Review

Environmental Chemistry and Safety
DOI: 10.26599/ECS.2026.9600037
2026, 2, 9600037

Treating Pollutants with Waste: Upcycling Spent Lithium-ion Battery Black Mass into Functional Materials for Water Purification

Xiaoqing Wei[1], Dejiao Shen[1], Zhexu Wang[1], Chenggang Zhou[1,2], Zhao Cai[1*], Bo Han[1*], and Qiang Gao[1*]

[1]Faculty of Materials Science and Chemistry, China University of Geosciences, Wuhan 430078, China
[2]Shenzhen Research Institute of China University of Geosciences, Shenzhen 518000, China

Abstract: The large-scale decommissioning of lithium-ion batteries (LIBs) production is progressing rapidly, and the demand for environmentally friendly recycling and material recovery is rising. Collectively, this review has presented a series of studies on recent progress in using waste LIB black mass to synthesize various materials for water treatment, including synthesis methods, material structure and application performance of derived adsorbents, Fenton catalysts, persulfate-activating catalysts, etc. The above are based on rational material design and processing to create high-efficiency, multi-functional water treatment materials from black mass. Anode graphite-based adsorbents are a typical representative type with good heavy metal adsorption performance, and cathode-derived catalysts show fast degradation of organic pollutants via oxidative pathways. This review briefly introduces the shortcomings of the current state and provides some directions for further research to promote the construction of an effective pollution treatment model in the circular economy era.

Key words: Treating pollutants with waste; Spent lithium-ion batteries; Water treatment; Adsorbents; Catalysts.

Citation: Wei X Q, Shen D J, Wang Z X, et al. Treating Pollutants with Waste: Upcycling Spent Lithium-ion Battery Black Mass into Functional Materials for Water Purification. *Environmental Chemistry and Safety*, 2026, 2, 9600037. https://doi.org/10.26599/ECS.2026.9600037

1. Introduction

With the rapid development of the world's electric vehicle and portable electronics industries, a large number of spent lithium-ion batteries (LIBs) have been generated, and thus serious issues in resource depletion and environmental pollution have arisen[1-4]. According to a joint report by Greenpeace and the China Environmental Protection Foundation, the total amount of decommissioned power batteries in the world by 2030 will be about 12.85 million metric tons, and China will account for more than 7 million metric tons[5, 6]. Improperly disposing of used LIBs can lead to the release of heavy metals and electrolytes in the soil and water[7]. Although good recycling should be realised to recover important materials such as lithium, cobalt and nickel[8-13], most of the traditional recycling technology is limited to extracting metals from black mass via pyrometallurgy or hydrometallurgy[14-16]. These ways are generally high-energy-consuming and generate considerable waste; moreover, they are in a linear system and do not fully utilise the high chemical value of battery components.

Concurrently, the water treatment industry also requires economically feasible and high-performance functional materials (e.g. adsorbents and catalysts) for the large-scale removal of pollutants in water, including dyes, antibiotics, heavy metals[17-18]. Conventional advanced materials usually have relatively complex synthesis methods, are high in cost, and depend on raw materials from the earth.

A critical bottleneck and untapped opportunity lie at the intersection of these two fields: the disconnect between spent LIB recycling and the rational design of advanced functional materials for environmental remediation. This review addresses the core scientific question: How can spent LIB black mass —beyond mere metal recovery —be engineered into high-performance, value-added materials for water purification, and what is the underlying structure-performance relationship that governs their functionality? The innovative "treating pollutants with waste" paradigm explored here represents a significant shift from recycling to upcycling. For instance, anode graphite can be transformed into advanced adsorbents or catalyst supports, while transition metals (Fe, Co, Ni, Mn) from cathodes can be engineered into efficient catalytic centers for oxidative degradation[19]. This strategy not only mitigates battery waste burden but also creates a novel, low-cost supply chain for water treatment materials, embodying circular economy principles.

This review systematically summarizes recent progress in this emerging field, with a deliberate emphasis on innovative material design strategies that convert waste directly into functional assets. It analyzes the synthesis-structure-performance relationships, discusses technical advantages and current limitations, and outlines future research priorities to guide this promising crossover field towards high-value battery upcycling and innovative, sustainable water treatment solutions.

Correspondence to: Cai Z, caizhao@cug.edu.cn; Han B, hanbo@cug.edu.cn; Gao Q, gaoqiang@cug.edu.cn
Received: March 3, 2026; Revised: April 27, 2026; Accepted: May 14, 2026
©The author(s) 2026. Published by Tsinghua University Press. This is an open access article under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0, http://creativecommons.org/licenses/by/4.0/).

2. Components and characteristics of spent lithium-ion batteries

2.1. Overall structure and composition

Lithium-ion batteries (LIBs) constitute complex systems whose core components include the cathode and anode, alongside other essential elements such as the separator, electrolyte, current collectors, and casing[20]. Cathode active materials typically comprise lithium cobalt oxide ($LiCoO_2$, LCO), ternary materials ($LiNi_xCo_yMn_{1-x-y}O_2$, NCM), lithium manganese oxide ($LiMn_2O_4$, LMO), or lithium iron phosphate ($LiFePO_4$, LFP)[21], while the anode primarily consists of natural or artificial graphite[22]. After discharge, dismantling, crushing, and sorting, the resulting black mass contains enriched electrode materials[23, 24]. Its composition varies with battery chemistry and processing routes, generally categorizable as cathode-dominant (metal oxides) or anode-dominant (graphite) black mass.

2.2. Fundamental properties of cathode materials and their water treatment potential

The distinctive physicochemical properties of cathode materials, particularly transition metal elements within their crystal structures, directly determine the functionality and application potential of derived water treatment materials, enabling tailored design for specific scenarios. For example, LFP material, with its high structural stability, abundant iron content, and environmental compatibility, is commonly used to construct Fenton systems that exhibits high reactivity at iron active sites with low ecotoxicity during catalytic degradation of organic pollutants[25]. Ni, Co and Mn can work together in the electronic system of NCM cathode materials to modify the structure of the catalyst and thus enhance its activation capacity for oxidants, such as persulfate[26]. Cobalt species in LCO are generally known as high-efficiency catalytic centres that can generate sulfate radicals through the decomposition of peroxymonosulfate (PMS)[27-29]. Mn (III)/Mn (IV), etc., are multivalent species in LMO materials that can mediate redox reactions and thus exhibit a good catalytic oxidation effect with relatively low environmental impacts (Table 1)[30].

Current technical pathways for converting cathode materials into water treatment functional materials fall into two categories: non-destructive surface modification or chemical treatment of the materials, and complete deconstruction-reconstruction process, using metal ions recovered from the leachate as precursors to resynthesize target materials. The following sections examine these pathways through specific research cases.

2.3. Physicochemical properties and water treatment potential of anode materials

Graphite is the anode material with certain physicochemical characteristics that are highly suitable for water treatment[31-33]. Firstly, graphite is relatively easy to expand[34]. Although the initial specific surface area is generally modest (1–20 m^2/g), expansion treatment can be employed to significantly increase it to 30–500 m^2/g; at this time, a large number of transport paths and adsorption sites for pollutants are provided. It is suitable for immobilizing active nanoparticles and therefore a good support material. Secondly, graphite is naturally catalytically active; therefore, many studies have shown that under the influence of hydrogen peroxide and persulfates, organic pollutants can be degraded through radical and non-radical pathways[35].

In addition, graphite and its expanded graphite or exfoliated derivatives (e.g. graphene oxide) have strong adsorption capabilities for organic pollutants with conjugated structures (e.g., dyes and antibiotics) due to π-π interactions[36]]. Oxygen-containing functional groups such as carboxyl and hydroxyl groups are easy to introduce to improve the adsorption effect of other pollutants, such as heavy metal ions[37]. Graphite has good structural stability and corrosion resistance; therefore, it will perform well in many aqueous chemical environments for a longer time. Graphite is not poisonous and environmentally friendly, so it meets the requirements for green water treatment development.

3. Comparison of the environmental impacts of pyrometallurgical, hydrometallurgical and direct recycling routes

To know which upcycling path is more environmentally friendly, all kinds of harm from the environment need to be examined. Generally speaking, the environmental impacts of pyrometallurgy, hydrometallurgy and direct conversion are quite different due to energy intensity, chemical consumption and other emission factors.

Pyrometallurgical processing generally has a high energy demand and releases significant direct greenhouse gas (GHG) emissions due to high-temperature smelting (>1400 °C) for alloy or slag recovery, which are mainly from fossil-fuel-based heating and slagging agents[38]. Although it is a good route for metal recovery, it often has poor selectivity for lithium and produces a large amount of flue gas and solid slag, requiring further treatment and increasing the overall carbon footprint[39-40].

Hydrometallurgical routes are based on leaching and solution purification, so they generally have a lower operating temperature but produce environmental pollution due to reagent production, acid consumption (e.g.,H_2SO_4), and wastewater treatment[41]. Although these have a relatively small energy consumption, the carbon footprint of chemical use and neutralisation is relatively high; life-cycle assessments (LCAs) often show an increase of about 4-10 kg CO_2-eq/kg of recovered cathode

Table 1. Composition and properties of main cathode materials used in LIBs[20, 21].

Material type	Chemical formula	Transition metal and content	Advantages
Lithium iron phosphate (LFP)[25]	$LiFePO_4$	Fe: ~35%	High stability, environmental friendliness, low cost, be suitable for constructing Fenton-like catalytic systems
Ternary materials (NCM)[26]	$LiNi_xCo_yMn_{1-x-y}O_2$	Ni+Co+Mn: ~60%	Multimetallic synergy results in enhanced catalytic activity
Lithium cobalt oxide (LCO)[27-29]	$LiCoO_2$	Co: ~60%	Cobalt exhibits high catalytic activity and a strong capability for activating PMS
Lithium manganese oxide (LMO)[30]	$LiMn_2O_4$	Mn: ~60%	Manganese exhibits multiple valence states and is environmentally benign

metals [42]. High-purity metal recovery can be achieved, but solvent loss and waste-stream treatment are still problems.

Direct conversion routes are relatively low-impact pathways that directly transform black mass or its components into functional materials (e.g., adsorbents, catalysts). Reduce or avoid the use of energy-intensive metal separation and high-temperature reduction steps to reduce energy consumption and avoid many high-impact chemical materials. Based on the preliminary carbon footprint analysis, the emission is as low as 0.5-1kg CO_2-eq/kg of the produced functional material[42], and most of these are caused by low-temperature thermal treatment (e.g., calcination at 300-600 °C) and activation. The first is that they do not produce pollutants during the upstream synthesis of raw materials, and there are no downstream extractive metallurgy costs.

Therefore, although all the routes promote resource circularity, direct conversion into functional materials is likely to be more feasible in terms of energy and carbon emissions; thus, it is better aligned with the principles of green chemistry by maximising atom economy and reducing the number of process steps. In the future, the division of functions and the scope of the standardisation system for LCAs will likely be further refined (e.g., per kg of products or per unit of water treatment capacity) in order to quantify the benefits of these standardisation initiatives more precisely.

4. Classification and performance of black mass-derived functional materials

4.1. Adsorbent materials

Transformation of black mass into high-efficiency adsorbent materials is a good way to realise "treating pollutants with waste" and advance cost-effective water treatment. Generally speaking, the three categories of adsorbents based on their origin and purpose are graphite-based materials, cathode-derived materials, and composite materials. Table 2 shows the target adsorbates, adsorption mechanisms and adsorption capacities of these.

Graphite-based adsorbents are typical examples. Adjust the specific surface area, pore structure and functional groups at the surface using these. For example, Geng et al. prepared micro-expanded graphite (MEG) adsorbents from spent LIB graphite anodes by perchloric acid oxidation; the specific surface area increased by 16.3% and the pore volume increased by 107%, and thus completely removed low-concentration methylene blue (MB) through synergistic van der Waals forces and electrostatic interactions [43]. Similarly, Natarajan et al. converted recycled graphite into graphite oxide (GO) using Hummers' method, which achieved an adsorption capacity of 134.1mg/g for Congo Red (CR) due to its relatively large specific surface area (37 m_2/g) and abundant oxygen-containing functional groups[44]. Recently, Premathilake et al. employed chemical oxidation to convert residual graphite powder from hydrometallurgical recycling into graphite oxide (GO) and graphene oxide (GrO), which demonstrated high adsorption capacities for organic dyes (MB and Malachite Green (MG), >550 mg/g) and heavy metal ions (Cd(II), Ni(II), Zn(II); up to 93 mg/g)[45]. Fan et al. prepared layered graphene from spent battery graphite by electrochemical exfoliation in a later study and obtained adsorption capacities of 73 mg/g for Sr(II) and 55 mg/g for Cs(I)[46]. This material also showed good regeneration and maintained an efficiency of more than 90% efficacy in subsequent adsorption-desorption cycles.

Cathode-derived adsorbents are based on transition metal-rich black mass (e.g., LFP, LMO), and metallic active sites can directly interact with pollutants or act as metal sources for synthesizing new adsorbents. Zhang et al. have used spent LFP and LMO black mass as heavy metal adsorbents after simple acid washing and heat treatment to achieve Pb(II) adsorption capacities of 39.54 and 31.83 mg/g, respectively. The adsorption behaviour followed the Langmuir isotherm and pseudo-second-order kinetic models, and monolayer chemisorption was the main mechanism. A higher-end way is hydrothermal synthesis of high-performance adsorbents from black mass[47]. Zou et al. have prepared a new zeolite material (AlFePO-Li) by leaching and hydrothermal treatment of spent LFP black mass (Figure 1), which demonstrates excellent adsorption capacity for Pb(II) at 723.8 mg/g[48]. The same group prepared a magnetic core-shell adsorbent through alkali dissolution and silica coating. This material effectively adsorbed Cu(II), Cd(II) and Mn(II) with capacities of 71.23, 80.31 and 68.73 mg/g, respectively, and had good magnetic separation properties[49].

Composite adsorbents overcome limitations of single-component materials through synergistic improvement. Commonly, metal oxides such as MnO_2 are placed on graphite surfaces or active groups are introduced through ball milling or hydrothermal methods during preparation. For example, Zhao et al. attached MnO_2 particles to thermally purified anode graphite (AG) and achieved removal rates of 99.9%, 79.7% and 99.8% for Pb(II), Cd(II) and Ag(I), respectively[50]. Hao et al. increased the Cd(II) adsorption capacity to 135.81 mg/g by ball milling activation and then MnO_2 loading[51], Yan et al. prepared an AMO@GO composite that achieved saturated adsorption capacities of 233.99, 353.13, and 257.95 mg/g for Cu(II), Pb(II), and Cd(II), respectively, surpassing most graphite-based adsorbents[52]. Hou et al. recently prepared a thiol- and $Fe(OH)_3$-rich dual-site adsorbent (SFG) from iron-containing graphite powder (6 wt% Fe) in a single-step chemical method (Figure 2). The material has a high adsorption capacity for

Table 2. Black mass-derived adsorbent materials and their characteristics.

Precursor	Adsorbent types	Adsorption object	Adsorption mechanism	Adsorption capacity
Anode materials	Graphite derived materials[43-46]	Organic dyes, certain heavy metals/radioactive nuclides	Physisorption (van der Waals forces)/ electrostatic interaction/π-π interaction	Dozens to hundreds mg/g
Cathode materials	LFP/NCM/LMO derived materials[47-49]	Heavy metals (Pb(II), Cu(II), Cd(II), etc.)	Surface coordination/ion exchange/chemical precipitation	Dozens to over 700 mg/g
Composite materials	Multiple black mass and other functional materials[50-53]	Various heavy metal ions	Synergistic effects of multiple mechanisms (e.g., ion exchange, surface complexation, coprecipitation, etc.)	Hundreds to thousands mg/g

清華大學出版社 Tsinghua University Press | SciOpen



Fig. 1. Schematic diagram of the preparation of zeolite-type adsorbent material AlFePO-Li from spent LFP[48].

Cu(II) at 185.2 mg/g, and both the Freundlich isotherm and the pseudo-second-order kinetic model were suitable fits; therefore, multilayer chemisorption occurred[53].

External circumstances of the experiment are also affecting the performance of the above-mentioned adsorbents, such as pH, ionic strength and interfering ions. Anion adsorption is generally promoted in an acidic environment[53], and the removal of cations is more efficient at a neutral to alkaline conditions[50]. Most materials show good regenerability and maintain more than 80% of their initial adsorption capacity after 4-6 adsorption-desorption cycles; thus, they are relatively stable in use[47].

4.2. Fenton catalytic materials

Heterogeneous Fenton catalytic technology utilizes transition metals (e.g., Fe, Co, Mn) to activate hydrogen peroxide (H_2O_2) or other peroxides, generating highly reactive hydroxyl radicals (•OH) or other reactive oxygen species (ROSs) for organic pollutants degradation[54, 55]. Utilizing valuable components from spent LIBs to prepare Fenton catalysts aligns with the "treating pollutants with waste" resource recovery goal. Derived catalysts mainly fall into five categories: (i) iron-based Fenton catalysts, (ii) polymetallic-based Fenton catalysts, (iii) graphite anode-derived catalysts, (iv) co-converted catalysts from multiple wastes, and (v) other metal-based catalysts. Table 3 compares the sources, target pollutants, and performances of typical Fenton catalytic materials.

Iron-based catalysts derived from LFP cathode material exploit its inherent iron abundance. For instance, Zhu et al. directly used LFP cathode acid leachate to treat phenol-containing wastewater, reducing costs by 29.3% while achieving over

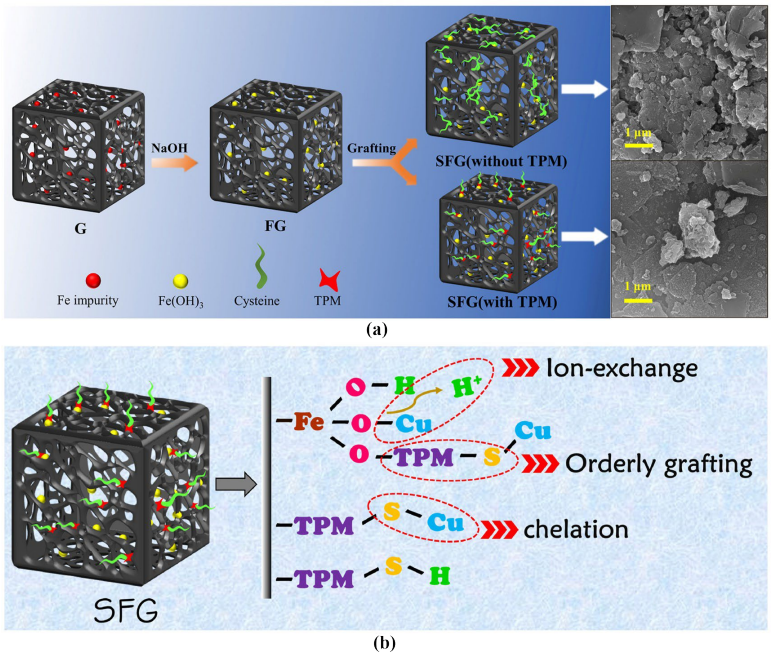


Fig. 2. Schematic illustration of (a) the preparation process of the SFG adsorbent and (b) its adsorption mechanism for Cu^{2+}[53].

Table 3. Black mass-derived Fenton catalytic materials and their main characteristics.

Precursor	Catalyst type	Target pollutants	Typical activation system	Degradation performance	Key mechanisms
Cathode materials	LFP derived iron oxides[56, 57]	Phenolic compounds, RB4, RhB	H_2O_2/NH_2OH	Degradation efficiency >90% (15–60 min)	Fe(II)/Fe(III) cycle, NH_2OH-mediated generation of •OH/$^1O_2$
	NCM derived polymetallic[58]	TCP	Peracetic Acid (PAA)	Degradation efficiency >96% (20 min)	Multimetal synergy, oxygen vacancies promoting radical generation
	Copper/manganese oxides[67, 68]	MB, SDZ	H_2O_2/photo-Fenton	Degradation efficiency >96% (45 min)	Enhanced charge separation, metal valence changes activating H_2O_2
Anode materials	Carbon supported metals[59-62]	TC, 4-CP, BPA	H_2O_2/electro-Fenton	Degradation efficiency >97% (60–70 min)	Zero-valent iron activation, •OH oxidation
Composite materials	Co-converted materials[64-66]	IBU, 4-CP	H_2O_2	Efficient degradation (1–2 h)	Component synergy providing functional groups and active sites

50% mineralization efficiency with significantly reduced biological toxicity[56]. Interestingly, Zou et al. transformed spent LFP into a sea urchin-like material (SULM) via a hydrothermal method, which enhanced Fe(III)/Fe(II) cycling in the presence of hydroxylamine to promote •OH and singlet oxygen ($^1O_2$) generation for rapid Rhodamine B (RhB) degradation (Figure 3)[57].

Polymetallic catalysts derived from ternary cathode material ($LiNi_xCo_yMn_{1-x-y}O_2$) leverage transition metal synergies. Feng et al. developed a catalytic membrane by supporting ternary LIB cathode material ($LiNi_xCo_yMn_2O_2$, LNCM) on polytetrafluoroethylene (PTFE) membrane, achieving 96.4% removal of 2,4,6-trichlorophenol (TCP) within 20 minutes through peracetic acid (PAA) activation (Figure 4). The degradation involved carbon-centered radicals and singlet oxygen ($^1O_2$) generated via synergistic multivalent metal redox cycling and oxygen vacancies[58].

Graphite-derived catalysts can be produced from spent battery anodes using methods such as exfoliation, activation or carbothermal reduction, and these carbon-based composites, including zero-valent iron/graphite materials, exhibit catalytic properties. For example, zero-valent iron/expanded graphite (ZVI/EG) prepared by electrochemical exfoliation and carbothermal reduction degraded 98.01% tetracycline hydrochloride (TC) in 60 minutes[59], and a porous metal-doped graphite catalyst (PMG) achieved a removal rate of 98.3% for TC within 2 minutes via superoxide radical pathways[60]. Graphite from used LIBs has been obtained, and researchers have developed specific characteristics of the oxidation process. Cao et al. treated graphite with acid leaching to increase the content of carboxyl groups to 35.83% and improved its function as an electro-Fenton cathode, achieving full degradation of bisphenol A (BPA) in 70 minutes[61]. Guan et al. have prepared a ZVI/expanded graphite composite that can degrade 4-chlorophenol (4-CP) with a rate of 97 per hour through •OH oxidation[62]. Based on the above progress, a recent study has also demonstrated the scalable production and practical application of used graphite anodes in continuous-flow Fenton-like systems for BPA degradation[63]. The work tested three types of decommissioned graphite and regenerated them using four combined wet/thermal methods. Among them, acid washing followed by calcination (AW+CT) performed best overall; based on catalytic activity, lithium recovery (99.92%), energy efficiency, metal safety and cost-effectiveness for BPA removal, it achieved a comprehensive score of 95.68 %. A fixed-bed column was set up and run continuously for one month to verify the continuous-treatment capability of the optimised material. A representative catalyst system showed a gradual decline in performance; however, AW+CT regenerated graphite achieved a near 100% reduction rate of BPA over time and maintained both stability and continuous catalytic activity under dynamic-flow conditions in the experiments. In addition, after a long period of operation, metal leaching in the treated water still met the discharge standards, so an environmentally friendly and feasible system for large-scale continuous wastewater treatment has been confirmed[66].

Co-converted catalysts from multiple waste streams have shown improved performance. Chen et al. prepared zero-valent iron/carbon (ZVI/C-X) and zero-valent iron-copper/carbon (ZVI-Cu/C) composites through carbothermal reduction of rolling mill-scale and spent LIB anodes, and showed good per-

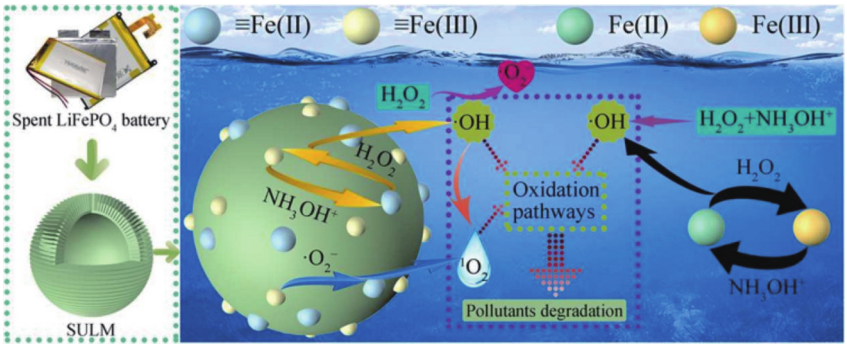


Fig. 3. Schematic illustration of the hydroxylamine-mediated activation of H_2O_2 by the iron-based SULM catalyst derived from spent LFP[57].

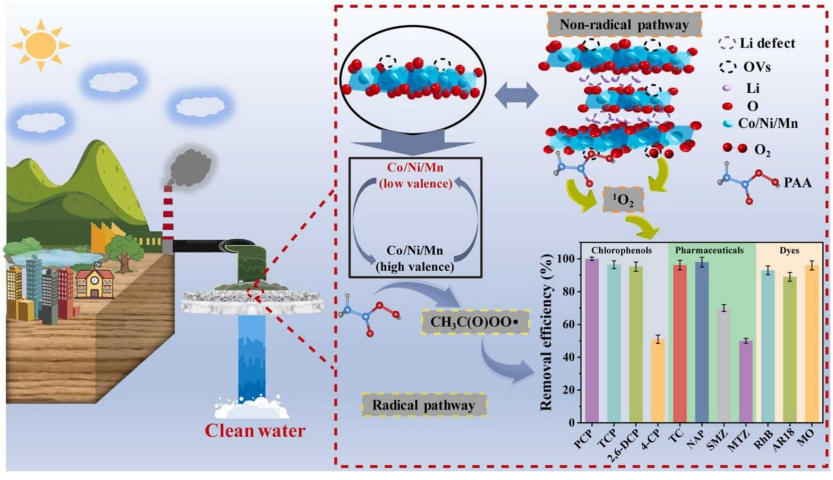


Fig. 4. Schematic illustration of organic pollutant degradation via peracetic acid activation by a catalyst derived from spent NCM[58].

清華大學出版社 Tsinghua University Press | SciOpen

formance in degrading ibuprofen (IBU) and 4-chlorophenol (4-CP) (Figure 5)[64-65]. Gao et al. have also produced a ZVI/graphite-plastic carbon composite (ZVI/GP) by co-processing graphite and plastic casing from spent LIBs, where graphite acts as a conductive matrix, and pyrolyzed plastic is added to introduce functional groups that enhance the degradation performance of 4-CP[66].

Copper-manganese-based catalysts derived from spent LIBs have been developed to some extent in spinel-type or composite forms for advanced oxidation reactions. Rocha and others used copper recovered from spent LIBs to prepare copper ferrite ($CuFe_2O_4$) and achieved a 96.1% reduction of Methylene Blue (MB) in 45 minutes in a photo-Fenton system; at the same time, there was a low metal leaching (Cu: 0.09 mg/L^{-1}; Fe: 0.37 mg/L^{-1})[67]. Chen and others have also prepared a MnO_2/nZVI composite catalyst using recovered manganese. Increase the mass ratio of MnO_2 to nZVI to 40:1, and the catalyst achieved 98.6% degradation of sulfadiazine (SDZ) under acidic conditions (pH 3) and showed stable performance over five consecutive cycles [68].

The above developments indicate that spent LIBs-derived Fenton catalysts can effectively degrade pollutants, and at the same time, high-value utilization of critical metals and graphite can be achieved to address both waste resource recovery and environmental pollution control. The economic benefits of these catalysts over the traditional commercial Fenton system have not been fully realised and are not well-documented. Research using continuous-flow treatment systems is also lacking, and most laboratory-scale batch experiments have yet to be applied in real-world, large-scale wastewater treatment. Therefore, the future direction of research should focus on the scalable production of derived catalytic materials, systematic evaluation of their performance in continuous-flow setups, and all-encompassing cost-benefit analyses. At the same time, more attention will be paid to the control of the material structure, research will be carried out on the application of these catalysts in treating real industrial wastewater, and their long-term stability under dynamic conditions will be guaranteed.

4.3. Persulfate activation materials

Persulfate-based advanced oxidation processes generate sulfate radicals ($SO_4^{\bullet -}$) with high oxidation potential, extended half-life, and broad pH adaptability. Converting black mass into persulfate-activating catalysts has emerged as a primary application pathway for "treating pollutants with waste" utilization of spent LIBs. A comparative summary of the performance of such black mass-derived catalysts is provided in Table 4.

Current research in the area focuses predominantly on cata-

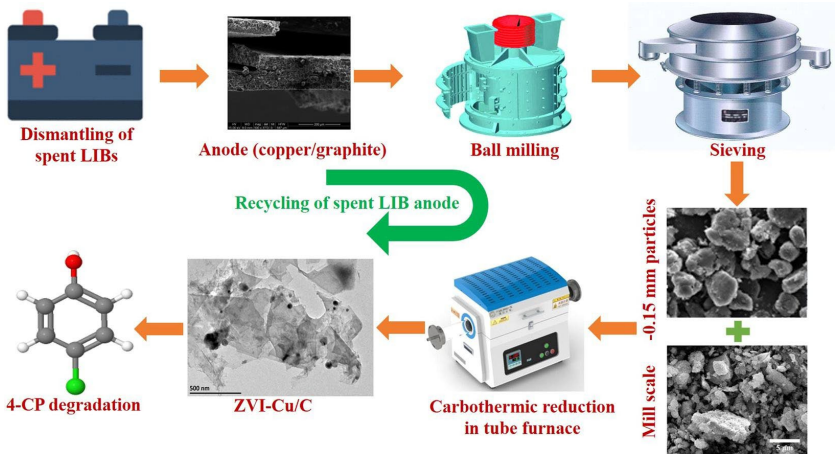


Fig. 5. Schematic illustration of preparation of ZVI-Cu/C and its application for 4-chlorophenol (4-CP) degradation via PMS activation[65].

Table 4. Application performance of persulfate catalysts derived from spent LIB battery black mass.

Precursor	Catalyst type (Example)	Target pollutant	Degradation efficiency	Primary activation mechanism	Main advantages
Cathode materials	Cobalt-based catalyst[69, 71, 72] (CM-850)	LFX	>94% degradation within 60 min	Co^{2+}/Co^{3+} cycle, radical and non-radical synergy	Easy preparation, low batch to batch variation
	Doped cobalt-based catalyst[73] (Co_3O_4-LIBs)	BPA	Rate constant: 0.523 min^{-1}	Al/Cu doping optimizes electronic structure, enhanced adsorption & charge transfer	Higher activity than commercial catalysts, low cost
	Ternary catalyst[75-82] (E-PD@NCM)	SMX	Degradation efficiency increased by 1.61 times	Oxygen vacancies induced by external electric field promote $SO_4^{\bullet -}$ and $^1O_2$ generation	Tunable electronic structure, high activity
Anode materials	Graphite based catalyst[83-85]	CBZ	Highly efficient degradation within pH 3–11	Electron transfer mediated by surface functional groups (C=O, C–OH)	No metal leaching, environmentally friendly, good universality
Composite materials	Cobalt from cathode & graphite from anode (CoO@C)[86]	ATZ	Complete degradation within 15 min	Metal-support synergy, electron transfer	Suitable for immobilized, continuous-flow operation, high stability
	LCO with biomass[87-91] (CoONAl-C)	Multiple pollutants	Near 100% PMS utilization	Multi-element (Co, O, N, Al, C) synergy	High degradation rate, low metal leaching, utilization of multiple waste streams

lysts derived from cathode materials, among which cobalt-based systems exhibit superior activity. For example, Wang et al. directly employed recovered LCO cathode material as a catalyst, achieving 98.2% degradation of carbamazepine (CBZ) within 10 minutes via peroxymonosulfate (PMS) activation. The process, driven by cobalt valence cycling, generated $^1O_2$, SO_4•$^-$, and •OH, and retained high efficiency across pH 5.0–11.0 and over six consecutive cycles[69]. Moreover, the concentration of leached cobalt ions was measured to be below 0.1 mg/L, well under the 1 mg/L limit set by the Chinese national discharge standard (GB 25467–2010) for water environments[70]. Similarly, Lin et al. directly utilized spent LCO black mass as a catalyst, exploiting its intrinsic defects and cobalt sites to activate PMS into SO_4•$^-$ and $^1O_2$. Under optimal conditions, their system degraded >99% of benzalkonium chloride (BAC) within 40 minutes, with a rate constant 1.9 times higher than that of commercial Co_3O_4[71]. Zhao et al. obtained a CM-850 catalyst by direct calcination of LCO cathode black mass, which achieved >94% removal of levofloxacin (LFX) within 60 minutes across a wide pH range, through Co(II)/Co(III)-mediated generation of SO_4•$^-$, •OH, and $^1O_2$[72]. Notably, residual elements from the current collectors, such as aluminum and copper, can further enhance catalytic performance. Liang et al. demonstrated that Al doping shortens the Co–O bond and promotes persulfate adsorption, while Cu doping lowers interfacial charge transfer resistance. Their synergistic effect increased the BPA degradation rate constant of Co_3O_4-LIBs to 0.523 min^{-1}, nearly double that of Co_3O_4 prepared from commercial precursors (Figure 6)[73]. Recent advances also show that certain lithium extraction processes can directly yield active cobalt-based catalysts. For instance, Liang et al. treated LCO cathode black mass with PMS to selectively leach lithium (Leaching efficiency of 96.6% at an initial pH of 11) while producing a cobalt oxide catalyst rich in oxygen vacancies. This catalyst activates PMS through combined radical and non-radical pathways to degrade CBZ efficiently across varied pH conditions and complex water matrices[74].

Beyond cobalt-based systems, ternary cathode materials have gained considerable interest due to their polymetallic synergy. Zhao et al. directly converted spent $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ cathode waste into an efficient PMS catalyst (NCM-650) (Figure 7). Leveraging the Co(II)/Mn(IV) redox coupling, the catalyst completely degrade RhB within 25 minutes via a predominantly $^1O_2$-mediated non-radical pathway, supported by radical species (•OH, SO_4•$^-$, •O_2^-), while maintaining high activity and stability over a wide pH range[75]. Similarly, Gao et al. transformed spent $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ black mass into a Ni-Co-Mn ternary catalyst (CM-650) via one-step calcination. The cooperative activation of PMS by the three variable-valence metals generated both radical (•OH, SO_4•$^-$, •O_2^-) and non-radical species ($^1O_2$), leading to complete iopamid degradation[76]. Further introduction of active sites such as oxygen vacancies or copper can enhance activity on this polymetallic basis. Dang et al. achieved simultaneous lithium extraction and catalyst preparation through electrochemical oxidation of $LiNi_xCo_yMn_2O_2$, obtaining an oxygen vacancy-rich material that completely degraded sulfamethoxazole (SMX) within 30 minutes with PMS[77]. Zhou et al. treated spent NCM black mass by external electric field polarization, producing an oxygen vacancy-enriched E-PD@NCM catalyst with SMX degradation efficiency 1.61 times that of the unmodified counterpart, primarily via SO_4•$^-$ and $^1O_2$[78]. Gong et al. employed sulfuric acid leaching to recover valuable metals from spent NCM, achieving high extraction efficiencies of 97.87% for Ni, 98.75% for Co, and 98.56% for Mn[79]. Using the leached solution supplemented with a copper salt, they synthesized a quaternary metal spinel-type oxide ($(MnCoNiCu)_3O_4$), which enabled complete degradation of phenol within 10 minutes and exhibited excellent stability, retaining over 90% degradation efficiency after four consecutive reaction cycles.

Deconstruction-reconstruction processes can often transform recovered metal ions into catalysts with favorable properties. Tang et al. processed spent NCM cathode powder through dissolution, lithium extraction, drying, and calcination to obtain a polymetallic catalyst (M/BP-BC-700) with a high specific surface area (302.8 m^2/g). This catalyst activated PMS to generate SO_4•$^-$ and $^1O_2$, enabling rapid degradation of MB, RhB, and ciprofloxacin (CIP)[80]. Xu et al. followed a similar synthesis route to treat NCM black mass, producing a polymetallic catalyst that also effectively degraded MB, RhB, SMX, and LFX[81]. Yang developed an integrated recovery process to extract Ni, Co, and Mn from spent NCM cathode powder and rapidly synthesized a trimetallic layered double hydroxide catalyst (NiCoMn-LDH) with a specific surface area of 115.98 m^2/g.

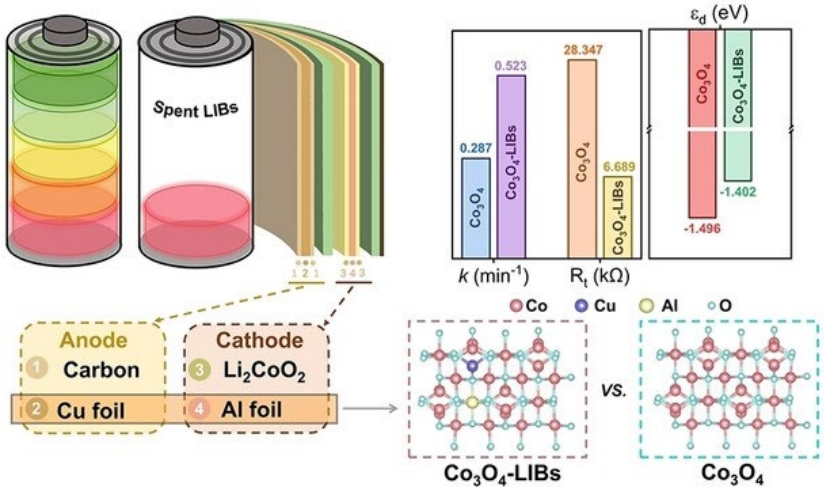


Fig. 6. Comparative analysis of Co_3O_4-LIBs (with co-doping of Cu and Al) and commercial Co_3O_4 catalysts[73].

清華大學出版社 Tsinghua University Press | SciOpen

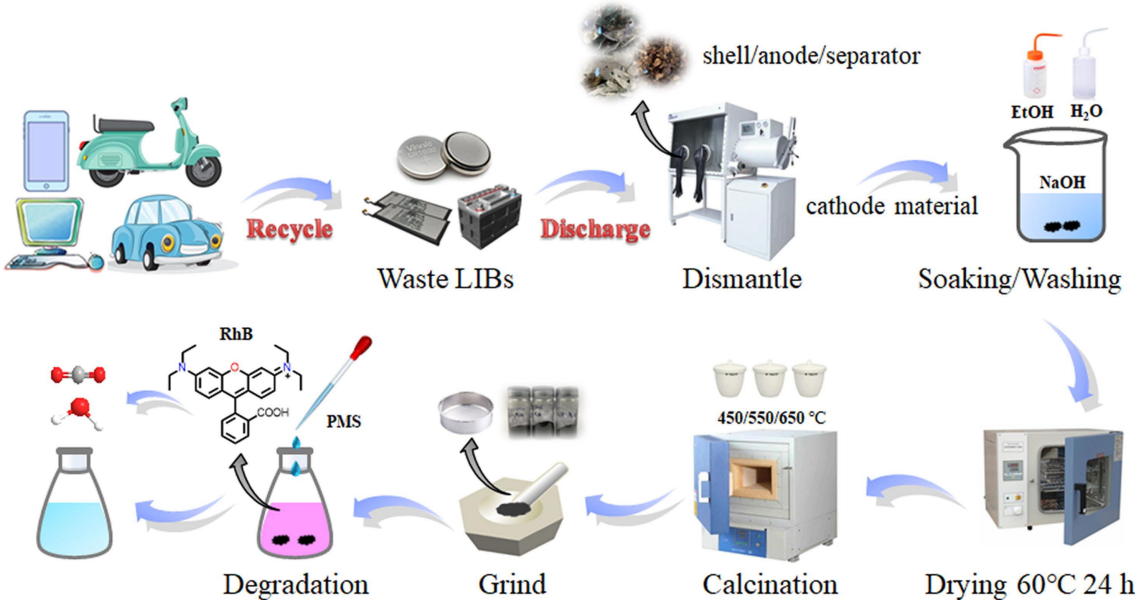


Fig. 7. Schematic illustration of catalyst preparation from spent $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ black mass for RhB degradation via PMS activation[75].

Under near-neutral conditions with very low dosages (catalyst 10 mg/L, PMS 0.1 mmol/L), it completely degraded tetrabromobisphenol S (TBBPS) within 100 seconds and exhibited good cycling stability[82].

Compared with cathode-derived catalysts, the non-metal path of anode graphite has the advantages of low metal leaching and environmental friendliness. Yan et al. used recycled graphite as a direct catalyst to demonstrate that surface carbonyl and hydroxyl groups activated peroxymonosulfate (PMS) for the degradation of carbamazepine (CBZ); at a pH of 3-11, 93% degradation efficiency was achieved in tap water[83]. Qian et al. calcined spent anode graphite at 800 °C, identified carbonyl groups as the main active sites for PMS activation; the system degraded 99.2% of atrazine (ATZ) in 6 minutes and was reusable[84]. Nitrogen doping and other modifications can also be used to alter the electronic structure of graphite. Yan et al. have shown that nitrogen-doped graphite promotes a $^1O_2$-dominated non-radical pathway via graphitic N-sites to enhance the degradation of RhB[85].

Combine cathode and anode materials to construct a high-performance catalyst synergistically, although research is still in its early stages. Chen et al. made CoO@C from cobalt-rich leachate and anode graphite. Metal-support interactions optimised electron distribution to achieve full degradation of atrazine (ATZ) in 15 minutes (Figure 8). Immobilised catalysts maintained a continuous-flow reactor efficiency of >90% for a 6L wastewater system[86].

Biomass-assisted co-conversion of black mass and waste biomass can be used to value-add multiple waste streams and produce high-performance composite catalysts. Zhou et al. used spent LCO black mass and wood chips for pyrolysis-reduction to produce CoO-C. Synergy of CoO and a carbon carrier achieved 99.99% degradation of CIP in 30 minutes and a high TOF (2.9714 min^{-1})[87]. Guo et al. combined LCO waste with tobacco stalks to build a multi-element-doped CoONAl-C catalyst (Figure 9), and this catalyst showed near-complete peroxysulfate utilisation and a degradation rate that was 2-42 times higher than that of conventional systems[88]. Hou et al. prepared a Co_9S_8-immobilized biochar composite (LCo-NSBC) with a three-dimensional (3D) honeycomb-like structure by a sol-gel method from spent LCO and polygonatum sibiricum residue. LCo-NSBC completely degraded CBZ within 50 minutes, performing comparably to a catalyst (Co-NSBC) prepared from commercial reagents while leaching far less cobalt (0.084 vs. 0.616 mg/L)[89]. Gao et al. combined spent NCM with buckwheat husks to produce a biochar-supported Ni^0/Co^0/MnO polymetallic composite catalyst ($850BC_{10}CM$) that activated PMS to degrade IPM over a pH 5.0–10.0 with a rate constant of 0.0944 min^{-1} within 25 minutes, exhibiting low metal leaching (0.035–0.089 mg/L) and good stability[90]. Hu et al. utilized rice husks and Co(II), Ni(II), Mn(II) ions from NCM leachate to synthesize a "dandelion-like" nanoparticle-cluster catalyst (X@DRHC, X=Co, Ni, Mn) on desilicated rice-huck carbon; it activated PMS to degrade various dyes over a wide pH range with good stability[91].

While catalyst design advances, mechanistic understanding is expanding from radical-dominated pathways to non-radical synergy. Li et al. showed that a Co-NC composite generated $^1O_2$ via the PMS→•OH→•O→$^1O_2$ route as the sole crucial active species for BPA degradation[92]. Liang et al. found that their manganese-based spinel ferrite activated persulfate via a surface electron-transfer mechanism, remaining stable under high salinity, humic acid, and alkaline conditions[93]. Structure-activity studies further guide catalyst optimization. Zhao et al. compared graphite catalysts calcined at different temperatures and found that AM-450 primarily followed a non-radical pathway dominated by surface electron transfer, while AM-850 mainly involved a radical pathway. The former exhibited a higher rate constant for CIP degradation (0.0514 vs. 0.0315 min^{-1}), highlighting how the carbon electronic structure directs the reaction path[94]. Lv et al. synthesized different MnO_2 phases (λ-MnO_2 and β-MnO_2) from spent LMO; β-MnO_2 degraded >95% of SDZ, with its high crystallinity and relatively high Mn(III) proportion identified as key to its activity[95].

Despite the above merits, the applied battery-derived persulfate catalysts still have deficiencies. Cobalt-based systems with concentrations of >0.1mg/L and their relatives are still prone to metal leaching, and the performance of graphite-

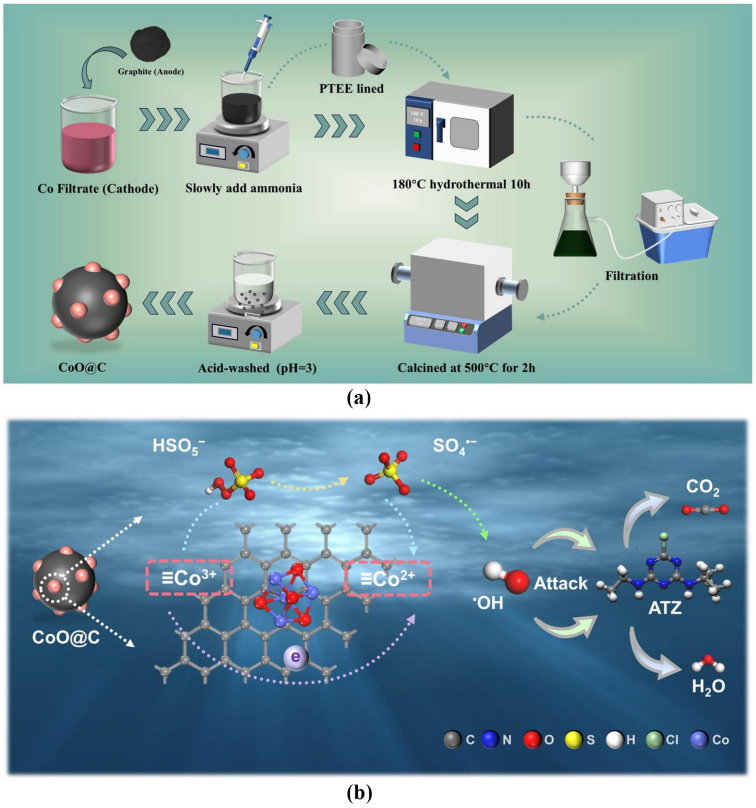


Fig. 8. Schematic illustration of (a) synthesis of CoO@C material and (b) its mechanism for atrazine (ATZ) degradation via peroxymonosulfate (PMS) activation[86].



Fig. 9. Co-conversion of Spent LCO and tobacco stalk waste for the synthesis of multi-element doped CoONAl-C catalyst[88].

based analogues needs to be enhanced. Although the degradation results obtained in the laboratory have been all-around good, they need to be applied to more difficult, real-water conditions in subsequent experiments. In the future, precise control over active sites will be achieved to suppress leaching, all-component valorisation of cathode-anode composites will be realised, and optimisation studies will be conducted in conjunction with long-term stability tests under realistic conditions. The above work will help to apply this technology in engineering practice.

4.4. Other water treatment functional materials

Black mass can also be converted into photocatalysta, ozone catalysts, catalytic wet air oxidation (CWAO) materials and disinfectants for advanced water treatment, among others. Hossain et al. synthesized phase-pure porous Co_3O_4 nanoparticles by pyrolysis for photocatalysis and showed good degradation activity and cycling stability of dyes (e.g., MB) under visible-light irradiation[96]. Abozeid et al. prepared a $C/Li_3Fe_5O_8/Ag$ heterojunction from spent anode graphite and achieved a 75% degradation rate of oxytetracycline (OTC) and

清華大學出版社 Tsinghua University Press | SciOpen

an 80% reduction rate of Cr(VI) under UV light[97]. Yue et al. transformed spent LFP into a $NaFeS_2$ visible-light catalyst that degraded 98% of MB in 20 minutes, and its degradation rate constant was 67 times than that of commercial TiO_2 (Figure 10)[98].

For ozone catalysis, Xu et al. have prepared thermally modified graphite from battery leaching residue to act as a good ozone catalyst and have also determined the specific functions of surface defects and pyridinic nitrogen[31]. Xu et al. developed a manganese-based oxide catalyst in catalytic wet air oxidation (CWAO) for this purpose; based on old ternary batteries, 98% of thiosulfate was removed and the performance surpassed that of existing manganese-based catalysts by 4.1 times[99]. Abdel-Rahim et al. have created an antimicrobial nanomaterial in disinfection by combining silver nanoparticles with nitrogen-sulfur dual-doped reduced graphene oxide (AgNPs@NSG), which is derived from waste batteries, and shown that it can inhibit the growth of various bacteria to an extent of 9.67-12.00 mm in the inhibition zone[100].

The above studies can extract high-value materials from spent batteries and are also highly applicable to difficult-to-treat water.

5. Conclusions and prospects

5.1. Research summary

Several ways have been investigated to develop high-performance upcycled water treatment materials from spent LIB black mass in this review. The first innovation of this "treating pollutants with waste" approach is a change in paradigm; that is to say, it no longer aims only to recover metals but uses the inherent chemical and structural characteristics of black mass components to produce functional materials for pollution treatment directly. Based on the above key conclusions, this new idea is supported: (i) The intrinsic value of black mass components (transition metals, graphite) can be rationally utilized to synthesize a variety of high-value materials, such as adsorbents, Fenton-like catalysts, and persulfate activators; (ii) These recycled materials have shown good or excellent pollutant removal performance in experiments compared with many traditional ones (e.g., high adsorption capacity, ultrafast degradation kinetics); (iii) Therefore, this approach can be used to reduce both the environmental impact of battery waste and the production costs of water treatment materials, thus achieving a material loop [101]. The scientific foundation of the above recycling process is introduced in this paper, and high-efficiency water purification materials from black mass are to be developed.

5.2. Current limitations

Although upcycling the black mass of waste LIBs into water-purification materials has shown positive results for both the recovery of waste resources and environmental protection, many scientific and technical problems remain unsolved; thus, these innovations cannot be widely applied or developed continuously at this time. The primary challenges are as followed:

(i) Lack of Validation for Material Stability and Practicality. Most of the studies are not conducted in a practical, real-world setting. There is a critical lack of robust assessment regarding the long-term operational stability, reusability, and efficacy of these materials in complex, real-world water matrices containing diverse interfering ions and natural organic matter. Performance claims derived from idealized conditions may not translate directly to practical scenarios.

(ii) Absence of Scalable and Standardized Synthesis Protocols. Current synthesis methods are predominantly batch-oriented, intricate, and difficult to scale. The transition from lab-scale proof-of-concept to industrial-scale production requires the development of continuous, energy-efficient, and standardized fabrication pathways that guarantee consistent material quality, morphology, and performance—a prerequisite for reliable water treatment applications.

(iii) Inadequate Holistic Environmental and Risk Assessment. A comprehensive evaluation of the net environmental benefit is often missing. Key concerns include the potential risk of secondary pollution from metal leaching during material use and disposal, as well as the energy and environmental footprint of the upcycling process itself. Systematic life cycle assessment (LCA) is essential to quantify the true environmental sustainability of this approach versus conventional waste treatment or material production routes.

(iv) Unclear Economic Viability and Cost-Benefit Analysis. Although the raw material (black mass) is a low-cost waste stream, the overall economic feasibility remains ambiguous. A detailed techno-economic analysis is needed to compare the total cost of the upcycling process (including collection, pretreatment, synthesis, and regeneration) against established

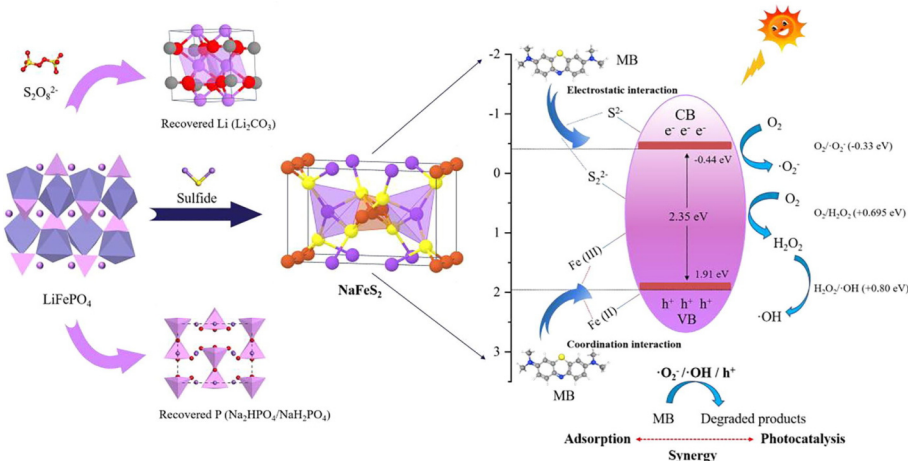


Fig. 10. Schematic illustration of MB degradation by $NaFeS_2$ visible-light catalyst derived from spent LFP[98].

commercial water treatment materials. Clear demonstration of cost-effectiveness is crucial for industry adoption.

5.3. Future perspectives

To advance this innovative field from promising concept to practical reality, future research should adopt a problem-driven approach that directly addresses the current limitations. Efforts must pivot from proof-of-concept demonstrations to targeted investigations aimed at overcoming the specific barriers to scalability, stability, and sustainability. The following research directions are critical:

(i) Advanced Material Design Focused on Robustness and Adaptability. Future synthesis strategies must move beyond optimizing activity in ideal conditions. Research should prioritize developing robust pre-processing and design protocols to handle the inherent variability of black mass feedstock, ensuring consistent material performance. Concurrently, atomic-level engineering (e.g., single-atom catalysts[102]) should be pursued not only for activity but also for enhanced stability and selectivity in complex media. Designing multifunctional, integrated systems for synergistic processes remains a key goal[103].

(ii) Translation-Oriented Engineering and System Integration. Bridging the lab-to-plant gap requires parallel advancements in material engineering and reactor design[104-106]. This includes innovating reliable material immobilization techniques and modular reactor concepts for easy integration into existing water infrastructure. Most importantly, pilot-scale studies under real-world conditions are indispensable to validate long-term performance[107], inform scale-up parameters, and generate robust techno-economic data.

(iii) Holistic and Standardized Sustainability Evaluation. A comprehensive validation of the technology's net benefit is paramount. This requires strengthening life-cycle assessment (LCA) to quantify environmental footprints accurately and, crucially, establishing standard protocols to assess long-term environmental safety[108], including systematic ecotoxicological studies and leaching tests under operational conditions. Clear metrics for environmental and cost competitiveness versus conventional methods are needed for stakeholder adoption.

In summary, converting spent LIB black mass into functional water treatment materials represents a transformative, dual-value solution for critical environmental challenges. By shifting focus to targeted research that addresses feedstock processing, real-world application engineering, and rigorous system-level analysis, this field can mature into a viable and sustainable pillar of the circular economy, offering scalable solutions for both resource recovery and environmental remediation.

Acknowledgements

This work was financially supported by the Shenzhen Science and Technology Program (No. JCYJ20230807113709019), China Institute of Atomic Energy (No. BJ030261224901).

Conflict of interest

The authors declare no competing financial interests.

References

[1] Harper, G.; Sommerville, R.; Kendrick, E.; Driscoll, L.; Slater, P.; Stolkin, R.; Walton, A.; Christensen, P.; Heidrich, O.; Lambert, S. et al. Recycling lithium-ion batteries from electric vehicles. *Nature*, 2019, 575: 75–86.

[2] Degen, F.; Winter, M.; Bendig, D.; Tübke, J. Energy consumption of current and future production of lithium-ion and post lithium-ion battery cells. *Nat. Energy*, 2023, 8: 1284–1295.

[3] Grey, C. P.; Hall, D. S. Prospects for lithium-ion batteries and beyond—a 2030 vision. *Nat. Commun.*, 2020, 11: 6279.

[4] Frith, J. T., Lacey, M. J., Ulissi, U. A non-academic perspective on the future of lithium-based batteries. *Nat. Commun.*, 2023, 14: 420.

[5] Li, Y. R.; Cai, J. H.; Wang, J. Y.; Xu, S. N.; Li, Y. J.; He, W.; Wang, Z. Z.; Yang, S.; Yan, X. A comprehensive review on reductive recycling of cathode materials of spent lithium-ion batteries. *Chem.*, 2024, 30: e202400566.

[6] Yang, L.; Zhang, B. C.; Pan, Q.; Niu, C. Y.; Ding, H. R.; Li, W. Y.; Deng, W. T.; Zou, G. Q.; Hou, H. S.; Ji, X. B. Reimagining lithium-ion batteries end-of-life: Upcycling for high-value cathode materials futures. *Nano Energy*, 2025, 143: 111359.

[7] Miao, Y. P.; Liu, L. L.; Zhang, Y. P.; Tan, Q. Y.; Li, J. H. An overview of global power lithium-ion batteries and associated critical metal recycling. *J. Hazard. Mater.*, 2022, 425: 127900.

[8] Zhang, B.; Xin, Q. Y.; Chen, S. Y.; Wang, B.; Li, H.; Wang, Z. H.; Bansal, P. Lithium-ion battery recycling relieves the threat to material scarcity amid China's electric vehicle ambitions. *Nat. Commun.*, 2025, 16: 6661.

[9] Shen, J.; Zhou, M. M.; Liu, W.; Shi, Y. L.; Tang, W. H.; Deng, Y. R.; Liu, R. P.; Zuo, Y. Z.; Zhang, J. J. Advanced direct recycling technology enables a second life of spent lithium-ion battery. *Energy Storage Mater.*, 2025, 74: 103964.

[10] Shen, J.; Zhou, M. M.; Tang, W. H.; Huang, Q. R.; Pi, H. C.; Liu, W.; Liu, R. P.; Li, L. Surface reconstruction strategy enables rapid upcycling highly degraded layered cathode. *Nano Energy*, 2025, 136: 110741.

[11] Zhou, M. M.; Shen, J.; Duan, Y.; Zuo, Y. Z.; Xing, Z. W.; Liu, R. P. The Le Chatelier's principle enables closed loop regenerating ternary cathode materials for spent lithium-ion batteries. *Energy Storage Mater.*, 2024, 67: 103250.

[12] Shen, J.; Zhou, M. M.; Liu, W.; Pi, H. C.; Liu, R. P. Dual-function surface–bulk engineering *via* a one-step strategy enables efficient upcycling of degraded NCM523 cathodes. *EES Batter.*, 2025, 1: 1245–1254.

[13] Zhou, M. M.; Shen, J.; Zuo, Y. Z.; Liu, R. P.; Zhao, J. J.; Zhou, G. M. The Fischer-lactonization-driven mechanism for ultra-efficient recycling of spent lithium-ion batteries. *Angew. Chem.*, 2025, 137: e202414484.

[14] Makuza, B.; Tian, Q.; Guo, X.; Chattopadhyay, K.; Yu, D. Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review. *J. Power Sources*, 2021, 491:229622.

[15] Yao, Y. L.; Zhu, M. Y.; Zhao, Z.; Tong, B. H.; Fan, Y. Q.; Hua, Z. S. Hydrometallurgical processes for recycling spent lithium-ion batteries: A critical review. *ACS Sustainable Chem. Eng.*, 2018, 6: 13611–13627.

[16] He, M. Y.; Jin, X.; Zhang, X. G.; Duan, X. X.; Zhang, P. Y.; Teng, L. M.; Liu, Q. C.; Liu, W. Z. Combined pyro-hydrometallurgical technology for recovering valuable metal elements from spent lithium-ion batteries: A review of recent developments. *Green Chem.*, 2023, 25: 6561–6580.

[17] Hanafi, M. F., Sapawe, N. A review on the current techniques and technologies of organic pollutants removal from water/wastewater. *Mater. Today Proc.*, 2020, 31: A158–A165.

[18] Qasem, N. A. A., Mohammed, R. H., Lawal, D. U. Removal of heavy metal ions from wastewater: A comprehensive and critical review. *npj Clean Water*, 2021, 4: 36.

[19] X. Zhiqian, C. Zhijie, W. Zhiliang, L. Xiang-Yang, L. Xuran, N.

清華大學出版社 Tsinghua University Press | SciOpen

Bing-Jie, Spent battery-derived materials for wastewater treatment, Innovations in Water Treatment 1(1) (2025) 2.

[20] Murdock, B. E., Toghill, K. E., Tapia-Ruiz, N. A perspective on the sustainability of cathode materials used in lithium-ion batteries. *Adv. Energy Mater.*, 2021, 11: 2102028.

[21] Whittingham, M. S. Lithium batteries and cathode materials. *Chem. Rev.*, 2004, 104: 4271–4302.

[22] Wu, Y. P., Rahm, E.; Holze, R. Carbon anode materials for lithium ion batteries. *J. Power Sources*, 2003, 114: 228–236.

[23] Ordoñez, J.; Gago, E. J., Girard, A. Processes and technologies for the recycling and recovery of spent lithium-ion batteries. *Renew. Sustain. Energy Rev.*, 2016, 60: 195–205.

[24] Li, L.; Zhang, X. X.; Li, M.; Chen, R. J.; Wu, F.; Amine, K.; Lu, J. The recycling of spent lithium-ion batteries: A review of current processes and technologies. *Electrochem. Energy Rev.*, 2018, 1: 461–482.

[25] Li, L.; Yin, Z.; Cheng, M.; Qin, L.; Liu, S. Y.; Yi, H.; Zhang, M. M.; Fu, Y. K.; Yang, L.; Tang, C. S. et al. A potential link between the structure of iron catalysts and Fenton-like performance: From fundamental understanding to engineering design. *J. Mater. Chem. A*, 2022, 10: 12788–12804.

[26] Yang, Y. Q.; Zhang, Y. B.; Gao, X. Y.; Yang, Z. T.; Wang, H. Z.; Zhang, X. D. Performance and mechanism of *in situ* prepared NF@CoMnNi-LDH composites to activate PMS for degradation of enrofloxacin in water. *Water*, 2025, 17: 24.

[27] Gao, Q.; Wang, G. S.; Chen, Y. R.; Han, B.; Xia, K. S.; Zhou, C. G. Utilizing cobalt-doped materials as heterogeneous catalysts to activate peroxymonosulfate for organic pollutant degradation: A critical review. *Environ. Sci.: Water Res. Technol.*, 2021, 7: 1197–1211.

[28] Li, M.; Zhang, X. X.; Wang, S. J.; Wang, C. Q. A review of cobalt-based heterogeneous catalysts for peroxomonosulfate activation and antibiotics degradation: Catalyst synthesis, characterizations, regulation, and mechanism. *Sep. Purif. Technol.*, 2025, 356: 129989.

[29] Pan, Y. K.; Cao, J. Z.; Xing, M. Y.; Zhang, Y. Y. Current mechanism of peroxymonosulfate activation by cobalt-based heterogeneous catalysts in degrading organic compounds. *ACS EST Eng.*, 2024, 4: 19–46.

[30] Zhou, X. Q.; Shen, S. T.; Wang, P. P.; Wei, X. F.; Zhang, R. C.; Tang, H. Y.; Wang, H.; Lu, W. W.; Wang, J. Research progress on catalytic activation of peroxymonosulfate based on manganese oxides. *J. Environ. Chem. Eng.*, 2022, 10: 108937.

[31] Xu, Z. M.; Wang, J.; Sun, S. H.; Shi, Y. C.; Sun, Z. H. I.; Cao, H. B.; Xie, Y. B. Simple route for graphite recycling from waste lithium-ion batteries to environmental functional materials. *ACS Sustainable Chem. Eng.*, 2022, 10: 13435–13443.

[32] Han, S. J.; Xu, L.; Chen, C.; Wang, Z. Y.; Fu, M. L.; Yuan, B. L. Recovery of graphite from spent lithium-ion batteries and its wastewater treatment application: A review. *Sep. Purif. Technol.*, 2024, 330: 125289.

[33] Tian, H. H.; Graczyk-Zajac, M.; Kessler, A.; Weidenkaff, A.; Riedel, R. Recycling and reusing of graphite from retired lithium-ion batteries: A review. *Adv. Mater.*, 2024, 36: 2308494.

[34] Ida, T. K., Sonowal, K.; Golder, A. K., Mandal, B. Simple environmental-friendly method for graphite recovery from spent lithium-ion batteries and its utilization for the synthesis of graphene oxide. *Sep. Purif. Technol.*, 2025, 374: 133758.

[35] Duan, X. G.; Sun, H. Q.; Wang, S. B. Metal-free carbocatalysis in advanced oxidation reactions. *Acc. Chem. Res.*, 2018, 51: 678–687.

[36] Zhao, M. F.; Liu, P. Adsorption of methylene blue from aqueous solutions by modified expanded graphite powder. *Desalination*, 2009, 249: 331–336.

[37] Yang, W.; Cao, M. L. Study on the difference in adsorption performance of graphene oxide and carboxylated graphene oxide for Cu(II), Pb(II) respectively and mechanism analysis. *Diam. Relat. Mater.*, 2022, 129: 109332.

[38] Cornelio, A.; Zanoletti, A.; Bontempi, E. Recent progress in pyrometallurgy for the recovery of spent lithium-ion batteries: A review of state-of-the-art developments. *Curr. Opin. Green Sustain. Chem.*, 2024, 46: 100881.

[39] Zhou, M. X.; Li, B.; Li, J.; Xu, Z. M. Pyrometallurgical technology in the recycling of a spent lithium ion battery: Evolution and the challenge. *ACS EST Eng.*, 2021, 1: 1369–1382.

[40] Liu, A. W.; Hu, G. W.; Wu, Y. F.; Guo, F. Life cycle environmental impacts of pyrometallurgical and hydrometallurgical recovery processes for spent lithium-ion batteries: Present and future perspectives. *Clean Technol. Environ. Policy*, 2024, 26: 381–400.

[41] Liang, Z. L.; Cai, C.; Peng, G. W.; Hu, J. P.; Hou, H. J.; Liu, B. C.; Liang, S.; Xiao, K. K.; Yuan, S. S.; Yang, J. K. Hydrometallurgical recovery of spent lithium ion batteries: Environmental strategies and sustainability evaluation. *ACS Sustainable Chem. Eng.*, 2021, 9: 5750–5767.

[42] Qiu, B. L.; Hou, Y. Z.; Shi, Z.; Du, P.; Xu, N.; Xie, H. W.; Liu, K. R.; Chen, J. S.; Li, B. C.; Han, Q. et al. Co-upcycling spent lithium-ion batteries and plastics into microwave absorbing materials with Ni-Co catalyst control. *Nat. Commun.*, 2026, 17: 2822.

[43] Geng, Z. W.; Liu, J. J.; Geng, Y. N.; Peng, M. M.; Xiong, M. P.; Shi, H.; Luo, X. B. Separation and recovery of graphite from spent lithium–ion batteries for synthesizing micro-expanded sorbents. *New J. Chem.*, 2022, 46: 20250–20259.

[44] Natarajan, S.; Bajaj, H. C. Recovered materials from spent lithium-ion batteries (LIBs) as adsorbents for dye removal: Equilibrium, kinetics and mechanism. *J. Environ. Chem. Eng.*, 2016, 4: 4631–4643.

[45] Premathilake, D. S.; Colombi, F.; Botelho, A. B. Jr, Soares Tenório, J. A.; Romano Espinosa, D. C.; Vaccari, M. Recycling lithium-ion battery graphite: Synthesis of adsorbent materials for highly efficient removal of dye and metal ions from wastewater. *Results Eng.*, 2024, 22: 102232.

[46] Fan, X. Y.; Zeng, X. F.; Han, Y. H.; Luo, X. Y.; Li, H.; Xiao, X. Y.; Bai, J.; Chen, M. J. Sr(II) and Cs(I) adsorbed by graphene synthesized from spent lithium-ion batteries anode materials *via* novelly electrochemical exfoliation. *J. Environ. Radioact.*, 2025, 290: 107799.

[47] Zhang, Y. H.; Wang, Y. C.; Zhang, H. H.; Li, Y.; Zhang, Z. B.; Zhang, W. Recycling spent lithium-ion battery as adsorbents to remove aqueous heavy metals: Adsorption kinetics, isotherms, and regeneration assessment. *Resour. Conserv. Recycl.*, 2020, 156: 104688.

[48] Zou, W. S.; Feng, X. Z.; Wei, W. F.; Zhou, Y. H.; Wang, R. H.; Zheng, R. J.; Li, J.; Luo, S. Y.; Mi, H. W.; Chen, H. Converting spent $LiFePO_4$ battery into zeolitic phosphate for highly efficient heavy metal adsorption. *Inorg. Chem.*, 2021, 60: 9496–9503.

[49] Zou, W. S.; Feng, X. Z.; Wang, R. H.; Wei, W. F.; Luo, S. Y.; Zheng, R. J.; Yang, D. Z.; Mi, H. W.; Chen, H. High-efficiency core-shell magnetic heavy-metal absorbents derived from spent-$LiFePO_4$ Battery. *J. Hazard. Mater.*, 2021, 402: 123583.

[50] Zhao, T.; Yao, Y.; Wang, M. L.; Chen, R. J.; Yu, Y. J.; Wu, F.; Zhang, C. Z. Preparation of MnO_2-modified graphite sorbents from spent Li-ion batteries for the treatment of water contaminated by lead, cadmium, and silver. *ACS Appl. Mater. Interfaces*, 2017, 9: 25369–25376.

[51] Hao, J.; Meng, X. Q.; Fang, S.; Cao, H. B.; Lv, W. G.; Zheng, X. H.; Liu, C. W.; Chen, M. J.; Sun, Z. MnO_2-functionalized amorphous carbon sorbents from spent lithium-ion batteries for highly efficient removal of cadmium from aqueous solutions. *Ind. Eng. Chem. Res.*, 2020, 59: 10210–10220.

[52] Yan, R. Z.; Li, B.; Zhou, M. X.; Li, J.; Xu, Z. M. Highly-efficient syn-

thesis of heavy metal adsorbents by using spent lithium-ion battery anode graphite *via* one-step mechanochemistry process. *Resour. Conserv. Recycl.*, 2023, 190: 106857.

[53] Hou, H. L.; Zhong, Q. F.; Zhang, Z. H.; Zhu, X. D.; Song, Y.; Xiao, J. One-pot synthesis of dual-sites adsorbent based on recycling spent Lithium-ion batteries: Matter cycle, orderly grafting, and copper adsorption. *J. Clean. Prod.*, 2023, 410: 137230.

[54] Liu, Y.; Zhao, Y.; Wang, J. L. Fenton/Fenton-like processes with *in-situ* production of hydrogen peroxide/hydroxyl radical for degradation of emerging contaminants: Advances and prospects. *J. Hazard. Mater.*, 2021, 404: 124191.

[55] Liu, Y.; Wang, J. L. Multivalent metal catalysts in Fenton/Fenton-like oxidation system: A critical review. *Chem. Eng. J.*, 2023, 466: 143147.

[56] Zhu, B. Y.; Song, R. S.; Pan, L. W.; Liu, Y. L.; Liu, Z. B.; Xue, T. F.; Li, X. G.; Zhang, J. Resource utilization of spent lithium iron phosphate cathode materials for mineralizing phenol-containing wastewater by Fenton process. *J. Environ. Chem. Eng.*, 2025, 13: 117339.

[57] Zou, W. S.; Li, J.; Wang, R. H.; Ma, J. Y.; Chen, Z. J.; Duan, L. L.; Mi, H. W.; Chen, H. Hydroxylamine mediated Fenton-like interfacial reaction dynamics on sea urchin-like catalyst derived from spent $LiFePO_4$ battery. *J. Hazard. Mater.*, 2022, 431: 128590.

[58] Feng, L. Z.; Liao, X. R.; Jiang, F.; Tong, N.; Dai, N. N.; Zhang, L. Z.; Gong, J. M. Oxygen vacancies-enriched spent lithium-ion battery cathode materials loaded catalytic membrane for effective peracetic acid activation and organic pollutants degradation. *J. Hazard. Mater.*, 2024, 480: 136444.

[59] Guo, Y. F.; Wang, C. M.; Ning, Y.; Huang, Q.; Zhang, L.; Xiao, P. Y.; Zhu, J. M.; Yuan, W. Y.; Xu, L. J. ZVI/EG composite derived from spent LIBs *via* electrochemical intercalation-carbothermal reduction for tetracycline hydrochloride degradation. *Chem. Eng. J.*, 2025, 522: 168075.

[60] Song, D. M.; Yu, J. D.; Wu, J.; Zhang, B. K.; Li, J. H. *In situ* enhanced catalytic degradation behavior of antibiotics by graphite anodes from spent lithium-ion batteries: The unique role of self-doped metals. *J. Clean. Prod.*, 2025, 486: 144495.

[61] Cao, Z. Q.; Zheng, X. H.; Cao, H. B.; Zhao, H.; Sun, Z.; Guo, Z.; Wang, K.; Zhou, B. Efficient reuse of anode scrap from lithium-ion batteries as cathode for pollutant degradation in electro-Fenton process: Role of different recovery processes. *Chem. Eng. J.*, 2018, 337: 256–264.

[62] Guan, J.; Li, Z. X.; Chen, S.; Gu, W. X. Zero-valent iron supported on expanded graphite from spent lithium-ion battery anodes and ferric chloride for the degradation of 4-chlorophenol in water. *Chemosphere*, 2022, 290: 133381.

[63] Peng, Y.; Zhang, Q. M.; Fan, Y. H.; Su, R. X.; Ren, W.; Xiao, X.; Luo, X. B. Recycling of spend graphite anodes in Fenton-like catalysis for green economy and long-term sustainable wastewater purification. *Chem. Eng. J.*, 2025, 520: 165825.

[64] Chen, S.; Li, Z. X.; Belver, C.; Gao, G. L.; Guan, J.; Guo, Y. G.; Li, H.; Ma, J.; Bedia, J.; Wójtowicz, P. Comparison of the behavior of ZVI/carbon composites from both commercial origin and from spent Li-ion batteries and mill scale for the removal of ibuprofen in water. *J. Environ. Manag.*, 2020, 264: 110480.

[65] Chen, S.; Long, F.; Gao, G. L.; Belver, C.; Li, Z. X.; Li, Z. X.; Guan, J.; Guo, Y. G.; Bedia, J. Zero-valent iron-copper bimetallic catalyst supported on graphite from spent lithium-ion battery anodes and mill scale waste for the degradation of 4-chlorophenol in aqueous phase. *Sep. Purif. Technol.*, 2022, 286: 120466.

[66] Gao, G. L.; Li, Z. X.; Chen, S.; Belver, C.; Lin, D. H.; Li, Z. X.; Guan, J.; Guo, Y. G.; Bedia, J. Synthesis of zero-valent iron supported with graphite and plastic based carbon from recycling spent lithium ion batteries and its reaction mechanism with 4-chlorophenol in water. *J. Environ. Manag.*, 2023, 325: 116490.

[67] Rocha, A. K. S., Magnago, L. B., Santos, J. J., Leal, V. M., Marins, A. A. L., Pegoretti, V. C. B., Ferreira, S. A. D., Lelis, M. F. F., Freitas, M. B. J. G. Copper ferrite synthesis from spent Li-ion batteries for multifunctional application as catalyst in photo Fenton process and as electrochemical pseudocapacitor. *Mater. Res. Bull.*, 2019, 113: 231–240.

[68] Chen, X.; Deng, F.; Liu, X.; Cui, K. P.; Weerasooriya, R. Hydrothermal synthesis of MnO_2/Fe(0) composites from Li-ion battery cathodes for destructing sulfadiazine by photo-Fenton process. *Sci. Total Environ.*, 2021, 774: 145776.

[69] Wang, X.; Hou, F. L.; Zhai, J. L.; Yan, J. L.; Gong, C.; Li, Y. H.; Zhu, W. J.; Luo, Y. M.; Yang, D. L.; Gao, X. Y. Effective peroxymonosulfate activation by lithium cobaltite recovered from spent lithium-ion batteries for enhanced carbamazepine degradation in a wide pH range. *Environ. Sci. Pollut. Res.*, 2024, 31: 51673–51686.

[70] Li, H. T.; Wang, H.; Gao, Q.; Han, B.; Xia, K. S.; Zhou, C. G. Hierarchical flower-like Co_2TiO_4 nanosheets with unique structural and compositional advantages to boost peroxymonosulfate activation for degradation of organic pollutants. *J. Mater. Chem. A*, 2020, 8: 20953–20962.

[71] Lin, S. J.; Niu, B.; Shi, X. D.; Hong, J. M.; Tan, R.; Xiao, J. F. Non-destructive approach for upcycling the cathode of spent lithium-ion batteries: Combined with the efficient treatment of organic wastewater. *Sep. Purif. Technol.*, 2025, 360: 130917.

[72] Zhao, Y. L.; Yuan, X. Z.; Jiang, L. B.; Li, X. D.; Zhang, J. J.; Wang, H. Reutilization of cathode material from spent batteries as a heterogeneous catalyst to remove antibiotics in wastewater *via* peroxymonosulfate activation. *Chem. Eng. J.*, 2020, 400: 125903.

[73] Liang, J. X.; Li, K.; Shi, F.; Li, J. D.; Gu, J. N.; Xue, Y. X.; Bao, C. Y.; Guo, M. M.; Jia, J. P.; Fan, M. H. et al. Constructing high-performance cobalt-based environmental catalysts from spent lithium-ion batteries: Unveiling overlooked roles of copper and aluminum from current collectors. *Angew. Chem. Int. Ed.*, 2024, 63: e202407870.

[74] Liang, B. H.; Gao, X. Y.; Gu, Q. C.; Liu, X. H.; Guo, T.; Wang, J. T.; Zhu, W. J.; Luo, Y. M. Highly efficient degradation of emerging pollutants using cobalt oxide recovery from spent $LiCoO_2$ batteries through autocatalytic lithium extraction. *Sep. Purif. Technol.*, 2025, 370: 133264.

[75] Zhao, Y. L.; Wang, H.; Ji, J. Q.; Li, X. D.; Yuan, X. Z.; Duan, A. B.; Guan, X.; Jiang, L. B.; Li, Y. Recycling of waste power lithium-ion batteries to prepare nickel/cobalt/manganese-containing catalysts with inter-valence cobalt/manganese synergistic effect for peroxymonosulfate activation. *J. Colloid Interface Sci.*, 2022, 626: 564–580.

[76] Gao, M. J.; Wei, H.; Teng, R. J.; Song, J. Q.; Huang, X. T.; Wang, G. Z.; Li, H. E. One-step calcination of Ni/Co/Mn ternary catalysts from spent lithium-ion batteries for iopamidol degradation *via* peroxymonosulfate activation. *J. Water Process. Eng.*, 2024, 59: 104996.

[77] Dang, S.; Hou, W.; Min, Y. L.; Wu, J. F.; Xu, Q. J.; Shi, P. H. Electrooxidation: A win–win strategy for the selective recovery of Li^+ from spent lithium-ion batteries and the preparation of highly active catalysts. *Chem. Eng. J.*, 2022, 435: 135169.

[78] Zhou, D. X.; Tang, R.; Min, Y. L.; Hu, Z. H.; Shi, P. H. External electric field-assisted electronic restructuring of transition metal oxides derived from spent lithium-ion batteries to enhance persulfate activation. *Appl. Surf. Sci.*, 2023, 625: 157120.

[79] Gong, M. Q.; Ren, X. Q.; Chen, J. T.; Mo, R.; Yang, S. Preparing of multi-metal spinel oxides for PMS activation from spent lithium-ion batteries: A non-closed-loop process. *J. Environ. Chem. Eng.*, 2025, 13: 115076.

[80] Tang, Y.; Yu, Y. L.; Cheng, J. H.; Cheng, S.; Cheng, Q. L.; Zhu, J.; Chen, X.; Wang, X. H. Recovery of cathode from spent lithium-ion batteries to prepare metal-based catalysts with inter-

valence cobalt/manganese for peroxymonosulfate activation: Identification of key influencing factors and transformation pathway. *J. Water Process. Eng.*, 2025, 76: 108261.

[81] Xu, L.; Liang, L.; Chen, C.; Chen, Z. H.; Lv, Z. B.; Fu, M. L.; Yuan, B. L. Upcycling spent lithium battery cathodes into efficient PMS catalysts for organic contaminants degradation. *J. Environ. Chem. Eng.*, 2023, 11: 111605.

[82] Yang, X. R.; Wan, Z. H.; Lin, S.; Zhou, L. Recycling strategy for spent lithium-ion batteries as an ultra-efficiency peroxymonosulfate activator. *Ind. Eng. Chem. Res.*, 2023, 62: 9104–9113.

[83] Yan, J. L.; Wang, X.; Zhai, J. L.; Gong, C.; Zhu, W. J.; Yang, D. L.; Luo, Y. M.; Gao, X. Y. Recovery of graphite from anode in spent lithium-ion battery as an efficient peroxymonosulfate (PMS) activator: Performance and mechanism. *Colloids Surf. A Physicochem. Eng. Aspects*, 2023, 663: 131090.

[84] Qian, X. F.; Ji, J. Q.; Zhao, Y. L.; Guo, J. Y.; Duan, A. B.; Yuan, X. Z.; Wang, H.; Zhou, S. Q.; Li, X. D. Rational design of waste anode graphite-derived carbon catalyst to activate peroxymonosulfate for atrazine degradation. *Environ. Res.*, 2024, 257: 119296.

[85] Yan, S. X.; Chen, X. P.; Yang, Y.; Zhou, T. Peroxymonosulfate activation by N-doped 3D graphene from spent lithium-ion batteries for organic pollutants degradation: An insight into the degradation mechanism. *Chem. Eng. J.*, 2024, 484: 149379.

[86] Chen, H. N.; Wei, Y.; Han, C.; Zhong, C.; Zhang, Z.; Qu, X.; Zhao, C. L.; Zhao, X. H.; Yang, L. W. Peroxymonosulfate activation by CoO@C catalyst from integrated recycling of spent lithium-ion battery: Performance and mechanism. *Sep. Purif. Technol.*, 2025, 355: 129658.

[87] Zhou, F. Y.; Liu, M. J.; Li, X. Y.; Zhu, D. D.; Ma, Y. S.; Qu, X.; Zhao, J. J.; Qiu, B. L.; Wang, D. H.; Lee, L. Y. S., et al. Preparation of CoO-C catalysts from spent lithium-ion batteries and waste biomass for efficient degradation of ciprofloxacin *via* peroxymonosulfate activation. *Chem. Eng. J.*, 2023, 471: 144469.

[88] Guo, T.; Gao, X. Y.; Yang, X. X.; Wang, J. T.; Yin, Y. C.; Hu, Y. R.; Luo, Y.; Luo, Y. M. *In-situ* synthesizing CoONAl-C catalysts from spent $LiCoO_2$ batteries and tobacco stems biomass: Nearly 100% peroxymonosulfate utilization. *Resour. Environ. Sustain.*, 2025, 22: 100280.

[89] Hou, F. L.; Gu, Q. C.; Liang, B. H.; Liu, X. H.; Yang, K. Y.; Li, W.; Zhu, W. J.; Luo, Y. M.; Gao, X. Y. Highly inhibited cobalt leaching: Co_9S_8 anchored on honeycomb-like biochar developed from spent lithium battery for efficient catalytic degradation of carbamazepine. *J. Water Process. Eng.*, 2025, 69: 106835.

[90] Gao, M. J.; Wei, H.; Cai, Q.; Teng, R. J.; Song, J. Q.; Pan, F.; Li, H. E. Performance and mechanism of the biochar-supported Ni^0/Co^0/MnO composite catalyst for peroxymonosulfate activation to degrade iopamidol. *J. Environ. Chem. Eng.*, 2024, 12: 114811.

[91] Hu, Z. Y.; Su, G.; Long, S. J.; Zhang, X. T.; Zhang, L. K.; Chen, Y. L.; Zhang, C.; Liu, G. G. Synthesis of X@DRHC (X=Co, Ni, Mn) catalyst from comprehensive utilization of waste rice husk and spent lithium-ion batteries for efficient peroxymonosulfate (PMS) activation. *Environ. Res.*, 2024, 245: 118078.

[92] Li, B.; Ma, B.; Wei, M. Y.; Li, Y.; Fan, X. B.; Zhang, F. B.; Zhang, G. L.; Xia, Q.; Peng, W. C. Synthesis of Co-NC catalysts from spent lithium-ion batteries for Fenton-like reaction: Generation of singlet oxygen with ~100% selectivity. *Carbon*, 2022, 197: 76–86.

[93] Liang, J. X.; Guo, M. M.; Xue, Y. X.; Gu, J. N.; Li, J. D.; Shi, F.; Guo, X.; Min, X.; Jia, J. P.; Li, K. et al. Constructing magnetically separable manganese-based spinel ferrite from spent ternary lithium-ion batteries for efficient degradation of bisphenol A *via* peroxymonosulfate activation. *Chem. Eng. J.*, 2022, 435: 135000.

[94] Zhao, Y. L.; Wang, H.; Ji, J. Q.; Li, X. D.; Yuan, X. Z.; Jiang, L. B.; Yang, J. J.; Shao, Y. N.; Guan, X. Degradation of ciprofloxacin by peroxymonosulfate activation using catalyst derived from spent lithium-ion batteries. *J. Clean. Prod.*, 2022, 362: 132442.

[95] Lv, X. X.; Deng, F.; Liu, H. L.; Zhang, Y.; Liu, Q. J.; Liang, Y. Q.; Kong, D. F.; Ahmad, M.; Chen, X. Recycling different crystal forms of MnO_2 from spent Li-ion batteries cathodes for SDZ degradation. *J. Environ. Chem. Eng.*, 2024, 12: 111622.

[96] Hossain, R.; Sahajwalla, V. Microrecycled Co_3O_4 from waste lithium-ion battery: Synthesis, characterisation and implication in environmental application. *J. Environ. Chem. Eng.*, 2022, 10: 107858.

[97] M Abozeid, A.; Ibrahim, I.; Elseman, A. M., Bakr, M. F., Salama, T. M. Facile synthesis of silver nanoparticles loaded spent cathodic Lithium-Ion battery components for enhanced bifunctional photocatalysis: Investigating the influence of magnetic properties. *J. Ind. Eng. Chem.*, 2024, 139: 464–472.

[98] Yue, X. H.; Zhang, F. S. Recycling spent $LiFePO_4$ battery for fabricating visible-light photocatalyst with adsorption-photocatalytic synergistic performance and simultaneous recovery of lithium and phosphorus. *Chem. Eng. J.*, 2022, 450: 138388.

[99] Xu, M. F.; Liang, J. X.; Xue, Y. X.; Gu, J. N.; Li, X. W.; Guo, M. M.; Li, K.; Jia, J. P.; Sun, T. H. Selective removal of thiosulfate from coke oven gas desulfurization wastewater by catalytic wet air oxidation with manganese-based oxide from spent ternary lithium-ion batteries. *J. Hazard. Mater.*, 2024, 470: 134215.

[100] Abdel-Rahim, R. D., Al-Ansari, S. H., Ali, G. A. M., Hassane, A. M. A., Kamoun, E. A., Gomaa, H.; Nagiub, A. M. A hybrid nanocomposite of silver nanoparticles embedded with end-of-life battery-derived sheets-like nitrogen and sulfur-doped reduced-graphene oxide for water treatment and antimicrobial applications. *Water Air Soil Pollut.*, 2024, 235: 623.

[101] Tong, Y. C.; Qin, C. L.; Zhu, L. Y.; Chen, S. Z.; Lv, Z. Z.; Ran, J. Y. From spent lithium-ion batteries to low-cost Li_4SiO_4 sorbent for CO_2 capture. *Environ. Sci. Technol.*, 2022, 56: 5734–5742.

[102] Li, X.; Wen, X.; Lang, J. Y.; Wei, Y.; Miao, J.; Zhang, X. C.; Zhou, B. X.; Long, M. C.; Alvarez, P. J. J., Zhang, L. Z. CoN_1O_2 single-atom catalyst for efficient peroxymonosulfate activation and selective cobalt(IV)=O generation. *Angew. Chem. Int. Ed.*, 2023, 62: e202303267.

[103] Chen, M. T.; Wang, N.; Zhu, L. H. Single-atom dispersed Co-N-C: A novel adsorption-catalysis bifunctional material for rapid removing bisphenol A. *Catal. Today*, 2020, 348: 187–193.

[104] Han, B.; Pan, Q. H.; Chen, Y. H.; Liu, D.; Zhou, C. G.; Xia, K. S.; Gao, Q. High-entropy perovskite oxide washcoated porous alumina ceramic as a superb catalyst for activating peroxymonosulfate to eliminate refractory organic pollutants. *Chem. Eng. J.*, 2023, 455: 140828.

[105] Pan, Q. H.; Gao, Q.; Gao, G. M.; Liu, M. Y.; Han, B.; Xia, K. S.; Zhou, C. G. Composition-engineered $LaCoO_3$-based monolithic catalysts for easily operational and robust peroxymonosulfate activation. *Chem. Eng. J.*, 2021, 424: 130574.

[106] Yi, Q. Y.; Tan, J. L.; Liu, W. Y.; Lu, H.; Xing, M. Y.; Zhang, J. L. Peroxymonosulfate activation by three-dimensional cobalt hydroxide/graphene oxide hydrogel for wastewater treatment through an automated process. *Chem. Eng. J.*, 2020, 400: 125965.

[107] Liu, G. C.; Liu, X. Y.; Yi, X. H.; Wang, F.; Chu, H. Y.; Xu, X. H.; Zhou, Y. M.; Wang, P.; Wang, J. F.; Wang, C. C. Fixed-bed catalytic antibiotics detoxification through singlet oxygen-mediated nonradical oxidation: Mechanisms and long-term performance. *Water Res.*, 2026, 289: 124791.

[108] Lai, Z. Y.; Long, J.; Lu, Y.; Luo, F. Q.; Zeng, L. X.; Lai, W. B.; Li, Y. X.; Qian, Q. R.; Chen, Q. H.; Zhang, K. et al. Direct recycling of retired lithium-ion batteries: Emerging methods for sustainable reuse. *Adv. Energy Mater.*, 2025, 15: 2501009.