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Review

A Patent Landscape Analysis on the Recycling of Lithium-Ion Battery Positive Electrode Materials: Trends, Technologies, and the Future

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Abstract: The massive production and utilization of lithium-ion batteries (LIBs) has intensified concerns about raw material shortage and end-of-life battery management. The development of effective recycling/reusing strategies, especially for the valuable active positive electrode materials, has attracted much interest from both academia and industry. This study presents a comprehensive patent analysis on the recycling technologies of spent LIBs. We screened and examined 672 patent filings associated with 367 application families, covering the period from 1994 to 2024. The analysis reveals an explosive growth in patenting activity since 2020, with China and the United States leading in geographical coverage. Hydrometallurgy continues as the most patented recycling technology, followed by direct regeneration, separation, and pyrometallurgy. Key innovations focus on improving leaching efficiency, developing novel purification methods, and exploring various relithiation strategies. The study also highlights the significant involvement of both companies and academic institutions in driving innovation. Our findings provide insights into the technological landscape, identify emerging trends, and lead to the discussion of potential future developments in LIB positive electrode recycling. This analysis serves as a valuable resource for researchers, industry stakeholders, and policymakers working towards sustainable energy storage solutions and circular economy strategies in the battery sector.

Keywords: lithium-ion batteries; patent analysis; positive electrode materials; recycling; end-of-life battery; technological evolution

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1. Introduction

The demand for transport electrification and renewable energy storage has led to a surging need for powerful batteries. Lithium-ion batteries (LIBs) dominate the battery market due to their high energy density and long cycle life [1]. Driven by the electrical vehicle (EV) sector, projections indicate that the demand for LIBs will soar to over 2.5 TW h by 2030, more than five times the capacity in 2022 (Figure 1a) [2]. Such extensive use of LIBs not only raises concerns about resource scarcity but also poses environmental challenges in disposing of tons of retired batteries.

Figure 1b schematically shows the inner structure of a typical LIB cell. Among the components, active positive electrode materials (APEMs), currently dominated by $LiFePO_4$ (LFP) and $Li[Ni_xCo_y(Mn\ or\ Al)_{1-x-y}]O_2$ (NCM or NCA), are determinative to battery performance and cost [3,4]. In particular, for EV battery systems using $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ (NCM811), APEMs account for 56.4% of the total material cost [5]. Even in LFP batteries, the spending on APEMs still represents the largest share of 33.9% (Figure 1c). The value of APEMs originates from their chemical compositions, where the typical constituent elements such as lithium, cobalt, and nickel have high levels of economic importance and supply risks [6]. Therefore, effective recycling/reusing strategies are attracting global attention to create circular supply chains and mitigate critical mineral demand. According to the International Energy Agency, the global recycling capacity exceeded over 300 GWh in 2023 and is projected to reach over 1500 GWh in 2030 [7]. A wide range of stakeholders, including specialized recycling firms, major battery manufacturers, chemical conglomerates, and mining corporations, are joining this competition, making substantial investments in R&D as well as establishing large-scale processing plants. One of the leading LIB recyclers is Brunp Recycling Technology Co., Ltd., a subsidiary of the world's largest battery manufacturer, CATL, based in China. Brunp operates pyrometallurgical facilities with an annual recycling capacity of 120,000 metric tons. European and American companies are also increasing their efforts in LIB recycling. For example, a modern EV battery recycling plant operated by Hydrovolt in Norway currently treats approximately 12,000 tons of battery packs per year and plans to expand the capacity to 300,000 tons by 2030. In North America, Ascend Elements has the capability to process 30,000 tons of end-of-life LIBs and scrap annually. Figure 1e shows some representative recyclers with their processing capacities.

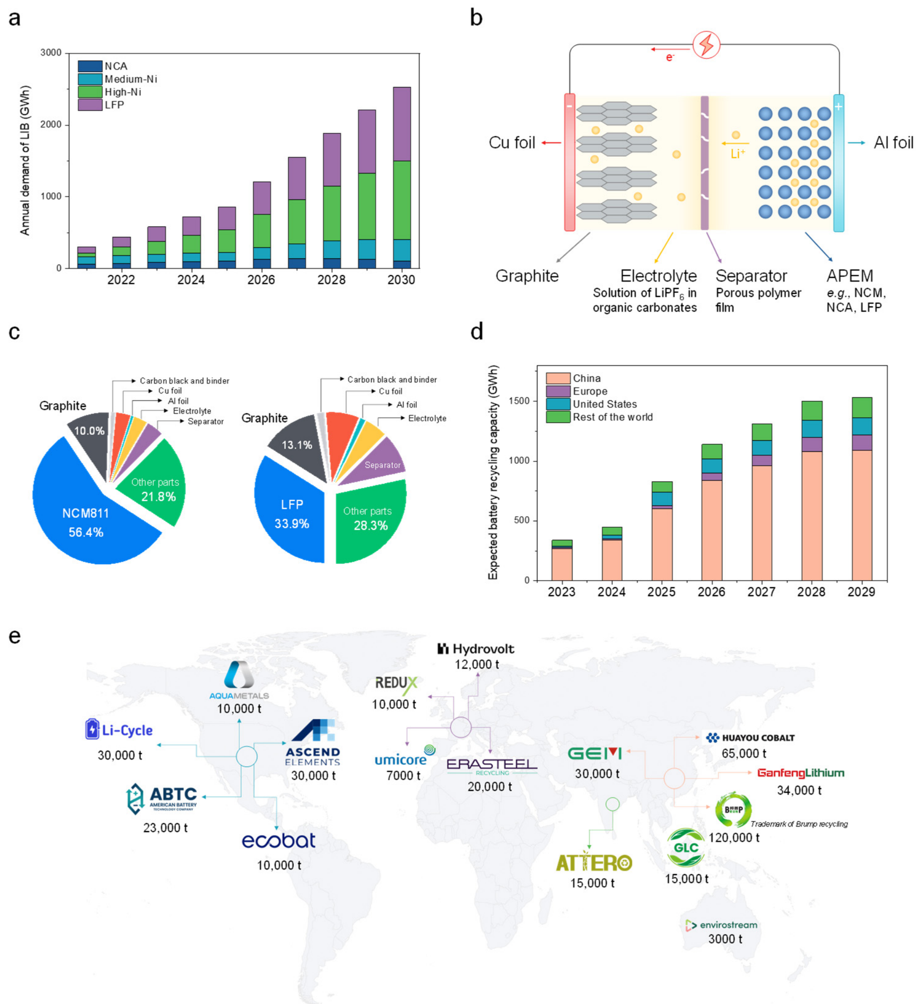

Figure 1. (**a**) A forecasted demand of LIBs with specified APEM chemistries. (**b**) A diagram illustrating the inner structure of modern LIB cells. (**c**) Material-level cost breakdowns of EV battery systems based on NCM811 ‖ graphite and LFP ‖ graphite cells. Other parts include the expenditures on cell/module/pack items as well as the battery management system. (**d**) The projected battery recycling capacity by region from 2023 to 2030. (**e**) Representative battery recycling companies with their stated recycling capacities.

Generally, the reclamation of the valuable APEMs from waste LIBs is divided into three routes: pyrometallurgy, hydrometallurgy, and direct regeneration. Extensive research efforts have been made to improve the recycling efficiency and feasibility, the research progress of which have been thoroughly reviewed [8–19]. However, apart from the literature results, strong engagement of the industry is better reflected by patents, which have been rarely evaluated. Patents represent commercially viable and technically feasible solutions that companies and institutions deem promising [20–24]. In the context of high commercial interest in LIB recycling, patent analysis can offer a valuable tool for the understanding of the technological landscape. Examining patent filings not only helps to identify innovative methods/processes and emerging trends for improved recycling efficiency, reduced costs, and enhanced quality of regenerated APEMs, but also reveals areas of intense competition, potential technological bottlenecks, and opportunities for collaboration or licensing.

Herein, we offer a comprehensive patent analysis by screening the patents relating to the APEM reclamation from spent LIBs. Based on statistical and technical data, the temporal evolution of patenting activities, legal status of patents, geographical distributions of the patent assets, and leading patentees are assessed. Furthermore, powerful patented innovations with the highest forward citations and the largest application family sizes are interpreted in detail. To gain insights into the trends in recycling APEMs, the technical details of the related patents including their technology topics, technical fields, and scope of innovation are analyzed and mapped.

2. Materials and Methods

The study sourced patents from the PatSnap platform, a comprehensive repository containing over 180 million patents across 170 jurisdictions. As shown in Figure 2, the screening process involved a series of Topic/Abstract/Content (TAC) items: (spent OR aged OR degraded OR retired OR end-of-life) AND (cell OR batter* OR accumulator) AND (Li OR lithium) AND (cathode OR positive OR oxide OR phosphate OR nickel OR cobalt OR manganese) AND (regenerat* OR recycl* OR restor* OR relithiat* OR recover* OR repair* OR recla* OR rejuvenat*). The truncation symbol (*) was used to retrieve alternate word endings. Additionally, the IPC code H01M was included to narrow the search results. The search resulted in 821 records up to the date of 20 September 2024. As patent applications are often filed in more than one patent office, these filings can be grouped into patent families. Here, International Patent Documentation (INPADOC) defined by the European Patent Office (EPO) was used to group the inventions. The 821 records were associated with 447 INPADOC families. Then, the patents were screened individually to remove the unrelated documents, leaving 672 patent applications (367 INPADOC families).

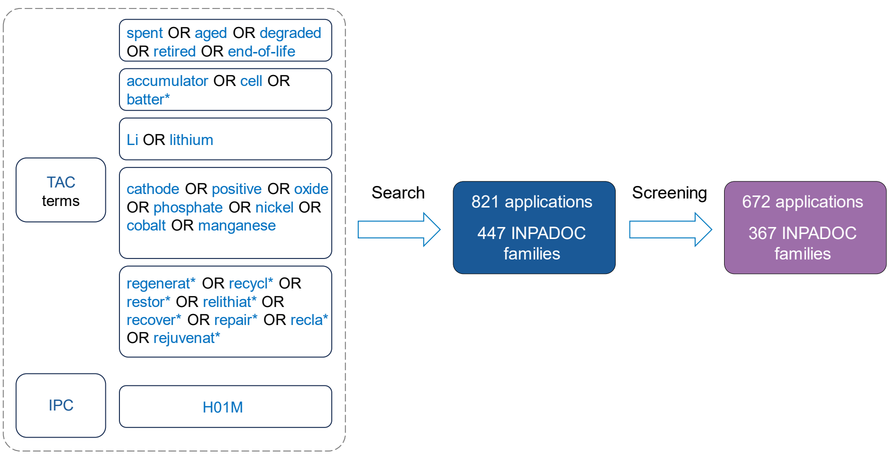

Figure 2. A chart of the patent-screening strategy used for the present work.

3. Overview of LIB Recycling Technologies and Industry

As shown in Figure 3, LIB recycling generally consists of three key phases: preconditioning, mechanical treatment, and chemical processing. While these treatments may not isolate APEMs initially, they ultimately recover valuable APEM constituents (e.g., lithium, nickel, and cobalt) or intact APEMs.

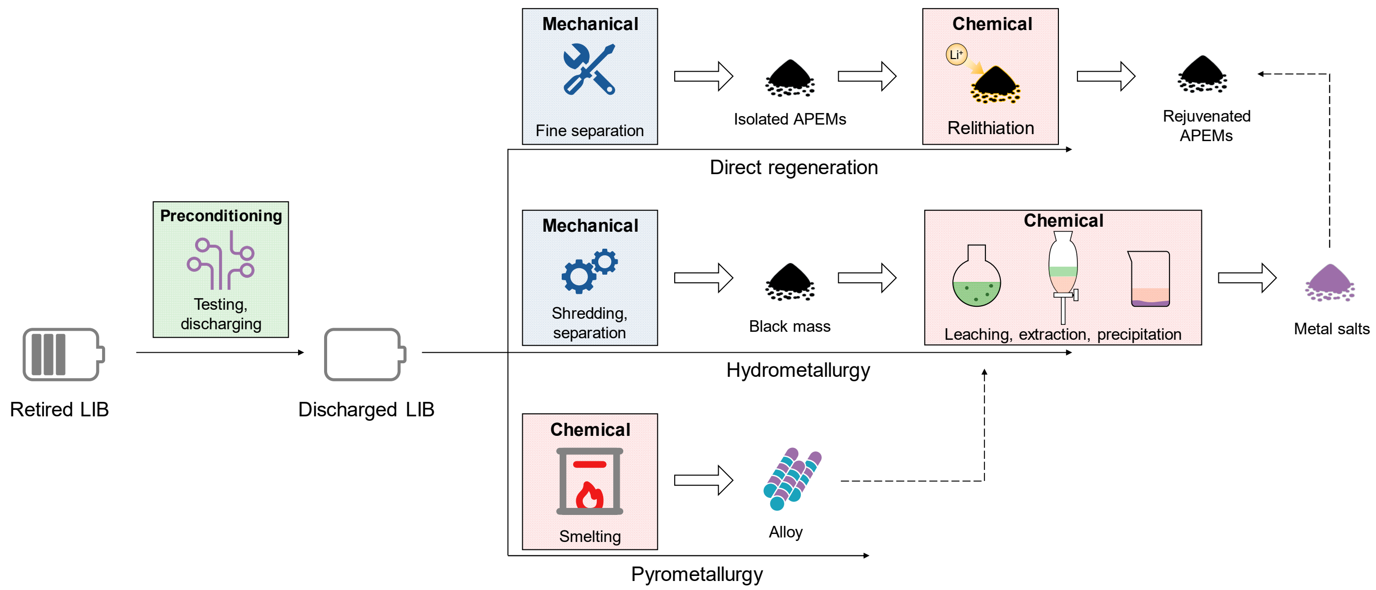

Figure 3. A schematic illustration of the typical LIB recycling processes and routes from retired LIBs.

1. Preconditioning stage: This initial phase involves steps that do not alter the internal structure of cells. It includes measures such as state-of-health testing, battery sorting based on the APEM chemistry, and discharging to ensure safety. A deep discharging also ensures the return of Li ions to APEM lattices for later recovery.
2. Mechanical stage: In this phase, the discharged cells are subject to mechanical treatments to separate APEMs from the spent LIBs. Depending on the battery type, following the chemical route, and other parameters, the requirements of the mechanical process are different [16,25–28]. In the case of pyrometallurgy, the mechanical stage can be largely simplified or even skipped, while for hydrometallurgical leaching, shredding and separation are necessary to obtain "black mass", a powder mixture of APEMs, graphite, and other electrode components. If direct regeneration is targeted, more sophisticated separation is required to isolate APEMs from other electrode components like binder and conductive carbon.
3. Chemical processing stage: After the mechanical process, the dismantled cells or crushed materials are subjected to the core chemical process of pyrometallurgy, hydrometallurgy, or direct regeneration. Pyrometallurgy uses high temperatures to smelt and to recover valuable metals [29]. As mentioned above, pyrometallurgy can smelt entire battery packs without mechanical pretreatment, yielding alloys of cobalt, nickel, and copper, while lithium and manganese typically remain in unrecovered slag. The recent EU Battery Regulation, however, mandates 50% lithium recovery from spent LIBs by 2027 and 80% by 2031, necessitating effective lithium and manganese extraction from slag [30]. In contrast, hydrometallurgy starts by dissolving the black mass through leaching, followed by purification and selective precipitation of the dissolved metals using specific reagents [9,31–33]. Direct regeneration aims to preserve the structural integrity of the APEM, allowing it to be reused without breaking it down into individual elements [34–36]. Note that these chemical processes are frequently

combined. For example, the metal alloy produced through pyrometallurgy needs to be further processed using hydrometallurgical techniques to produce individual battery-grade salts.

From the early stage of battery preconditioning to the final reproduction of new APEMs, every phase in the recycling process has come under intense scrutiny. Researchers and engineers are seeking ways to optimize or even completely revolutionize current techniques, aiming to enhance the cost-effectiveness, enlarge the processing capacity, and reduce the environmental impact.

4. Temporal Evolution of Patenting Activities

After the commercialization of LIBs in the early 1990s, the recovery of valuable metals from end-of-life LIBs soon gained interest. The earliest patent according to our search results is EP0656669B1, which was filed in 1994 by a German company named Keramchemie GMBH. This invention relates to a hydrometallurgical treatment of used batteries to recover metallic raw materials, including lithium and manganese. This patent did not specify whether the source batteries were rechargeable ones, since LIBs were at their very early stage. In a later patent (KR1019980063266A) developed by Canon in 1996, the inventors explicitly claimed a recovering process and apparatus for sealed batteries including LIBs. It highlighted the importance of electrolyte evacuation prior to cell disassembly. Figure 4a shows the annual patenting applications and approvals. Accordingly, five stages can be roughly identified in the technology development. The early period of from 1994 to 2004 could be deemed as an embryonic stage, where the concept of APEM recycling emerged along with the commercialization of LIBs. Then it stepped into a dormancy stage with no patent registrations from 2005 to 2008. This might be due to the limited scale of LIB applications and low recycling benefits, which failed to generate sufficient investment interest. Thereafter, starting from 2009, the recycling of APEMs entered a revival phase. New applications began to resurface, suggesting renewed interest and innovation in this field. This revival coincided with the proliferation of smartphones, which led to the widespread adoption of LIBs. From 2020 to 2024, patent activity in LIB APEM recycling surged, with 423 requests recorded, representing 62.9% of the total. However, data for 2023 and 2024 remain incomplete due to delays in the patenting process, as most jurisdictions publish applications 18 months after filing, suggesting the actual number may be higher. This apparent surge reflects the maturation of the EV market and suggests a potential shift toward more sustainable, circular battery production and disposal practices, though full data are needed to confirm its extent. Figure 4b details the distribution of patent applications over the discussed time periods.

The legal status of the 672 intellectual property rights is summarized in Figure 4c. Among them, 245 applications, representing the largest share of 36.5%, are currently under legal protection (active state). Granted patents, having undergone rigorous examination by patent authorities, generally exhibit high technical value. A substantial proportion—226 patents—remain as pending, indicating that these applications are newly developed, are still under review by patent offices, and have yet to be either granted or rejected. A total of 29 patents are at the PCT-designated stage, remaining active internationally, while 46 applications have lost the potential to enter additional countries. Meanwhile, 108 patents are inactive, having been either expired, abandoned, withdrawn, rejected, or invalidated. The significant share of both active and pending patents confirms the ongoing innovation and interest in this area of technological development.

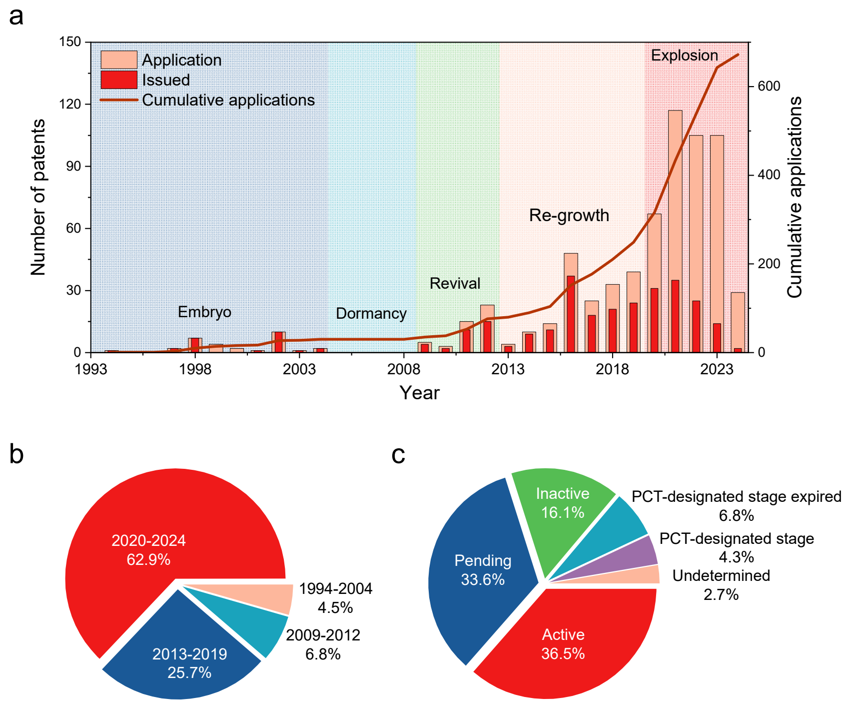

Figure 4. (**a**) Trend in patent filing and approval relating to APEM recycling for LIBs. (**b**) Distribution of applications across various time periods. (**c**) Simplified legal status of inventions.

5. Top Countries and Key Players in the Patent Filing

Figure 5a illustrates the geographic coverage of where patent applications have been filed, indicating the most targeted geographic markets for the potential utilization of the technologies. China leads with 214 patent filings, followed by the United States with 153. Together, the two nations account for over half (54.4%) of the total developed patents, highlighting their intensive interest in commercializing APEM recycling technologies. This leadership can be attributed to several factors. China, the leading manufacturer and user of LIBs, has a vested interest in developing sustainable recycling solutions to support its rapidly growing EV industry and reduce dependence on raw material imports. Similarly, the United States is a major player in the global battery supply chain, driven by its robust technological infrastructure and commitment to energy storage advancements. As a result, both countries are heavily invested in solving the technical and economic challenges associated with battery reclamation, positioning them at the forefront of inventions in this field. Following America, the World Intellectual Property Organization (WIPO), the EPO, and India received 75, 64, and 38 patent requests, respectively. The spread of the patent activities across a variety of jurisdictions reflects widening recognition of the importance of LIB recycling technologies.

Figure 5b highlights the top assignees with the 10 largest patent portfolios in this technological field. Different from the dominance of China and the U.S. in geographic coverage, the top assignees are from diversified regions. Leading the list is Worcester Polytechnic Institute, a private American research university, which invented 37 patents. Next is an Indian company, Attero Recycling Pvt Ltd. It requested legal rights for 31 inventions. Guangdong and Hunan Brunp Recycling Technology Co., Ltd., two subsidiaries of CATL as introduced above, co-filed 30 patents. After Brunp is a nonprofit limited liability company (LLC), UT-Battelle, which also has a strong academic background with members from the University of Tennessee and Battelle Memorial Institute. It contributed 22 related patents. Other top patent applicants include Green Li-Ion Pte Ltd. from Singapore, Japanese automobile giant Toyota Motor Corp. (Toyota City, Japan), the Regents of the

University of California, German chemical giant BASF AB, and Ascend Elements Inc. from the U.S. The inset of Figure 5b further breaks down the patent distribution by assignee type. Specifically, companies account for 64.3% of the patents, while academic institutions represent a notable share of 28.5%. The high level of engagement from both sectors suggests that LIB recycling is not only attracting significant investment from commercial entities but also remains a dynamic area of scientific investigation, driving technological progress from multiple fronts.

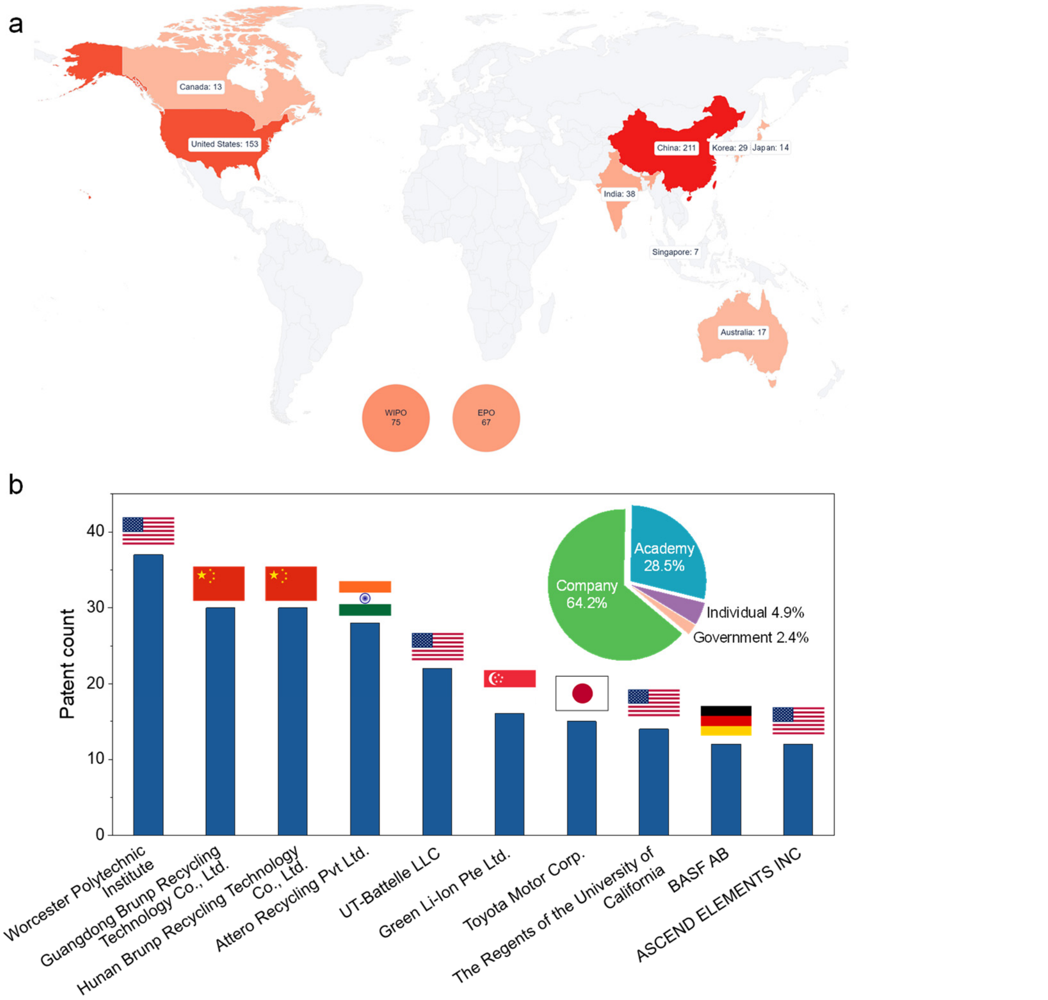

Figure 5. (**a**) The global spread of patent applications focusing on the recycling of APEMs. (**b**) The top patentees in this field.

6. Important Patents (Patents with the Highest Forward Citations and the Largest Family Sizes)

The significance of a patent hinges on many factors. Among them, citation count serves as a critical measure of its influence and importance. A high number of forward citations indicates broad recognition among inventors, underscoring its capacity to influence the field and spur subsequent technological progress. Table 1 lists the five most cited inventions in APEM recycling technologies. The count considers the citations of the whole patent families, of which the oldest publication numbers are presented as the representative ones. Leading the list is a patent family represented by US20050100793A1. The invention, patented by PolyPlus Battery Co., Inc., (Berkeley, CA, USA) introduces an electrolytic cell with a protected cathode for recovering active metals, such as lithium, from sources like industrial waste and spent LIBs. It employs a solid electrolyte membrane to isolate reactive lithium metal from the recovery medium under ambient conditions, enabling extraction via reactions

$$\text{Anode}: 2\text{LiOH} = 2\text{Li}^{+} + 2\text{e}^{-} + \text{H}_2\text{O} + ½\text{O}_2 \quad (1)$$

$$\text{Cathode}: 2\text{Li}^{+} + 2\text{e}^{-} = 2\text{Li} \quad (2)$$

Table 1. List of the five most cited patents in the field of APEM recycling.

Publication Number	Title	Legal Status	Current Assignee	Publication Date	INPADOC Family Cited by Count
US20050100793A1	Active metal electrolyzer	Active	PolyPlus Battery Co., Inc.	12 May 2005	1427
US20130302226A1	Method and apparatus for recycling lithium-ion batteries	Active	Worcester Polytechnic Institute	14 November 2013	273
AU2003205087C1	System and method for removing electrolyte from energy storage and/or conversion device using supercritical fluid	Active	Eco-Bat Indiana LLC, Indianapolis, IN, USA	6 November 2008	228
KR1019980063266A	Process and apparatus for recovering components of sealed-type battery	Inactive	Canon, Inc., Tokyo, Japan	7 October 1998	225
CA2319285A1	Method for neutralizing and recycling spent lithium metal polymer rechargeable batteries	Inactive	Avestor, Portland, OR, USA	13 March 2002	200

This marks a significant advantage over traditional high-temperature molten salt methods, with the advantage of versatility across diverse lithium-containing waste streams. With its 1427 citations, electrochemical lithium recovery has spurred extensive R&D, leading to pilot-scale reactors with diverse configurations [37]. However, limitations include scalability challenges due to the membrane cost and complexity, which may restrict widespread adoption.

The second patent, US20130302226A1, held by Worcester Polytechnic Institute (Worcester, MA, USA), remains active with 273 citations. It describes a streamlined hydrometallurgical recycling process where degraded APEMs are dissolved into a mixed metal ion solution and converted into new APEM precursors via co-precipitation. This reduces steps compared to conventional leaching–purification cycles with the advantage of lower reagent use. Its limitation is the need for the precise control of solution chemistry, potentially raising costs. It has sparked significant industrial interest, evidenced by citations from firms like Ascend Elements (e.g., US12040463B2, US12071677B2), which leverages streamlined hydrometallurgy for its 30,000-ton facility as introduced above.

Following that is AU2003205087C1, a patent filed by Eco-Bat from the United States, which has been cited by 228 forward patents. The invention includes a method of removing an electrolyte from retired using a supercritical fluid. Although it is not directly related to APEM recovery, the removal of the harmful electrolyte facilitates the subsequent recycling process. KR1019980063266A and CA2319285A1 are relatively distant patents, which have attracted 225 and 200 citations, respectively. Both of them offer safety protocols prior to the dismantling of spent batteries, highlighted by electrolyte releasing and cell freezing, respectively.

As the applicants are willing to seek protection for their critical innovations in multiple territories, the family size of a patent is also a measure of its importance. Table 2 shows five inventions with the largest INPADOC application family sizes. Again, the oldest publication number is chosen to represent the patent family. Accordingly, the most cited patent US20050100793A1 is also the most protected one, having 54 submissions. The second patent, CN114174545A, with 34 family applications, was developed by BASF. It uses a hydrometallurgical process for recovering lithium from waste LIBs, treating black mass containing lithium and fluoride salts with a polar solvent and an alkaline earth hydroxide, then isolating lithium products from the separated liquid. After that, the third-largest patent family represented by US20170005374A1 (26 applications) was created by Umicore SA. It presents a pyrometallurgical method that uses a copper smelter to recycle retired LIBs with low cobalt contents (e.g., LFP and $LiMn_2O_4$). It enhances copper blister production rates, yet reduces energy use by taking advantage of the metallic Fe, Al, and/or carbon from LIBs. The fourth patent, US20190024212A1 (25 family members), filed by an individual U.S. inventor, focuses on recovering lithium from lithium sources, including waste LIBs, using acid digestion and membrane separation. After this, MYPI2018000006A0, introduced by Attero Recycling, has 25 applications. In this proprietary technology, the majority of elements are separated by a physical process instead of a chemical process, reducing the generation of liquid and solid effluents.

Table 2. A list of the five inventions with the largest patent family sizes in the field of APEM recycling.

Publication Number	Title	Legal Status	Current Assignee	Publication Date	INPADOC Family Size
US20050100793A1	Active metal electrolyzer	Active	PolyPlus Battery Co., Inc.	12 May 2005	54
CN114174545A	Process for recovery of lithium from waste lithium-ion batteries	Pending	BASF AB, Ludwigshafen, Germany	11 March 2022	34
US20170005374A1	Process for recycling Li-ion batteries	Active	Umicore SA, Brussels, Belgium	5 January 2017	26
US20190024212A1	Recovery of lithium from acid solution	Granted	Larry Lien (US)	24 January 2019	25
MYPI2018000006A0	Method of recovering metals from spent Li-ion batteries	Active	Attero Recycling Pvt Ltd., Noida, India	6 January 2017	25

Three of the ten highlighted patents target lithium recovery, employing electrochemical, hydrometallurgical, and membrane extraction methods. The high solubility of lithium and its low abundance in typical LIBs render conventional pyrometallurgical and hydrometallurgical processes inefficient or uneconomical [38]. Increased research effort on lithium recovery has propelled the development of emerging technologies like mechanochemical approaches, bioleaching, and electrochemical methods [38]. This trend is also reflected in recent patents. For instance, EP4286549A1 (Karlsruhe Institute of Technology, Karlsruhe, Germany, 2023) introduces a mechanochemical process for LIB recycling. Taking LCO as an example, the mechanochemical reduction reaction can be expressed as follows:

$$2LiCoO_2 + 2Al = 2Co + Li_2O + Al_2O_3 \quad (3)$$

This method utilizes mechanical energy to drive reactions, offering lower energy use than traditional hydrometallurgy and high recovery rates. US20240318277A1 published by BRAIN Biotech AG in Zwingenberg, Germany, in 2024, discloses a method for selective bioleaching. This method utilizes microbial agents to extract lithium. While US20230020052A1, from the Iowa State University Research Foundation located in Ames, IA, USA, disclosed in 2023, employs electrochemical deposition to recover lithium. This technique preconcentrates residual lithium from solid-electrolyte interphases, electrolytes, and the positive electrodes. It also yields battery-grade graphite with reduced costs and complexity. WO2024097221A1 (Novalith Tech Pty Ltd. from Sydney, Australia, 2024) introduces supercritical CO_2-assisted leaching to recover lithium from black mass or shredded battery material. US20240003019A1 (University of Kentucky Research Foundation, Lexington, KY, USA, 2024) reclaims lithium via an electrochemical purification process in a flow electrolyzer after pretreatment of the black mass. The emphasis of the new EU Battery Regulation on lithium reuse is expected to further drive interest in advancing lithium recovery.

7. Technical Analysis of the Granted Patents

To thoroughly assess the current state and future potential of APEM recycling, we have examined the technical aspects of the retrieved patents, encompassing technology topics, IPC classifications, and innovation scopes. Patent families have been utilized to prevent duplicate counting of similar inventions. Figure 6a presents a word cloud of subject areas across 367 patent families, visually highlighting dominant themes. Notably, Physical Chemistry leads with 253 families, followed by Inorganic Chemistry (226) and Chemical Engineering (142), with additional areas like Environmental Engineering (38), Process Engineering (24), and Waste Management (22) also represented. Figure 6b illustrates the IPC group code distribution. H01M10, spanning the full range of secondary batteries, stands out as the predominant classification (354 families). Other IPC groups include H01M4 (electrodes), C22B7 (working up raw materials other than ores, e.g., scrap, to produce non-ferrous metals and compounds thereof), C22B26 (obtaining alkali, alkaline earth metals or magnesium), C22B3 (extraction of metal compounds from ores or concentrates by wet processes), etc. All these are strongly correlated with the technical objectives of APEM recycling.

Beyond these broad classifications, we have meticulously reviewed all the active patents to identify their core innovations. Among the 102 active patent families, one (US10371753B1) is related to the determination of the state of health for LIBs, which can be classified into the preconditioning process of LIB recycling. The remaining 101 groups can be classified into four types of technologies: separation, hydrometallurgy, pyrometallurgy, and direct regeneration. Hydrometallurgy accounts for the largest proportion with 58 patent families, which include a variety of innovations in leaching, purification, and target products. For example, KR101708149B1 presents a wet milling process to reduce the use of leaching agent. Deep eutectic solvent is employed in US20200399737A1. CN112142077A develops an air oxidation strategy to precipitate $FePO_4$ from the leaching solution of degraded LFP. The second-largest group is direct regeneration, which is covered by 28 patent families. The oldest patent US20100124691A1 amongst the active patents is related to the direct regeneration of LIBs, which rejuvenates pouch-type degraded LIBs through a manifold to replace the electrolyte. Patent US20170040651A1 introduces a supersonic treatment to remove the problematic surface film on the cycled positive electrode. However, the loss of active lithium inventory in the degraded APEMs remains as an issue. Therefore, a range of relithiation strategies are disclosed, such solid-state (CN104466293A, CN104600284A, and CN108448193), electrochemical (US20180175444A1, IN201917051653A, and US20210226263A1), hydrothermal (US9484606B1), solvothermal (US20220328800A1), ionothermal (US20220376240A1), and pulse liquid-phase discharging (CN105375081A) approaches. As a preliminary step, separation has attracted much interest with 13 patent families falling in this category. For example, patent CN109860753A uses microwave heating to roast the spent LIBs directly, shortening the preprocessing time. Hydraulic crushing is employed in CN111786008A to dissociate the positive electrode materials from the current collector. Alternatively, US20210257685A1 uses a polyol fluid to release the PVDF binder, enabling rapid delamination of the positive electrode material from the current collector. Pyrometallurgy is the least-filed recycling technology with only four related patent families having active members. US20170005374A1 has been discussed above as the patent having the third-largest family size. CN112661201A presents the use of self-propagating reaction initiated by magnesium powder to produce Ni-Co-Mn alloy from used NCM materials. CN112779421A relates to the reclamation of lithium from a carbothermic reduction. In fact, base or acid leaching is still used in the two patents. Patent AU2021106578A4 focuses on the Co recovery from spent LCO batteries. It also involves a carbothermal reduction process.

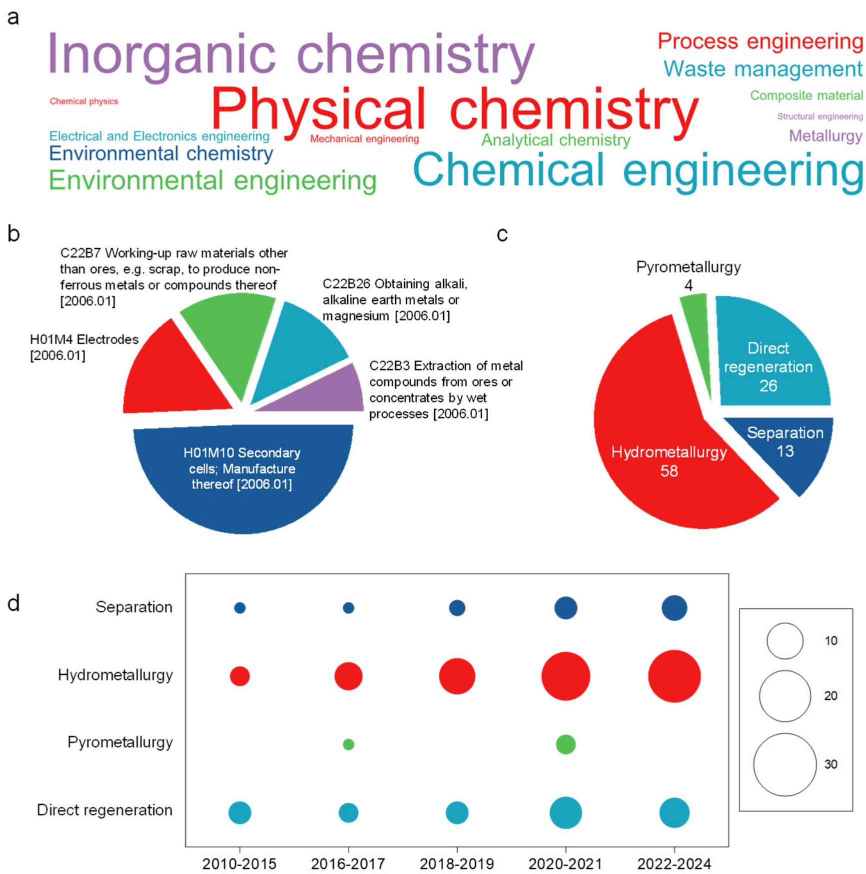

Figure 6. (**a**) Word cloud depicting subject areas for 367 patent families relating to APEM recycling. (**b**) Distribution of patents by IPC subclass codes. (**c**) Categorization of patents by innovation strategies and their proportions. (**d**) Chronological progression of these technological innovations.

To reveal the innovation pathway in APEM recycling, Figure 6d maps the chronological spread of these technological innovations. Between 2010 and 2015, direct regeneration led the patent landscape, surpassing hydrometallurgy by one additional family. In subsequent periods, hydrometallurgy emerged as the most patented field, showing a consistent upward trend, paralleled by gradual increases in separation innovations. Although hydrometallurgy currently leads, incomplete 2023–2024 data hinder predictions about whether direct regeneration will gain momentum. Despite scalability and cost-efficiency challenges, direct regeneration technologies are highly sought after in academia [13,16,34,35,39].

8. Summary and Outlook

The surge in the demand of EVs and renewable energy storage markedly increases the urgency of LIB recycling, particularly the reuse of APEMs that are rich in valuable metals like lithium, cobalt, and nickel. Our patent analysis reveals a technological evolution from conventional methods to efficient and environmentally friendly solutions.

Early LIB recycling relied on pyrometallurgy, smelting batteries into alloys (with lithium often lost to slag), and hydrometallurgy, leaching black mass but generating waste. Recent advancements mark a shift. For instance, supercritical CO_2-assisted leaching (WO2024097221A1, 2024) recovers lithium from black mass with low environmental impact. Electrochemical deposition (US20230020052A1, 2023) preconcentrates lithium from entire LIB parts. Bioleaching (US20240318277A1, 2024) employs microbial agents for selective lithium extraction, avoiding harsh chemicals. These innovations reflect a global push towards circular battery economy.

To further guide this trajectory, we recommend the following: (1) technological cooperation: strengthen industry–academia collaboration to accelerate the scaling and commercialization of emerging recycling methods; (2) policy support: support recycling infrastructure, like centralized sorting and black mass processing facilities; and (3) investment priorities: direct capital toward hydrometallurgical and pyrometallurgical optimization to meet the battery recycling goal, while increasing pilot efforts in more sustainable techniques, including direct regeneration, bioleaching, and electrified processes.

In summary, this analysis highlights a shift from high-energy and low-efficiency processes to advanced eco-friendly solutions. China and the U.S. lead geographically, reflecting intensive R&D efforts, while assignees span diverse regions, showing wide participation of industry and academia. These insights are expected to guide future research, development, and investment decisions in the rapidly evolving field of LIB recycling.

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Abbreviations

The following abbreviations are used in this manuscript:

LIB	Lithium-ion batteries
APEM	Active positive electrode materials
LFP	$LiFePO_4$
NCM	$Li[Ni_xCo_yMn_{1-x-y}]O_2$
NCA	$Li[Ni_xCo_yAl_{1-x-y}]O_2$
TAC	Topic/Abstract/Content
INPADOC	International Patent Documentation
EPO	European Patent Office
PCT	Patent Cooperation Treaty
LLC	Limited liability company

WIPO	World Intellectual Property Organization
PVDF	Polyvinylidene fluoride

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