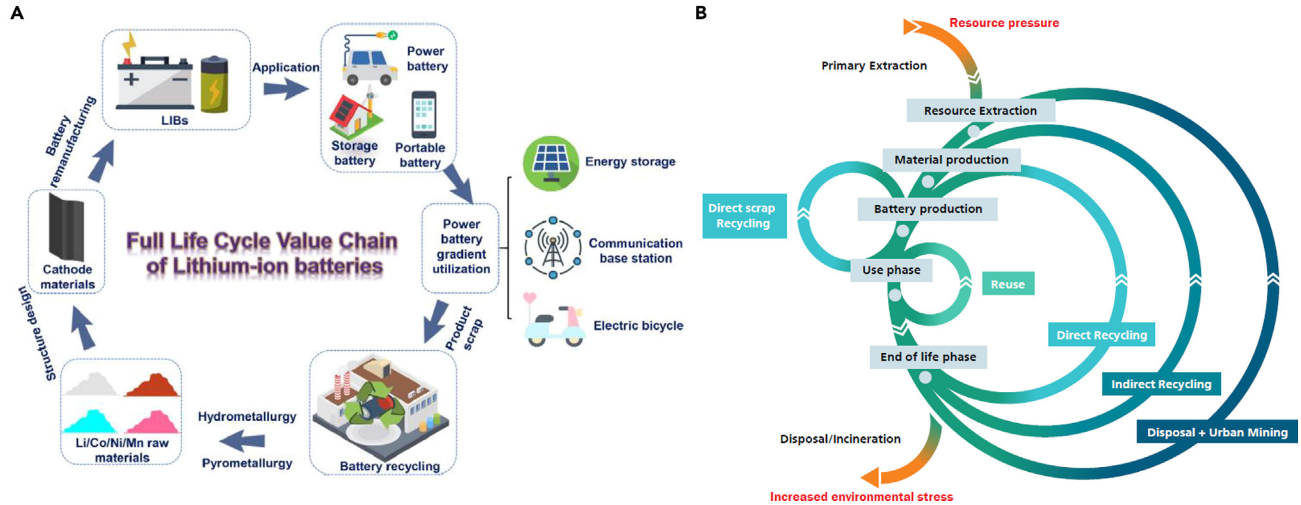

Figure 1. Developments of the battery

(A) Life cycle chain of LIBs. Copyright 2023, Elsevier, Reproduced with permission.[9]

(B) The circular economy of waste LIBs. Copyright 2023, Elsevier, Reproduced with permission.[11]

recycling technologies, policies, prospects and challenges is conducted. In this work, the significance of battery recycling, policies, and strategies are emphasized in Section 2, and techniques, challenges of recycling are considered in Section 3 and Section 4, respectively. Besides, the recycling policies and strategies of the EU, USA, and China are summarized to provide legal support and policy protection for the recycling industry. By comprehensively reviewing the recycling technologies and conducting a comparative analysis of approaches, valuable insights into the current status and distinguishing features of various recycling methods can be obtained. It provides some perspectives for the development and innovation of recycling technologies.

SPENT BATTERY RECYCLING AND STRATEGIES

Effects of battery recycling

Batteries achieve extensive applications across diverse fields, including electricity, transportation, and daily living, as depicted in Figure 2A.[20] The widespread adoption of batteries is driven by the need to address the detrimental effects of oil-based transportation and associated exhaust emissions, which are significant contributors to global warming and the heightened strain on natural resource availability.[7] Nevertheless, the average service life of batteries is typically limited to 4–6 years, leading to a significant accumulation of waste stockpiles primarily due to inadequate disposal practices, as illustrated in Figure 2B.[21] It is worth noting that China is projected to generate over 45,000 tons of discarded batteries by 2025, with a total weight exceeding 50,000 tons.[22] This statistic underscores the immense potential and prospects within the waste battery industry. However, due to the increasing demand for batteries, the market necessitated over 100 kilotons of Li materials in 2020.[23] So, the reuse of spent batteries is one significant approach to address the large demand of raw materials for manufacturing, as indicated in Figures 2C and 2D.[24] Hence, it becomes imperative to put forth an efficient and environmentally friendly approach to battery recycling.

An effective closed-loop recycling chain is illustrated in Figures 1A and 1B, where valuable materials are recycled in battery gradient utilization.[9] The improper handling of batteries, in turn, has adverse impacts on both human beings and the environment. Notably, the toxic chemical substances of batteries lead to pollution of soil, water, and air, consequently jeopardizing human health and the ecological equilibrium.[26] Hence, recycling of waste battery is an urgent matter. Besides, the waste battery recycling industry, through processes involving sorting, extraction, and reuse of valuable metals, not only generates employment opportunities and drives economic development, but also reduces the manufacturing costs of new batteries and enhances the overall sustainability of the battery industry.[27] Consequently, waste batteries harbor valuable resources such as Li, Ni, Co, Fe, and Mn (see Figure 2C), which can be effectively recycled and reused, thereby curbing the excessive exploitation and consumption of natural resources.[24] Therefore, mere disposal of spent batteries is deemed undesirable, as it fails to capitalize on the valuable elements contained within them and causes irreversible harm to the ecosystem and human population. By implementing efficient and environmentally friendly methods for battery recycling, it becomes possible to maximize the recovery of valuable materials, reduce environmental pollution, stimulate economic growth, and conserve precious natural resources. Moreover, it is advantageous for the sustainable development of the battery industry.[21]

Policies and strategies

With the global proliferation of EVs, the establishment of policies for the recycling of spent batteries has become crucial. Simultaneously, the standardization and management of the waste battery industry have been duly influenced, prompting countries to enact regulations to

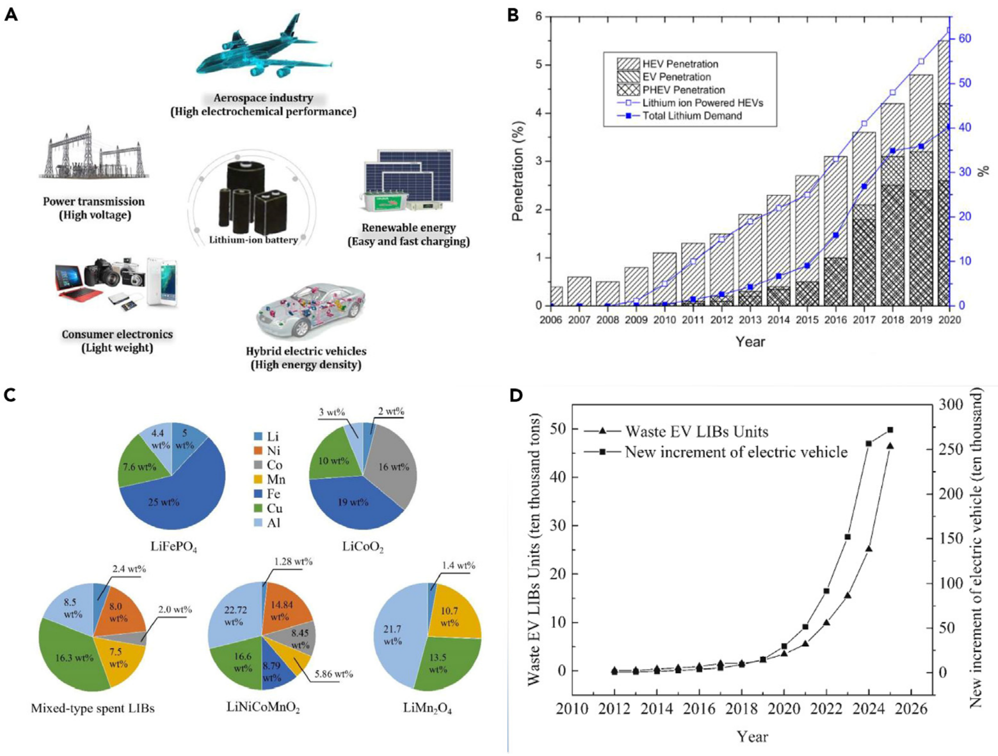

Figure 2. Current and future development of battery

(A) Application scenarios. Copyright 2021, Elsevier, Reproduced with permission.[20]

(B) Global production trends of electric vehicles. Copyright 2012, IEEE, Reproduced with permission.[25]

(C) Valuable metals in spent batteries. Copyright 2021, Elsevier, Reproduced with permission.[24]

(D) Waste batteries in China. Copyright 2017, Springer Nature, Reproduced with permission.[21]

govern the management and processing procedures of spent batteries.[28] So, an overview of pertinent policies and regulations of the EU, the US, and China as illustrative examples is presented, and the green recycling routes with high efficiency is pursued.

European Union

EU first pays attention to recycling, which has formulated special laws and regulations on waste batteries.[29] In 1991, Council Directive 91/157/EEC was issued on cells policy of waste cells and storage of batteries with Hg, Cd, and Pb.[30] The Netherlands stipulated that manufacturers and importers of mobile phone batteries must be solely responsible for collecting and producing in 1995. Then, battery retailers are obligated to recycle used cells in Denmark, Sweden, and other European countries, and they implemented a special excise tax of 6–8% on batteries sold. According to ref. 31, the recycling rate of waste batteries and mobile phone batteries has exceeded 75% in Denmark and 95% in Sweden. Germany actively implements the Waste Electrical and Electronic Equipment (WEEE) directives 2006/66/EC and 2012/19/EU, forming a legal system for waste LIBs management.[32] In 2015, the Foundation for Common Recycling System recycled 45.9% of the spent portable cells in Germany and the recycling rate of the waste LIBs reached 100%.[33] Meanwhile, in recent years, EU also has been pursuing a goal of net greenhouse gas emissions reductions of more than 55% by 2030, and additionally aims to collect 45% of portable batteries by 2023, 63% by 2027, and 73% by 2030, and 51% of LMT (Light Transportation Vehicle Batteries) by 2028, and 61% by 2031.[34]

USA

USA issued the Resource Conservation and Restoration Act (RCRA) in 1976, and established a framework for hazardous waste management.[35] Particularly, New York and California are the forerunners of the US in LIBs recycling.[36] In 2006, California Battery Recycling Act (AB1125) was enacted, requiring the establishment of a battery collection system for multi-purpose rechargeable batteries to recover and legally reuse retired rechargeable batteries.[37] An unprofitable social service agency, USA "Rechargeable Battery Recycling Corporation", is established and responsible for operating spent battery recycling.[38] Moreover, the USA also introduces the awareness of WEEE management to education, which is conducive to the development of waste battery management.[36] In particular, California is planning to end the sale of gas/diesel-fueled cars by 2035. Besides, owing to the rapidly increased EVs, the "Battery Safety Initiative for Electric Vehicles" in 2023 mandates that data related to EV batteries is collected to understand safety-related battery defects and improve the safety of EVs.[39]

China

In 2003, China unveiled some recycling policies for pollution prevention, and the pollution prevention and management measures of WEEE were proposed in 2008.[40] Four stages of electrical waste management, the informal manual disassembly stage (1980–2000), recycling pilot stage (2001–2008), development stage (2009–2020) and maturity stage (2020-), were introduced. In 2016, a comprehensive responsibility system for battery manufacturers was issued, where a network of battery collection and recycling was required.[41] Besides, collection, classification, transportation and recycling technologies of waste batteries and prioritized recycling were in operation. In 2018, pilot programs for the recycling and utilization of new energy vehicles were launched.[42] Then, the nationwide pilot projects were established, and the decommissioned batteries were classified, tested, repaired, reproduced, and used for national energy storage projects. In particular, China has established "Administrative Measures for the Recycling of Power Storage Batteries for New Energy Vehicles" due to the augmentation of recycling rate of spent batteries, so the development of common recycling for spent batteries is improving.[43]

Section summary

EU, USA, and China are actively formulating waste LIBs recycling policies and standardizing the system and process of waste battery recycling. Table 1 summarizes the policies and measures of these countries on waste battery recycling in recent years. The formulation of battery recycling policies by countries holds significant importance in several aspects and has a profound impact on achieving zero carbon emission targets. First, implementing battery recycling policies helps address the environmental challenges associated with the disposal of spent batteries. Battery waste contains hazardous materials that can harm the ecosystem and pose risks to human health if not properly managed. By establishing robust recycling policies, countries can effectively manage and mitigate these environmental risks, reducing pollution and promoting a sustainable approach to battery disposal. Second, it contributes to the conservation of natural resources, so countries can recover these valuable materials from spent batteries, reducing the reliance on raw material extraction and minimizing the depletion of natural resources. Furthermore, battery recycling policies play a crucial role in achieving zero carbon emission targets. The widespread adoption of EVs is a key strategy for transitioning to a low-carbon transportation sector. However, the production and disposal of batteries contribute to the overall carbon footprint of EVs. By establishing comprehensive recycling policies, countries can assure that end-of-life batteries are managed in a standardized recycling process to improve efficiency, minimizing greenhouse gas emissions associated with battery production and disposal. This, in turn, supports the overall goal of achieving zero carbon emissions in the transportation sector.

In summary, the development and implementation of battery recycling policies hold significance in addressing environmental challenges, conserving natural resources, regulating of the recycling process with less pollution and power consumption, improving of the recycling efficiency, and contributing to the achievement of zero-carbon emission targets, particularly in the context of transitioning to a sustainable and low-carbon future.

RECYCLING TECHNIQUES

Regarding battery recycling, the general process is as follows. First, the examination, testing, and recharging of waste batteries are performed using specialized instruments and equipment, enabling their direct utilization as secondary batteries.[60] Second, recycling technologies are implemented to extract valuable materials from batteries through processes such as dismantling, dissolution, and extraction, followed by their subsequent reutilization or remanufacturing.[61] Also, recycling technologies are emphasized in the section.

Recycling category

With the variational focus on energy power and the development of battery technology, EVs are the emergent and popular forms of transport, and are also the main contributors to the rise in the number of waste battery.[62] Spent battery is recycled to achieve secondary employment of valuable metals, and the pressure on the mining of raw materials for batteries is relieved.[10] Presently, battery recycling technologies are classified according to different criteria as outlined in Figure 3, such as, direct recycling[63] and indirect recycling.[64] The former is classified according to the different principles and methods applied to the treatment of waste, while the latter is divided depending on whether the battery is completely dismantled during the recycling process.[65] Then, physical recycling technology,[66] chemical recycling technology,[67] and biological recycling technology[68] are analyzed according to the properties. Also, it is extensively employed in the recycling of waste batteries. Lastly, integrated recycling technologies are described,[41] in order to understand their characteristics. Consequently, recycling technology is a key step in the secondary application of spent battery, and learning about the characteristics of various recycling methods is a prerequisite for efficient and green recycling of waste battery.

Dismantling classification

Direct recycling

Spent battery can be classified into direct and indirect recycling depending on whether the recycling process is completely dismantled or not.[63] Direct recycling is the process of collecting and sorting waste batteries, physical treatment, material recovery, and disposal of waste residues to extract and recover valuable metals and other recyclable materials from waste batteries. This is a simple approach to battery recycling that allows direct access to LIB active materials without disassembly.[69] Waste battery is recycled via peeling, shell removal, separation, and other steps, where physical separation, magnetic separation, and moderate heat treatment are mainly adopted to recover the most spent battery. Jiang et al.[70] found that LiOH-Li_2CO_3 eutectic molten salt can be applied to $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ in direct regeneration, which is

Table 1. Policies and measures for recycling used batteries

Nation	Year	Name	Outline
EU	2000	Instruction 2000/53/EC	• Dismantling, recycling vehicles
	2006	Directive 2006/66/EC	• Definition minimum collection objective, recycling objective and recycling rate • Outspreading producer duty for cell producers and importers[44]
	2012	Instruction 2012/19/EC on WEEE	• WEEE action according to the rule of prevention, restoring and safety disposal[45]
	2013	Instruction 2013/56/EU	• Limit the usage of Cd and Hg in portable cells[46]
	2016	Instruction (06/66/EC)	• Recycling rate of spent cells from 25% up to 45%[31]
	2018	Instruction 2018/851	• Recommendation circular economy[47]
			• Achieving collection efficiency and recovery rate[46]
	2021	Fit for 55	• Net reduction in greenhouse gas emissions surpassing the intermediate target of 55% by 2030[48]
	2022	Batteries: deal on new EU rules for design, production and waste treatment	• Collection targets are set at 45% by 2023, 63% by 2027 and 73% by 2030 for portable batteries, and at 51% by 2028 and 61% by 2031 for LMT[34]
	2023	Revision of Directive 2010/75/EU on industrial emissions (REFIT)	• Excluding assembly of battery cells and battery packs from the scope of the directive[49]
USA	2006	California Cell Recycling Act	• Establishing a system for collecting, recycling and proper legal disposal[37]
	2010	New York rechargeable cell law	• Providing free rechargeable batteries by manufacturer[50]
	2014	Vermont main single-use cell law (Act 139)	• Landfill of Ni-Cd and lead-acid batteries prohibition • Subsidy collection and recycling of waste cells[51]
	2018 2019 2022	California AB-2832 Recycling: Lithium-Ion Assembly Bill 2832 The American Battery Materials Initiative Battery Safety Initiative for Electric Vehicles	• Cost-efficient recycle or recovery of 100% waste LIBs[52] • Convening the Lithium-Ion Car Battery Recycling Advisory Group • First lithium-ion US battery recycling regulation • Accelerating the development of the full end-to-end battery supply chain
	2023	New Source Performance Standards Review for Lead Acid Battery Manufacturing Plants and National Emission	• Minimizing emissions of fugitive lead dust, • Making lead-bearing battery parts or process input material, including but not limited to grid casting facilities[53]
	2023	Battery Safety Initiative for Electric Vehicles	• Collecting and analyzing data related to EV batteries • Investigating safety-related battery defects[39]
China	2015	Electric vehicle power cell recovery technology policy	• Principle of power cell recycling[54]
	2016	Carrying out outstretched producer duty system	• Spent cell collection and recycle network • Establishment of monitoring system[55]
	2017	Regulations for new energy vehicle products	• Promoting the secondary utilization of waste batteries[55]
	2019	Guides for Automobile LIBs recycling service	• Collecting and transporting waste cells for cascading usage or recycling[56]
	2020	Industry Standards for Comprehensive Utilization of Waste LIBs in Automobiles	• Ni, Co, Mn $\geq$ 98%, Li $\geq$ 85% and waste water recovery efficiency $\geq$90%[57]
	2021	Management of power storage battery utilisation for new energy vehicles	• Adoption of structures and connections are easy to maintain, dismantle and disassemble, facilitate their dismantling, disassembly and recycling at the end of their lives[58]
	2022	Accelerating the study and formulation of management measures for the recycling of power storage batteries for new energy vehicles	• Trapezoidal batteries for rent instead of sale, Waste for raw materials[59]
	2023	Administrative Measures for the Recycling of Power Storage Batteries for New Energy Vehicles	• Development of common recycling standards for spent batteries • Improving the recycling system of waste batteries[43]

effective in direct regeneration of waste cathode material. Besides, Shen et al.[71] investigated the environmental impact associated with the direct recycling of lithium batteries produced in a closed loop compared to traditional open-loop battery manufacturing, and the results show a 54% reduction in environmental effects. Figures 4A and 4B demonstrate the process of adopting a direct recycling method to recover the spent $LiFePO_4$ battery. As a result, damage to the chemical properties of the active substance is avoided.[62] Unfortunately, the purity of the active materials gained is poor, which is not conducive to further processing and manufacturing.

Indirect recycling

Indirect recycling refers to the secondary utilization or re-treatment of waste battery before valuable materials are derived from them.[64] A significant proportion of recycled batteries are directly reusable, as illustrated in Figures 4C and 4D. Compared to the direct recycling process, indirect recycling process provides dismantling. Meanwhile, it usually includes the following methods: Battery recharging, where some types of spent battery (i.e., Cd-Ni and Ni-Cd-MH battery) are recharged to prolong their lifespan. Hu et al.[72] demonstrated that decaying Li-MnO_2 battery can be employed as a rechargeable Li-air battery, and it is possible to extend its lifetime. Besides, Li et al.[73] proposed a green, effective, and simple method to recover spent $LiFePO_4$ battery, i.e., combining the $LiFePO_4$ battery charging mechanism with the slurry electrolysis process. The results indicate that the re-synthesized $LiFePO_4$ provides better and stable cycling properties. Battery remanufacturing, where useful parts of spent battery are disassembled, separated and reassembled to make a new battery or battery pack, as depicted in Figure 4E. Kampker et al.[61] proposed a new framework where individual battery cells and battery systems are treated as a core for remanufacturing, resulting in the complete recovery of the residual value for secondary usage. Energy recovery, where the chemical energy in spent battery is converted into electrical or thermal energy for other applications. Moreover, Dougal et al.[74] analyzed the performance of an automatic energy recovery and consolidation system for waste batteries, and found that the system is capable of recovering most of the energy in waste batteries. Other recycling, where other beneficial materials from waste battery are retrieved and recycled, i.e., plastic casing, electrolyte liquid, etc. These methods enable a reduction in environmental pollution and energy savings. Hou et al.[64] adopted direct and indirect methods to recover expired oxytetracycline and active material for the anode of LIBs, and found that the carbon material is obtained by the indirect recycling method with a wider range of applications. Nevertheless, direct recycling is more commonly employed in industrial recycling than indirect recycling due to its simplicity, lower cost and suitability for large-scale recycling.

Section summary

Direct recycling is a simple and cost-effective approach to recycling spent batteries as a whole, offering a wide range of applications and a high recyclability rate. The important step in indirect recycling, as opposed to the direct recycling process, is achieved by dismantling spent batteries and then recycling them in a targeted manner. It is characterized by fine resource recovery, environmental friendliness, and high technical requirements. The former is ideal for large-scale recycling, while the latter is applicable to the recycling of specific types of used batteries. Therefore, according to the type, scale, and recycling requirements of waste batteries, suitable recycling methods can be selected to maximize resource recycling and environmental protection of waste batteries.

Property classification

With the advancements in technology, numerous techniques have emerged for the recycling of spent batteries. These techniques involve the separation of different battery components using suitable recycling methods, achieved by studying and comparing the characteristics of various recycling approaches. The objective is to obtain valuable metallic materials through efficient, cost-effective, and environmentally-friendly methods.[75] The following section provides an overview of several recycling techniques.

Physical recycling

Physical recycling technology refers to a manual approach that encompasses the separation, sorting, and screening of waste batteries through physical methods, thereby isolating valuable substances from the battery.[76] This technique involves the application of physical properties, such as size, density, and magnetic properties, to separate different components and recover reusable materials.[66] For instance, physical recovery technology is employed to recover metals, plastics, and other valuable materials from spent batteries. The devices utilized in the application of physical recovery technology are summarized in Figure 5, which include the wet impact crusher, low-temperature ball mill, magnetic roller, modified crusher, and centrifuge to achieve the efficient separation and extraction of different components.[77] The wet impact crusher is a blade breaking machine where water is applied as a medium. It uses the vanes to break the battery, and the injection of water to form a slurry to take away the crushed particles by using the screen plate.[78] Moreover, a cryogenic ball mill combines mechanical forces and a cooling system, which adopts low temperatures for the ball milling of spent batteries.[79] Magnetic rollers provide separation by means of the vortex and centrifugal forces generated, which take advantage of the differences in density and size of the materials.[80] Compared to wet impact crushers, improved crushers require nitrogen charging of the transition and crushing chambers to expel oxygen or moisture and do not require electrical discharge.[81] Furthermore, falcon centrifuges employ centrifugal force and gravity to separate and screen materials from spent batteries.[82] Hence, physical recycling technology equipment can effectively treat used battery, separating the valuable substances from them and providing a basis for subsequent reuse.

A typical process for physical recycling technology is illustrated in Figures 6A and 6B, specifically highlighting the steps of ultrasonic cleaning and the recovery of the anode material.[83,84] In the ultrasonic cleaning process, the cathode material is separated from the

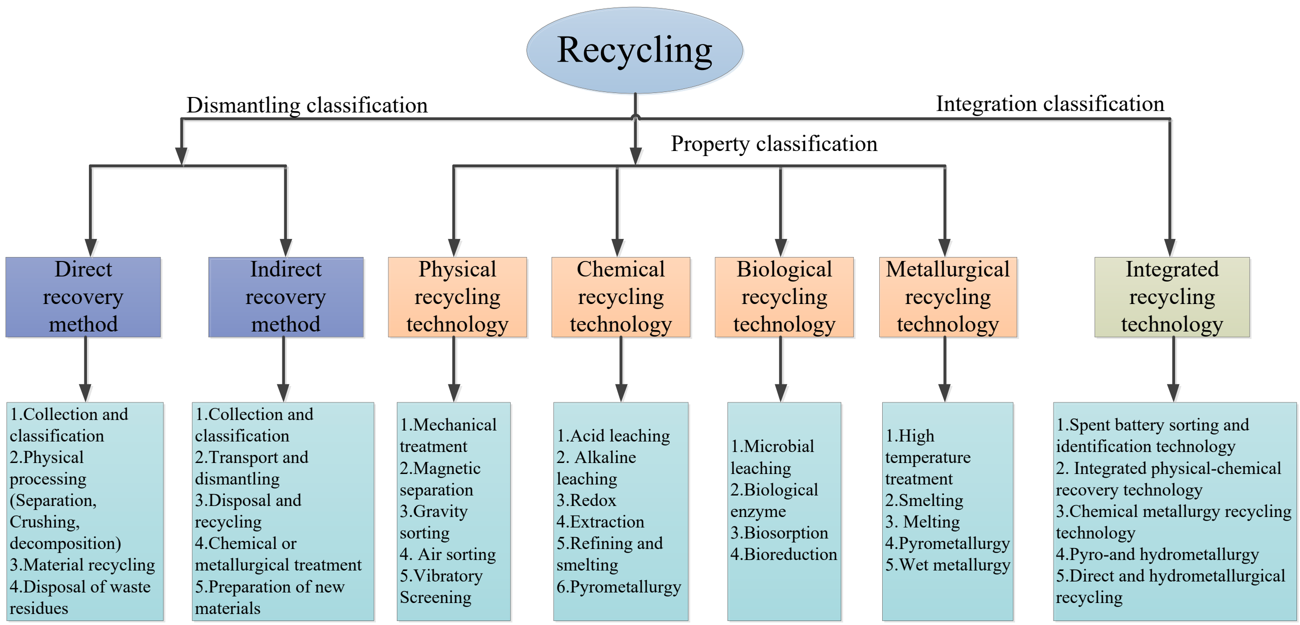

Figure 3. Spent batteries recycling technology classification depending on dismantling, property and integration

aluminum foil.[60] The application of ultrasound enhances the dissolution rate of polyvinylidene fluoride (PVDF) by facilitating solvent convection, thereby improving the efficiency of cathode material stripping. He et al.[83] studied the separation and recovery of spent battery cathode materials via ultrasonic cleaning, where the mechanism of separation is revealed to be the dissolution of PVDF and ultrasonic cavitation. As depicted in Figure 6A, the cavitation phenomenon is demonstrated during ultrasonic cleaning.[85] However, the subsequent process of battery recycling involves the dismantling, separation and analysis of the active material of spent LIBs. For example, Blankemeyer et al.[86] examined battery pack designs from multiple manufacturers, identifying connecting elements to characterize them, and the results influence the prospects for automation and propose an automated disassembly solution. Zhu et al.[87] proposed a combination of pneumatic separation and froth flotation. The results indicate a Cu recovery of 92.08% and an Al recovery of 96.68%. An experimental study of spent LIBs employing the dry and wet crushing method was described by Zhang et al.[78] The particle size distribution is analyzed and the crushed products are characterized by X-ray diffraction (XRD). Figure 6B depicts the application of physical technology to the waste battery recycling process, i.e., the stages of discharge, disassembly, separation, high temperature calcination, dissolution, leaching and filtration. A portion of the recovered material is quantified for metal content by inductively coupled plasma–atomic emission spectrometry (ICP–AES).[66,88] Furthermore, XRD is used to characterize the active substances in the residues (see Figure 6B).[70] These processes perform an important role in physical recycling technology, where the ultrasonic cleaning and battery recovery process enable efficiently stripping of materials, analysis of components and ultimately the recovery and utilization of valuable substances.

Physical recycling technology offers several advantages, including its simplicity, cost-effectiveness, environmental friendliness, and potential for large-scale automated processing. These features make it well-suited for the bulk recycling and treatment of spent batteries.[75] However, it is important to note that physical recycling techniques have certain limitations when it comes to treating hazardous substances present in spent batteries, such as organic solvents, acids, and alkalis. Consequently, achieving complete recycling of spent batteries becomes challenging.[89] Therefore, it is crucial to incorporate other recycling methods, such as chemical recycling and biological recycling techniques, to address the limitations of physical recycling techniques. These complementary technologies offer improved handling of hazardous substances and higher recovery rates for valuable materials from used batteries.[90] Considering the specific characteristics and advantages of different recycling technologies is essential when aiming to achieve optimal results in battery recycling. By integrating multiple approaches, a comprehensive and efficient recycling process can be developed.

Chemical recycling

Chemical recycling technology is the chemical separation and extraction of valuable and harmful substances from waste batteries employing chemical methods.[67] Li et al.[91] proposed a low-temperature chlorination process utilizing ammonium chloride as the chlorinating agent to recover Sn from spent lead batteries, resulting in a sodium stannate product with a remarkable total Sn recovery rate of 94%. Ma et al.[92] obtained Al and C from spent LIBs as reducing agents in the roasting process, and demonstrated that the Al-C reduction roasting method exhibits higher efficiency compared to the conventional C reduction roasting method. Zhu et al.[93] achieved the preparation of high purity

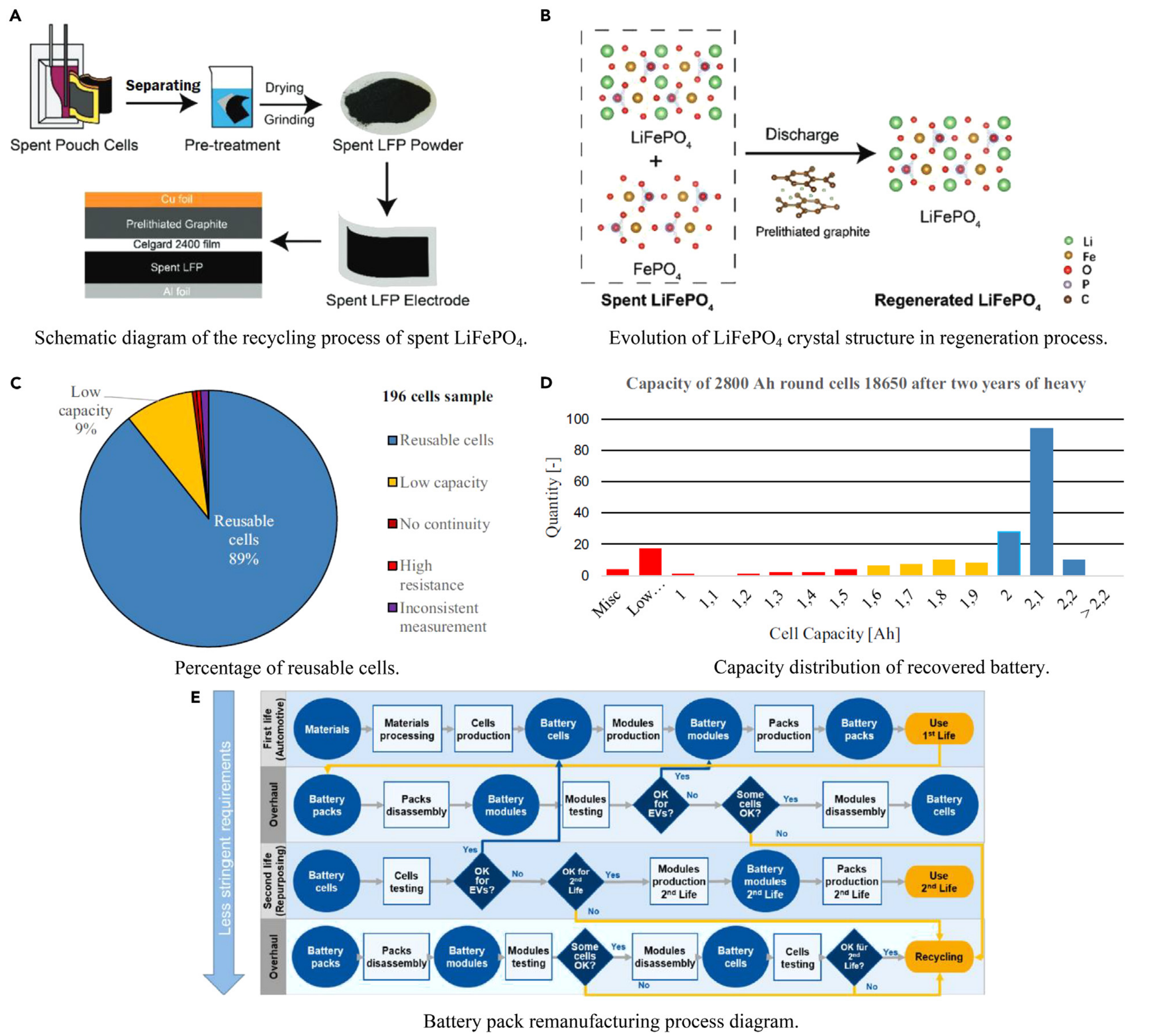

Figure 4. Direct and indirect recovery technologies

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(C–E) Copyright 2023, Springer Nature, Reproduced with permission.[63].

graphite for LIBs by employing efficient detoxification of waste carbon residues from spent batteries through constant pressure acid leaching technology. Tran et al.[94] applied a deep eutectic solvent recovery method for LIBs, resulting in leaching efficiencies exceeding 90% for both Co and Li. These methods, including hydrogenation, reduction roasting, chlorination, acid leaching, and solvent methods, are well-established in the literature.[95] The recovery process by chemical approaches (chlorination, acid leaching, solvent method) is exhibited in Figures 6C and 6D. Reduction roasting is applied in the recycling of spent battery to recover valuable metals such as Ni, Co, Li, etc., which are based on the reduction reaction of metal oxides at high temperatures.[96] Waste batteries are pre-treated and the cathode material in them (i.e., the cathode material in nickel hydride battery, LIBs) usually contains metal oxides such as NiO, CoO, MnO_2, etc.[12] During reduction roasting, waste battery or its dismantled positive material is contacted and reacted with reducing agents (i.e., carbon, hydrogen, etc.) at high temperature. Under high temperature conditions, the reducing agent is capable of reacting chemically with the metal oxide, which reduces the metal oxide to its corresponding metal (see Figure 6C).[97] Moreover, the acid leaching method is performed by removing the external packaging and non-metallic parts after pretreatment. Then, the waste battery is placed in an acidic solution (i.e., sulfuric acid, hydrochloric acid, etc.) for soaking or stirring 100. Further, the pH of the solution, temperature and other chemical additives are adjusted to promote the precipitation or crystallization of the target metal, which leads to a pure valued metal, as presented in Figure 7.[99] A simple solvent method for the

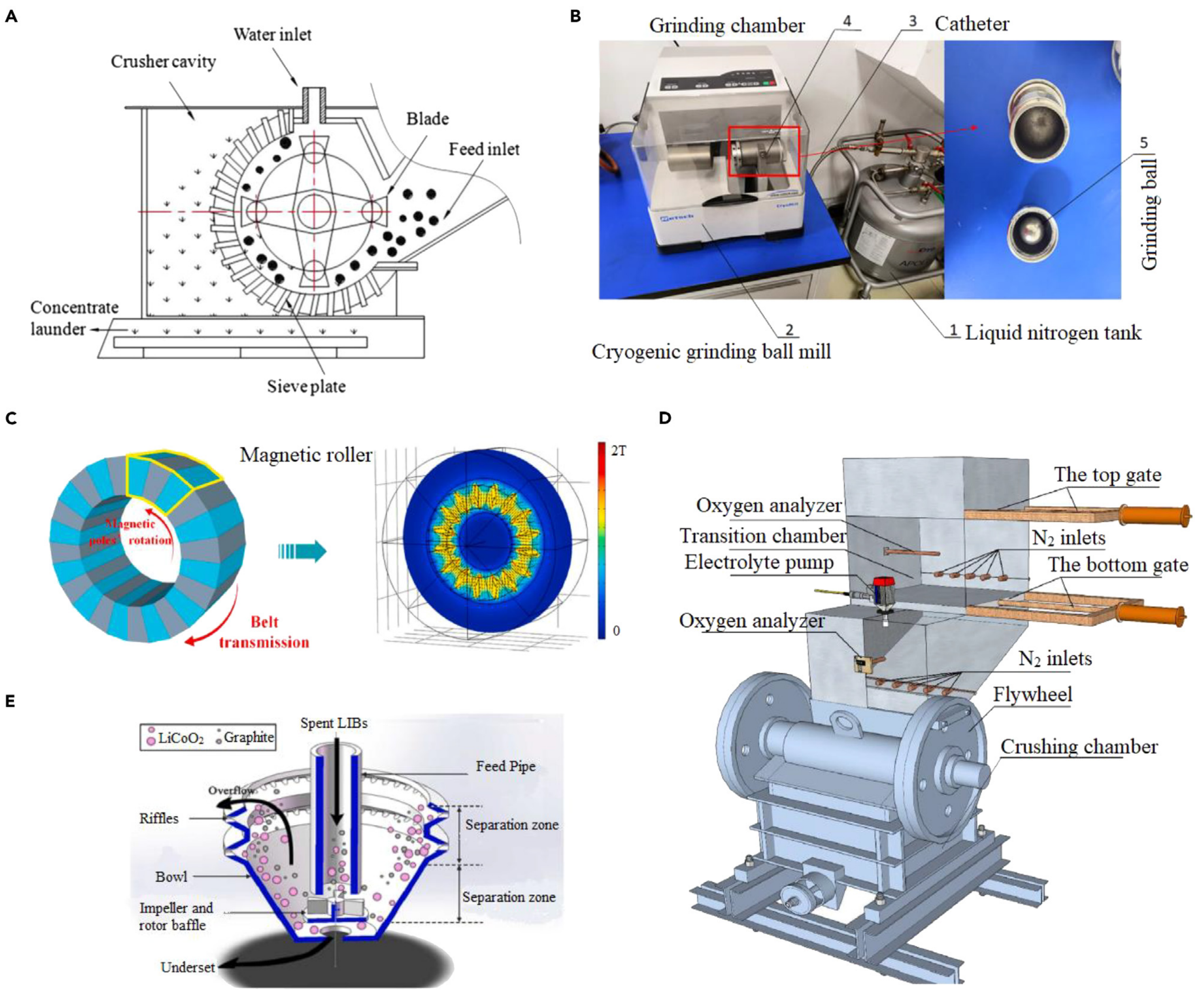

Figure 5. The equipment applied to physical recovery

(A) Wet impact crusher structure. Copyright 2013, Elsevier, Reproduced with permission.[78]

(B) Diagram of the cryogenic ball mill and grinding room. Copyright 2020, Elsevier, Reproduced with permission.[79]

(C) The magnetic rollers (left) and magnetic flux density distribution (right) on the horizontal circular roll vortex separator. Copyright 2021, Elsevier, Reproduced with permission.[80]

(D) The refitted crusher. Copyright 2020, Elsevier, Reproduced with permission.[81]

(E) Centrifugal machines. Copyright 2023, Elsevier, Reproduced with permission.[82]

recovery of $LixCoO_2$ from spent LIBs As depicted in Figure 6D.[89] The spent LIBs are manually dismantled to gain fragments of $LixCoO_2$ cathodes combined with Al foil, which are poured into an organic solvent. The $LixCoO_2$ waste is stirred vigorously at room temperature until it is completely removed from the Al foil.[85] By this time, the PVDF, dissolved in the solvent, is filtered and screened by crushing using ethanol and a sieve, respectively. Subsequently, the obtained $LiCoO_2$ scrap is subjected to heat treatment at various temperatures (1 h), that is 250°C, 300°C and 350°C.[100] Then, the final powder is mixed in different proportions with the obtained $LixCoO_2$ using S powder to gain a homogeneous powder mixture.

Chemical recycling technology is distinguished by its ability to effectively treat and eliminate hazardous substances from used batteries, while facilitating the efficient extraction and recovery of valuable materials.[101] However, it should be noted that chemical recycling techniques necessitate the consumption of significant quantities of chemicals and the handling of potentially harmful byproducts such as chemical wastewater and gases, which necessitate appropriate disposal methods and adherence to stringent environmental regulations.[6] The implementation of chemical recycling methods must be accompanied by robust waste management practices to mitigate any potential environmental impacts associated with the treatment and disposal of chemical waste products.

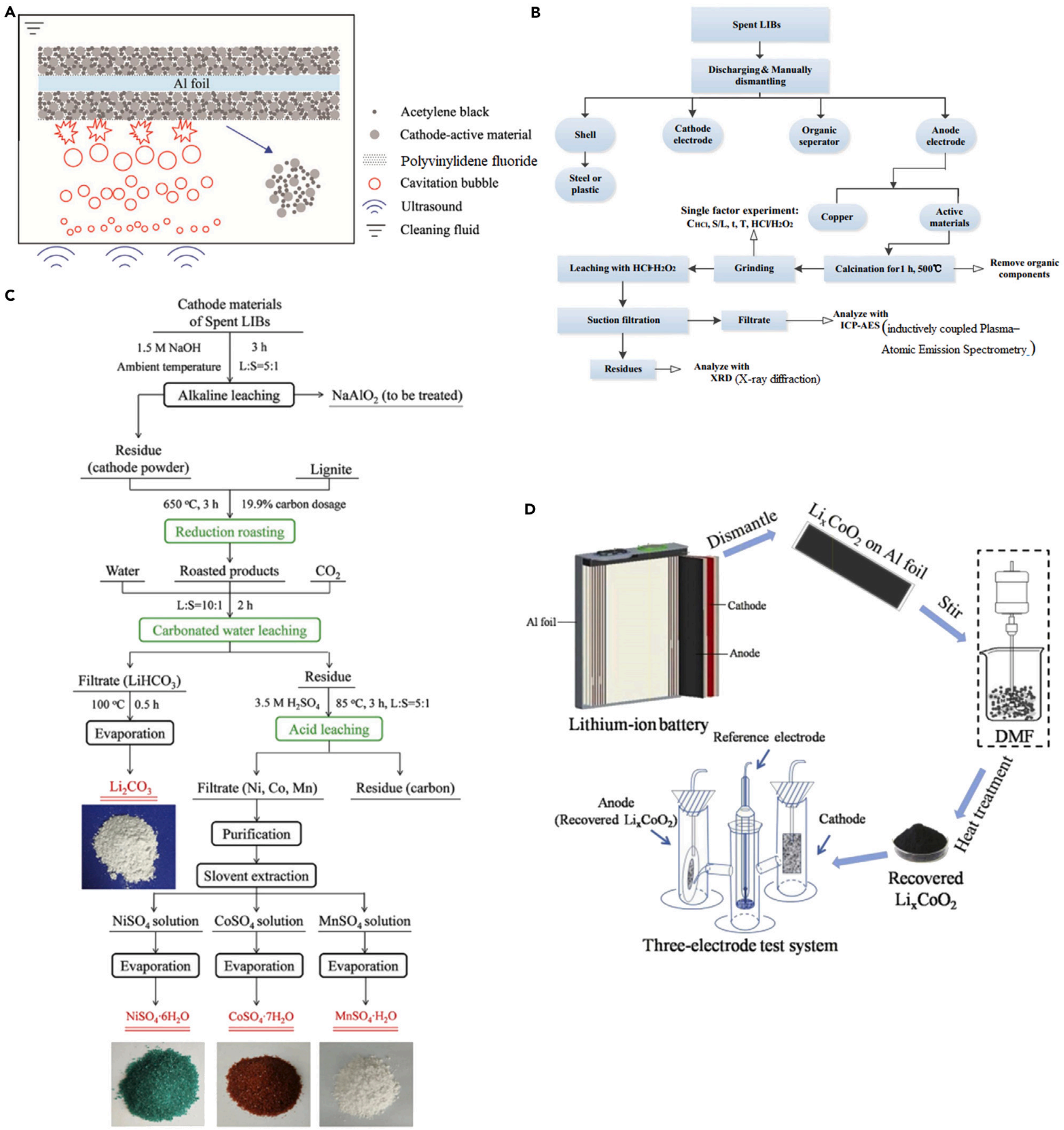

Figure 6. Physical and chemical recycling approaches

(A) Diagram of cleaning using ultrasound. Copyright 2015, Elsevier, Reproduced with permission.[83]

(B) Process flow diagram for the physical recovery of spent lithium battery cathode material. Copyright 2016, Elsevier, Reproduced with permission.[84]

(C) Reduction roasting process flow chart for recovery of valuable metals. Copyright 2017, Elsevier, Reproduced with permission.[97]

(D) The flow chart of the Li_xCoO_2 recovery process using the simple solvent method. Copyright 2014, Elsevier, Reproduced with permission.[100]

Biorecycling

Biorecycling is currently in the early stages of research and exploration in the domain of battery recycling, with limited practical implementation and adoption in actual production settings.[102] Echavarri-Bravo et al.[103] conducted a study to investigate the metal durability and metal

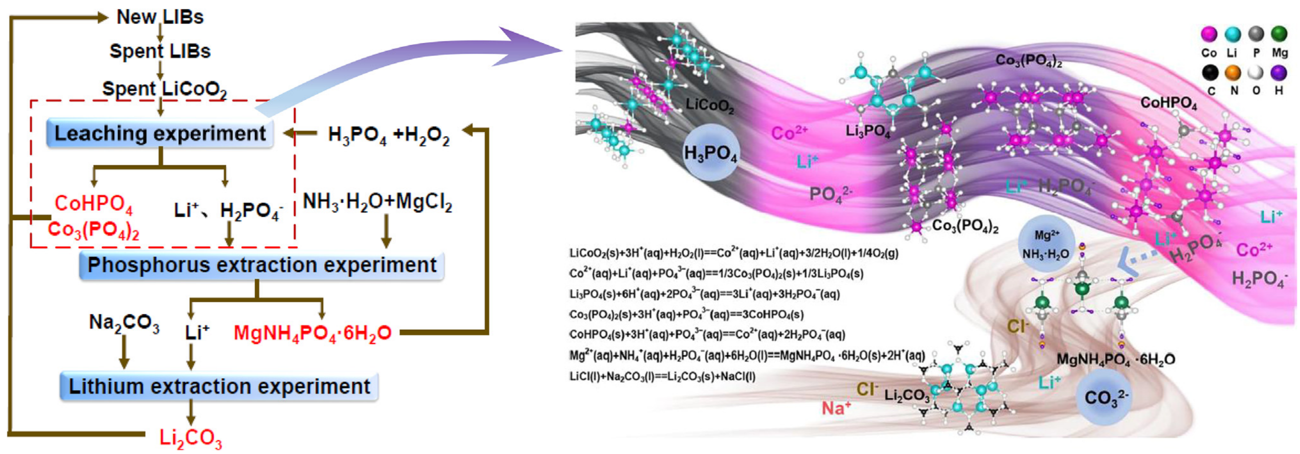

Figure 7. The acid-metal reaction process in the chemical recycling of valuable metals and the associated mechanisms

bioavailability reduction capabilities of two distinct strains of Desulfovibrio and Morganella. Nonetheless, the potential applications of biorecycling technology in battery recycling are promising. For example, the utilization of microorganisms or enzymes to degrade organic substances of batteries, the breakdown of battery casing materials, and the separation of metal components are among the prospective avenues.[104] One notable approach involves the use of *Aspergillus niger* to enhance bioleaching efficiency. Bahaloo-Horeh et al.[105] investigated the adaptation of metal-tolerant *Aspergillus niger* for enhancing the bioleaching process of valuable metals from spent LIBs. The research demonstrated the beneficial impact of fungal metabolites on the leaching of metals from waste LIBs. Figure 8 presents a comprehensive depiction of the multi-phase reaction involving bio-organic acids and metal particles, along with the original powder and surface morphology of the residue post-leaching.[106] Although biorecycling technology faces numerous challenges and limitations, that is, materials complexity,[107] recycling efficiency and rate,[108] biological adaptability,[109] it presents an opportunity to recover and reuse resources by leveraging the natural capabilities of microorganisms in breaking down and transforming the various components of waste batteries.[68] Furthermore, biorecycling technologies have the potential to offer lower environmental impact and energy consumption compared to conventional physical and chemical methods.[110]

The application of biorecycling technology holds promise for the effective biodegradation of organic substances in used batteries, eliminating the need for chemical agents, facilitating the efficient recovery of valuable materials from spent batteries.[105] However, it is important to note that biorecycling technology imposes stringent demands on operating conditions and the adaptability of microorganisms. Meanwhile, technology maturity,[103] complexity of recovered substances,[104] industry scaling, economic viability,[102] environmental influence,[111] and policy support of biorecycling technology are challenged. Furthermore, the maturity and stability of the technology still require further improvement and development to be fully viable and reliable for large-scale implementation. So, further studies and advancements in biorecycling methods hold significant potential for the sustainable and environmentally friendly recycling of waste batteries.

Metallurgical recycling

Metallurgical recovery technology typically accomplishes through high-temperature treatments, smelting, and melting techniques aimed at isolating metals from waste and obtaining reusable metal materials,[112] while encompassing the application of physical and chemical principles derived from metallurgical processes.[102] This technology, also referred to as integrated physical-chemical recycling, relies on the underlying concept. Notably, hydrometallurgy and pyrometallurgy are widely employed metallurgical recovery technologies.

Hydrometallurgy. In recent years, hydrometallurgy has experienced significant growth as a viable technology for reclaiming Ni, Co, and Li from waste LIBs.[113] This method offers several advantages, including high recovery efficiency, low energy consumption and cost, and minimal impurities and harmful gas emissions. As a result, it is widely regarded as an ideal approach for waste LIBs recovery and has been globally implemented.[114] The hydrometallurgical recovery process typically involves pretreatment, leaching, metal recovery, and other steps, as depicted in Figure 9. Hydrometallurgy entails dissolving and extracting metals from the waste in solution, followed by the separation of metal substances through precipitation and extraction. It is particularly suitable for treating waste liquids, solutions, and wastewater containing metal ions, as it achieves high metal recovery rates and purity.[115]

According to the difference in leaching agents, hydrometallurgy can be divided into various categories, including inorganic acid leaching,[117] organic acid leaching,[118] alkaline leaching,[119] deep eutectic solvent leaching,[94] and biological leaching.[68] However, it is changed by the generation of significant amounts of acidic wastewater and the production of harmful gases during electrolyte decomposition. Hence, there is a growing demand for an environmentally friendly, cost-effective, and efficient method for the industrial reclamation of LIBs.

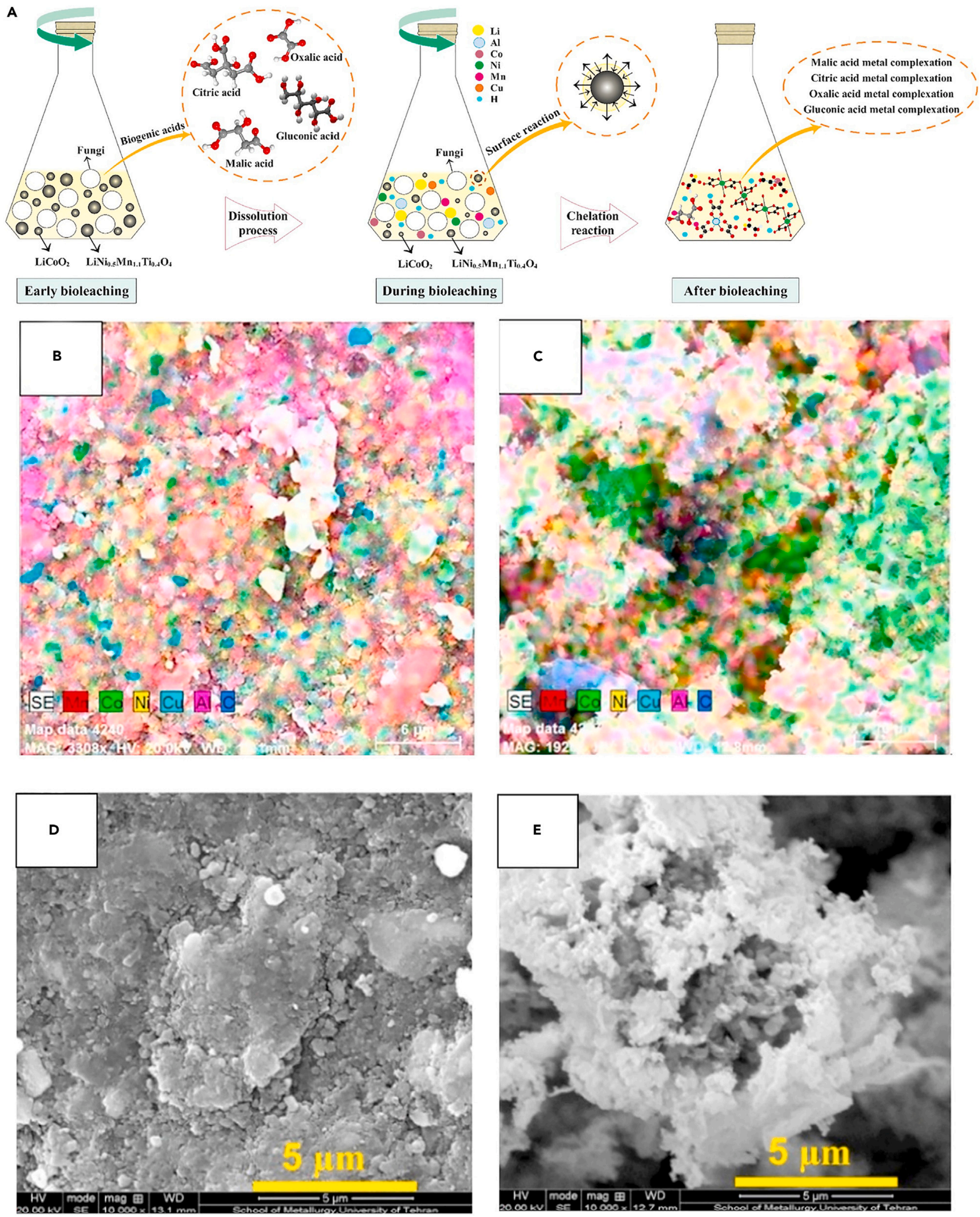

Figure 8. Bio-recycling technology

(A) Possible multi-phase reactions between bio-organic acids and lithium battery particles. Copyright 2018, Elsevier, Reproduced with permission.[105]

(B and D) Primitive powder and (C and E) surface morphology of leaching residues by biological methods. Copyright 2022, Elsevier, Reproduced with permission.[106]

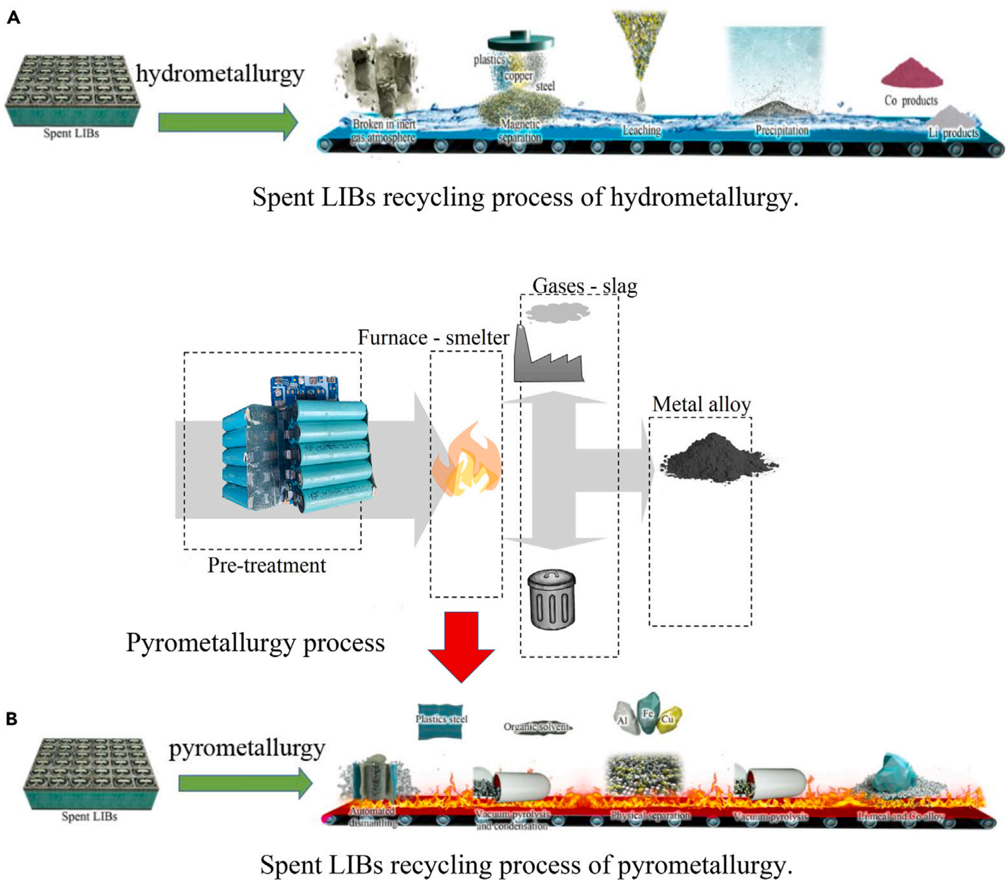

Figure 9. Hydrometallurgy and pyrometallurgy

(A) Copyright 2020, American Chemical Society, Reproduced with permission.[116]

(B) Copyright 2023, Elsevier, Reproduced with permission.[10]

Pyrometallurgy. Pyrometallurgy employs high-temperature melting to liquefy the metals present in the waste, allowing for their separation through physical segregation or chemical reactions.[120] This method is primarily utilized for solid waste materials that contain metals, particularly spent metal parts, waste batteries, and used electronics, among others. Figure 9 also depicts the process flow of pyrometallurgical applications in the industry, which involves the recovery of alloys containing Ni, Co, Cu, Fe, and some residual metal elements from waste LIBs through high-temperature treatment.[116] In particular, Co is the most crucial element in LIBs, and the technical advantages of pyrometallurgy rely on the successful recovery of Co. However, the effective retrieval of Li presents challenges due to high economic costs and energy consumption. Furthermore, the extraction of valuable elements at elevated temperatures has a specific environmental impact. Reddy et al.[121] proposed a recovery method of adding pyrolusite in smelting, where CO-Ni-Cu-Fe alloy and Li-Mn slag are obtained by reducing the waste LIBs in the MNO-SiO_2-Al_2O_3 slag system. MnO content is 47.03 wt. %, and LiO_2 content reaches 2.63 wt. %.

Metallurgical recycling technology is widely employed in the efficient separation of metal components from spent batteries, enabling effective recycling and reuse.[114] This method is well-established, technically mature, and highly feasible. Moreover, metallurgical recycling technology allows for the maximum extraction of valuable metal resources from used batteries, thereby reducing resource waste and environmental pollution.

Section summary

Various recycling technologies provide advantages and disadvantages in the recycling of spent batteries. Physical recycling techniques are characterized by their simplicity, low cost, and environmental friendliness. However, they are limited to complex battery structures and material compositions. On the other hand, chemical recycling technology demonstrates high efficiency in recovering valuable metals and chemicals from various battery types. Nonetheless, the chemical recycling process generates by-products, including waste liquids and exhaust gases, which require proper management and disposal. Biorecycling technology is still in its early stages of development and has limited applications, but it holds significant promise. Besides, metallurgical recovery technology is widely utilized in industrial settings. Nevertheless, metallurgical recovery processes carry a substantial energy and environmental burden and necessitate a careful evaluation of resource consumption and slag disposal.

The selection of the appropriate technology relies on factors, such as the battery type, recycling objectives, and environmental considerations. Further research and development of integrated recycling methods, which combine the strengths of multiple technologies, can significantly enhance the efficiency, environmental friendliness, and sustainability of waste battery recycling. Hence, it is imperative to continue investigating and developing integrated recycling methods that leverage the advantages of various technologies for the efficient, eco-friendly, and sustainable recycling of spent batteries.

Integration classification

Integrated recycling

Integrated recycling technology encompasses the sorting and identification of various types of waste batteries, followed by the utilization of combined physical, chemical and metallurgical technology for comprehensive recycling and resource recovery.[41] This approach enables the efficient and sustainable utilization of resources from diverse battery sources.

Classification and identification. The successful implementation of integrated recycling technology for waste batteries hinges upon a thorough classification and identification process, encompassing physical characteristics classification, marking and labeling identification, and chemical composition analysis.[122] So, the classification of physical characteristics relies on attributes such as shape, size, and connection method of waste batteries. And the identification and labeling of spent batteries play a crucial role in determining vital battery parameters, including resistance, capacity, voltage, composition, and other essential factors.[123] To ensure accurate battery type determination, advanced chemical analysis techniques such as mass spectrometry and elemental analysis are employed.[89,124] The comprehensive approach to waste battery classification and identification lays a strong foundation for efficient and sustainable recycling practices, contributing significantly to the field of energy conservation and waste management. Currently, classification and identification techniques such as X-ray fluorescence spectroscopy and infrared spectroscopy are employed to achieve swift and precise determination of the type and composition of spent batteries. These techniques enable rapid and accurate identification of the elemental and molecular components present in the batteries.[98] The physical characteristics of the battery, including its appearance, marking information, battery voltage, and weight, are examined. Additionally, chemical analysis techniques are employed to determine the chemical composition of the battery, such as the positive and negative electrode materials and electrolyte composition. It ultimately determines the battery's chemical type, such as Ni-Cd, NiMH, and Li-Ion batteries.[125]

The classification and identification of batteries hold immense significance and value in the battery recycling industry.[126] With the continuous development and innovation of battery technology, the emergence of new battery types, such as solid-state batteries and sodium-ion batteries, has further underscored the importance of robust classification and identification methodologies. Looking ahead, there is a clear trajectory toward achieving higher levels of accuracy and automation in this domain. Leveraging advanced sensing technology and machine learning algorithms offers the potential to develop an intelligent battery identification system, enabling automatic identification and classification, while simultaneously enhancing work efficiency and accuracy. Embracing this prospect holds promise for a more sustainable and efficient battery recycling landscape.

Physical-chemical recycling. Integrated physical-chemical recycling technology involves various processes, including mechanical crushing of waste battery, hydroxide method, ion exchange and solvent extraction, as shown in Figure 10A.[83] This approach enables the efficient extraction and recovery of valuable metals from spent batteries and exhibits promising, resulting in the treatment of challenging hazardous materials that are resistant to degradation. The advantages include the promotion of recycling practices and resource conservation, which in turn reduces the negative impact on the environment and ecosystems. However, there are certain disadvantages associated with this process, including the need for specialized equipment and technical expertise. Additionally, the generated waste or by-products may be toxic and require separate treatment and processing, resulting in increased costs.[127] Furthermore, the physical and chemical complexity of certain types of waste batteries adds complexity and difficulty to the recycling process.

Chemistry-metallurgy recycling. The application of chemistry-metallurgy in the green recycling process is depicted in Figure 10B. The green closed-loop integrated recycling technology decreases the pollution of metal salts with unreacted acid, while the acid and alkali solutions are applied to reclaim valuable metals from the cathodes of spent battery, which achieves secondary usage of waste solutions.[128] It provides the opportunity to efficiently recover valuable metals and enhance the productivity of resource usage, while confronting the shortcomings of high technical complexity and the generation of waste or by-products for proper disposal. Besides, the treatment process of spent batteries involves high temperature and high-pressure conditions, and safety and energy costs are still issues to be considered at the moment.

Pyro-and hydrometallurgy recycling. An LIBs recycling method, the Umicore VAL'EAS process, is proposed by combining pyrometallurgy and hydrometallurgy.[112] It is suitable for various battery types regardless of raw materials, specifications, and shapes, as presented in Figure 10C.

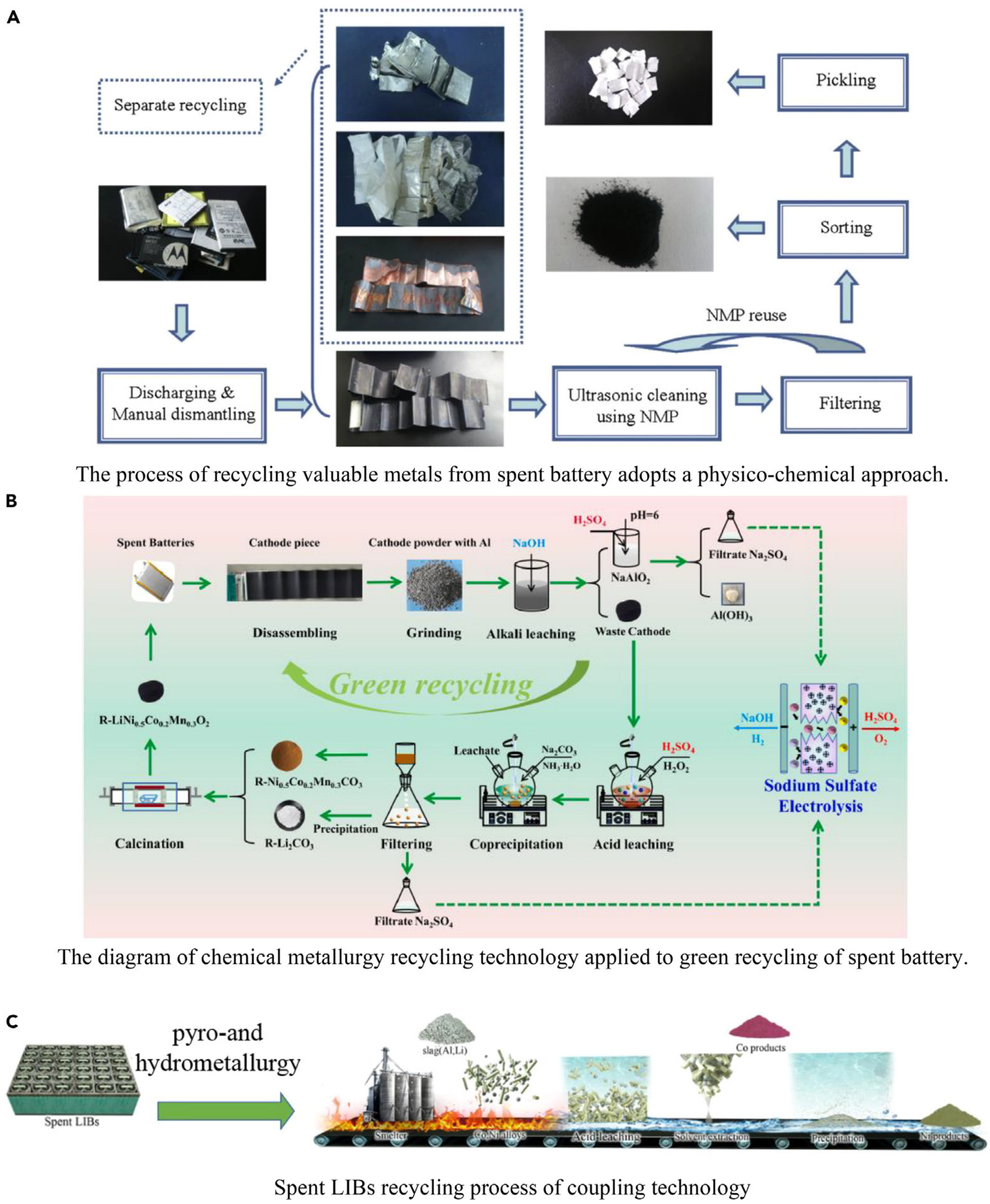

Figure 10. Integrated recycling approach

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(C) Copyright 2020, American Chemical Society, Reproduced with permission.[116]

The waste battery is crushed, graded and processed by other steps, whose high-temperature treatment is carried out via pyrometallurgy, from which valuable metal elements are recovered.[129] During the high-temperature treatment process, the metal elements are separated from the other components in the battery, and a purer metal product is obtained. Then, the pyrometallurgical products are subjected to hydrometallurgical treatment.[130] Further valuable metal elements can be extracted by leaching and other chemical reactions in this step. Meanwhile, for the heat treatment, the material change process can be categorized into three parts: the evaporation of electrolyte at about 300°C, the plastic pyrolysis at 700°C, and the reduction of remaining feed at 1200°C–1450°C.[75] Compared with other pyro-recycling processes, a significant merit is that energy can be obtained via burning waste batteries, which reduces energy consumption. Besides, a gas purification system is installed in the furnace, which collects solid dust, solid particles and reduces the emission of toxic gases and volatilization of mechanical compounds. So, safe and nontoxic filtered slag with aluminum and lithium can be obtained and applied to building materials.

Table 2. Summary of recovery approaches

Author	Cell style	Recovery approach	Outcome
Beheshti et al.[133]	LIBs	Al recycling process/secondary Al production	Al, Cu and Li
Chagnes et al.[95]	LIBs	Solvent extraction	Co, Ni, Mn and Li
Fink et al.[69]	LIBs	Roll-to-roll direct recycling	Al and Cu
Haga et al.[134]	LIBs	Leaching, solvent extraction and electro-winning	Co and Ni
Mishra et al.[112]	LIBs	Pyro-hydrometallurgy and bio-metallurgy	Li and Co
Tan et al.[75] and Treffer et al.[135]	LIBs	Pyrometallurgy and hydrometallurgy	Li, Co and Ni
Wang et al.[26]	LIBs, lead-acid batteries	Mechanochemical technology (mechanochemical activation, redox reactions, etc.)	Li, Co, Ni, Mn; Pb
Kim et al.[76]	LIBs pack	Physical treatment/chemical treatment	Co, Ni, Mn and Li
Sangwan et al.[136]	NMC batteries	Pyro-metallurgical	Co, Ni, Mn and Li
Zhao et al.[127]	$LiFePO_4$	Solvent, thermal treatment, polymer solution	Al
Zueva et al.[137]	Household cell	Polyamine flocculation	Mn and Zn
Wang et al.[12]	Lead-acid batteries	Vacuum roasting	Pb and S
Larouche et al.[131]	LIBs	Direct and hydrometallurgy recycling	Li

Direct and hydrometallurgy recycling. The direct recycling combined with the hydrometallurgical recycling approach is an integrated method to obtain a higher recycling efficiency for waste batteries.[131] As described in section 3.2.1, spent batteries are sorted and stripped to separate the battery components for direct recovery methods, where reusable parts are directly recovered. In the other hand, electrode materials are not directly recoverable and treated by hydrometallurgical recycling, while the electrode material is chemically dissolved, so that valuable metal ions are dissolved in the solution. Then, the metal ions are reduced to metal precipitates for further extraction and purification by reaction control and precipitation processes. Meanwhile, other components of the waste batteries are processed to ensure environmental friendliness. For instance, Zhang et al.[132] provided an overview of various metallurgical processes for the production of manganese from resources, particularly direct-hydrometallurgical leaching and recovery processes. The results indicate that the direct reductive leaching process is more promising. Besides, the combination of direct recovery and hydrometallurgical methods is also faced with the challenges of process optimization, environmental impact and energy consumption.

Section summary

To sum up, integrated recycling technology achieves the goals of efficient recycling, environmental protection and economic benefits of waste batteries via the integrated application of multiple recycling methods, which offers the advantages of diversity and adaptability. Table 2 presents an overview of the diverse recycling methods employed for different battery types, thereby supporting the sustainable development of the waste battery recycling industry as a crucial measure. It encompasses the recovery and treatment of both hazardous and valuable substances in waste batteries, offering a comprehensive, efficient, and environmentally friendly approach.

Summary

As the main battery application, EVs are also the primary source of waste battery. It is significant to recycle the waste battery, reduce the waste of resources and achieve goals of zero-carbon and sustainable development. The recycling technology for waste battery is outlined in Section 3. An overview of technologies for recycling waste battery is provided under various classification criteria, which compare the characteristics of various recycling technologies as summarized in Figure 11, to provide a theoretical basis for proposing a green and efficient recycling process chain. Hence, an integrated approach to recycling, combining the benefits of multiple technologies, contributes to more efficient, environmentally friendly and sustainable recycling of waste batteries.

CHALLENGES OF RECYCLING

In recent years, the market for EVs ownership is skyrocketed. The demand for battery production is increasing rapidly, while the pressure to exploit natural resources is growing. Countries have begun to pay more attention to the recycling of waste battery, nevertheless, faced with the following problems and challenges.

Technology challenges

The recycling of diverse battery types presents complex and multifaceted challenges that span various scientific disciplines, including physics, chemistry, and biology. Direct and indirect recovery methods face limitations in preserving the chemical nature of the active substances, resulting in less pure recovered materials and reduced efficiency with high energy costs, respectively. Besides, physical recycling techniques

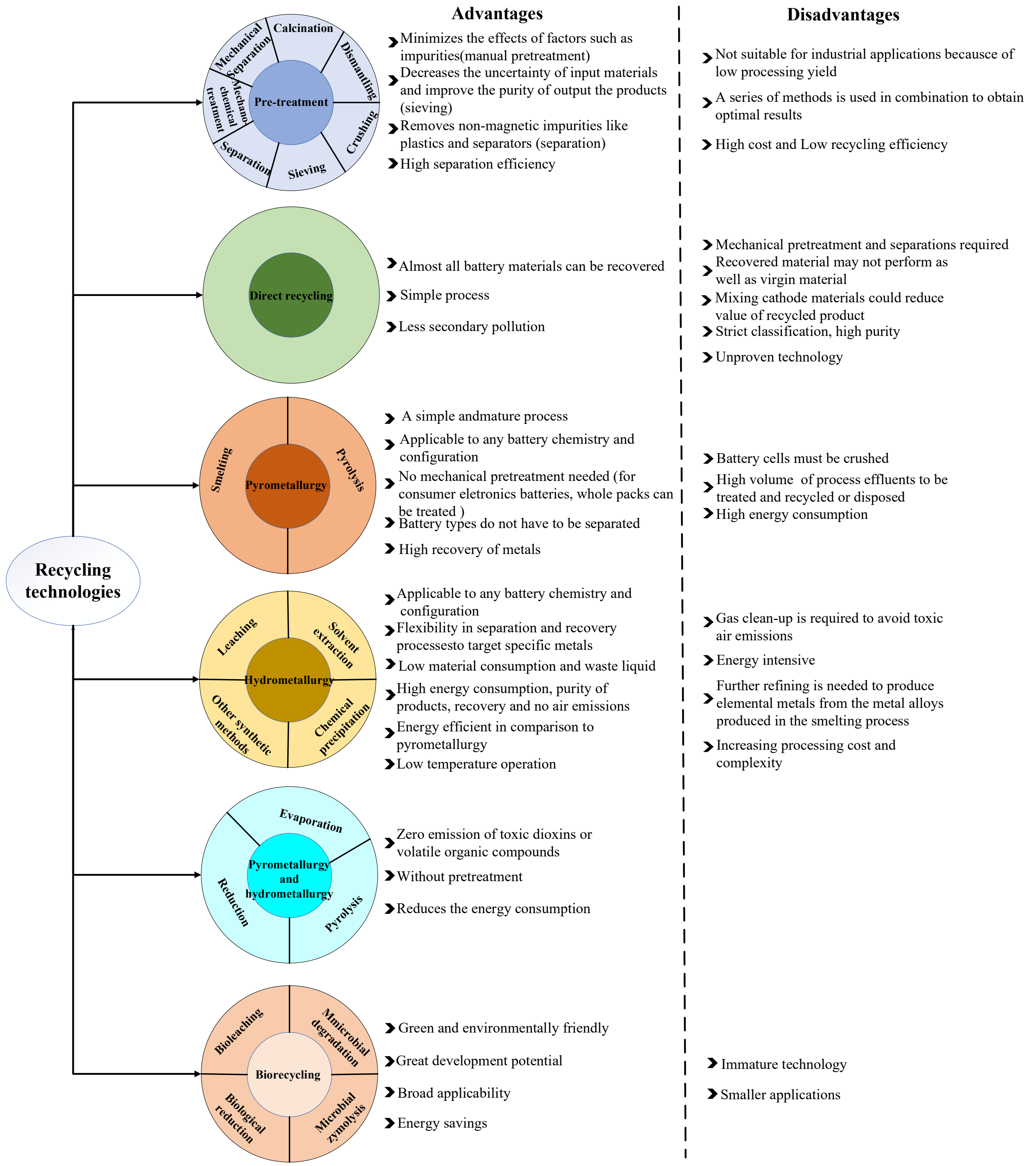

Figure 11. Summary of the characteristics of recycling technology

generate hazardous substances, hindering the advancement of recycling approaches. Chemical recovery methods are challenged by the production of hazardous by-products such as gases and chemical effluents. Metallurgical recovery technologies are hindered by high energy consumption and increased process complexity. Besides, the application of biorecycling technology remains restricted due to technological immaturity and inadequate recycling policies. Meanwhile, the integrated recovery technologies such as direct recovery combined with hydrometallurgical recycling also requires optimization to reduce the generation of by-products and waste of resources. Moreover, chemical dissolution processes are involved in the combined recovery process, which can generate wastewater and exhaust gases with an impact on the environment.

As technology continues to evolve and in-depth research progresses, innovative biorecycling methods and applications are expected to emerge, offering promising solutions for future sustainable battery recycling. So, requiring consideration of environmentally friendly waste disposal methods to minimize damage to the ecosystem. Further, there exists a trade-off to be made between energy efficiency and environmental friendliness, to develop and apply an energy efficient and green recycling technology and route.

Cost implications

The cost of battery recycling is high, which involves multiple stages such as recycling, transportation and disposal. Moreover, there are more impurities in waste battery, which makes recycling and disposal more difficult and requires more human, material and financial resources. Besides, the market demand for waste battery is not high enough to create a large-scale economic benefit, and the waste batteries are inherently complex in composition, where a variety of hazardous substances and valuable materials are involved. Additionally, the types of batteries have different chemical compositions and structures, so the recycling process needs to be customized, which further raises costs.

Recycling channels

The existing waste battery recycling industry lacks standardized management and the recycling channels are opaque and fragmented. The lack of uniform standards and guidance in different regions and enterprises, which can adopt different recycling methods and processes to form a reasonably competitive environment in the recycling market. It evokes information asymmetry, resource waste and environmental risks. Moreover, there is an absence of effective recycling systems and norms, which requires the establishment of more sophisticated and effective recycling systems and channels.

Regulatory issues

Insufficient publicity and low public awareness of waste battery recycling make it difficult to form a scale effect because of low recycling volumes, leading to insufficient public awareness of the importance and significance of recycling. The lack of adequate publicity is likely to cause people to overlook the potential environmental and health hazards of waste batteries. Besides, the regulatory system for waste battery recycling is inadequate, which requires stronger government regulation and more stringent regulations and standards to ensure compliance and safety in the recycling process.

In sum, it is necessary for the government, enterprises and society to work together and strengthen cooperation and coordination. This drives the development and application of battery recycling technology. Moreover, establishing a sound recycling system and norms to improve the efficiency and cost-effectiveness of recycling. Meanwhile, strengthen regulation and public awareness to increase public awareness and participation in the recycling of waste battery.

CONCLUSIONS AND PERSPECTIVES

Spent battery recycling is vital to the economy, environmental protection and resource recycling. It addresses the accumulation of spent batteries, the pollution and the harm caused to humans. Meanwhile, a contribution is provided to alleviate resource shortage and climate warming. There is a strong link between batteries, which contain a large number of chemicals, and the environment, economy, health and resources. Therefore, recycling spent batteries provide enormous benefits. Recycling policies and strategies provide support and security for waste battery recycling. Many countries establish regulated and guided recycling policies that focus on the recovery of valuable metals from spent batteries, i.e., Li, Ni, Mn, and Co. These policies drive the standardization and sustainable development of the entire recycling industry chain.

Recycling technology is a key aspect of the spent battery industry. Various types of batteries offer different compositions and treatment requirements, so knowing the characteristics of different technologies makes it possible to choose the right recycling method and improve recycling efficiency. In particular, integrated recycling technology is currently the best recycling approach, which is of great interest due to its zero contamination. Biorecycling technology is not yet widely adopted, however, high recovery rate, green and efficient features make it a good prospect for development. Furthermore, the development of new material recycling methods is one of the priorities of future research. In summary, waste battery recycling is of great importance to several fields. By developing policies, adopting appropriate recycling technologies and conducting research on new materials, we can achieve more effective, environmentally friendly and sustainable recycling of spent batteries.

ACKNOWLEDGMENTS

This work was supported by the Innovation team of Guizhou Province CXTD2022-009, Guizhou Provincial Natural Science Foundation ZK [2023]073, and Guizhou Province Science and Technology Innovation Base Construction Project QKHZYD[2023] 010.

AUTHOR CONTRIBUTIONS

Z.K.: Conceptualization, Investigation, Interpretation, Compilation, Visualization, Writing–original draft, Writing–review and editing. Z.H.: Conceptualization, Investigation, Interpretation, Compilation, Writing–original draft, Writing–review and editing. Q.P.: Conceptualization, Supervision, Funding acquisition, Investigation, Interpretation, Compilation, Writing–review and editing. Z.S.: Writing–review and editing. H.X.: Writing–review and editing. R.Y.: Writing–review and editing. G.F.: Writing–review and editing. J.Z.: Funding acquisition, Writing–review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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