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Review Article

Electronic Waste-derived Materials for Advanced Wastewater Treatment

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ABSTRACT: The rapid expansion of the electronic industry has resulted in an unprecedented accumulation of electronic wastes (e-wastes). E-wastes contain substantial amounts of heavy metals, polymers, and hazardous organic compounds that, if improperly managed, can pose serious risks to human health and the environment. Nevertheless, recent studies have highlighted the potential of e-waste to be transformed into functional materials aligning with sustainable development principles. This review comprehensively summarizes advanced methodologies for transforming e-waste into value-added materials, including thermal treatment, chemical activation, oxidative exfoliation, biomass-based green reduction, wet-chemical synthesis, and direct electrode recycling. The resulting e-waste-derived materials (EDMs) exhibit distinctive physicochemical properties, including high specific surface area, abundant functional groups, inherent electrical conductivity, and embedded metallic component. Representative case studies further demonstrate their efficiency in removing dyes, pharmaceuticals, heavy metals, and other contaminants, while simultaneously enabling resource recovery. Despite these promising outcomes, challenges remain regarding large-scale implementation, material stability, and prevention of potential secondary pollution. Future research should prioritize environmentally benign synthesis routes, systematic life-cycle assessments, and integrated treatment strategies to enhance the efficiency and sustainability of wastewater remediation using EDMs.

Keywords: Electronic waste; Aops; Adsorbent; Bioelectrochemical; Photocatalysis; electrochemical.

1. INTRODUCTION

The rapid development of the electronics industry has generated substantial quantities of e-waste, comprising a complex mixture of metals, polymers, and oxidants. The global volume of e-waste is projected to increase dramatically, exceeding 82 million tons by 2030 (Figure **1**) [1]. Traditionally, e-waste has been considered an environmental burden due to its toxicity, persistence, and potential for causing secondary pollution (Table **1**) [2]. However, in recent years, increasing attention has been paid to its potential as a secondary resource. Through appropriate treatment and valorization strategies, e-waste can be transformed into functional materials, offering both effective waste management and novel applications in environmental remediation[1, 2]. These synthesized materials derived from e-waste exhibit unique physical and chemical characteristics, including high surface area, abundant functional groups, inherent conductivity, and even embedded metallic components [3-6]. To be specific,

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EDMs can be classified into several categories, including metal oxides (e.g., Fe2O3, CuO, ZnO), carbon-based materials (e.g., biochar, activated carbon, graphene-like structures), and composite materials (e.g., metal–carbon or metal–oxide heterojunctions) [7, 8]. Among them, e-waste-derived metal oxides commonly exhibit high catalytic activity and strong redox potential, while carbon-based materials demonstrate excellent adsorption capacity and electrical conductivity. Composite systems further integrate these advantages, generating synergistic effects in electron transfer, radical generation, and pollutant degradation [9, 10]. These multifunctional materials can serve as substitutes for traditional adsorbents and catalysts, while simultaneously promoting high-value resource recovery and advancing the circular economy [11-20]. Such features render them highly suitable for applications in adsorption, advanced oxidation processes (AOPs), photocatalysis, and electrochemical systems [21, 22]. Compared with conventional materials, e-waste-derived alternatives not only exhibit superior pollutant removal performance but also enable simultaneous resource recovery, consistent with the principles of the circular economy and sustainable development. [23-25]. Nevertheless, significant challenges remain regarding large-scale implementation, long-term stability, and the risk of potential secondary contamination, which must be addressed before practical deployment can be achieved.

In this review, we primarily focus on summarizing the methodologies for converting electronic wastes into functional materials and subsequently discuss their applications in wastewater treatment, which are examined from three main perspectives: adsorption, photocatalysis/AOPs, and electrochemical/ bioelectrochemical systems.

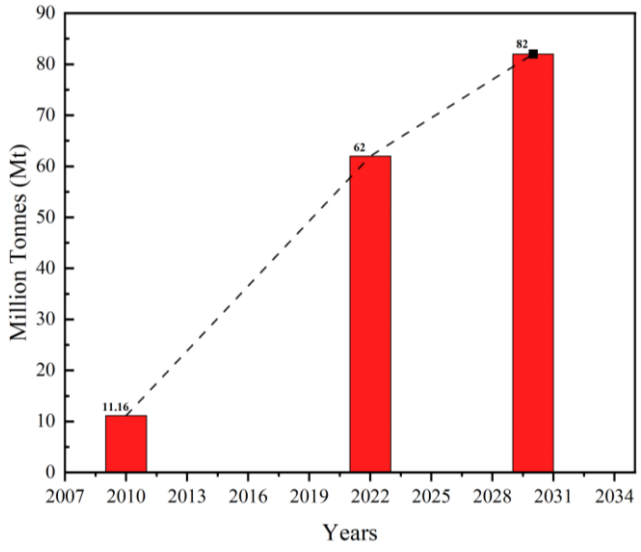

Figure 1: The generation of e-waste has been steadily increasing worldwide, and projections suggest that its volume will exceed 82 million tons by 2030 [26].

2. APPROACHES TO TRANSFORM ELECTRONIC WASTE INTO FUNCTIONAL MATERIALS

2.1. Thermal Treatment and Chemical Activation

The non-metallic components of e-wastes (such as PCB powder, LCD glass and waste toner) are commonly subjected to pyrolysis, calcination, or alkaline activation at 250 to 800 °C to remove organic residues and generate a porous skeleton structure [9, 54, 55]. Alkalis (e.g., KOH) react with Si-O and Al-O bonds to form aluminosilicate frameworks, which significantly enhance the specific surface area, pore volume, and cation-exchange capacity [56]. The resulting materials remove heavy metals primarily through ion exchange, surface complexation, and electrostatic attraction. For example, non-metallic PCB fractions activated with KOH at 250 °C under N_2 were converted into aluminosilicate materials capable of efficiently removing Cd^{2+}, Cu^{2+}, Pb^{2+}, and Zn^{2+}, with performance superior to commercial ion-exchange resins [57]. Similarly, Cu-enriched heterogeneous catalysts obtained by calcination or pyrolysis of PCBs were shown to activate H_2O_2 via a Fenton-like pathway, enabling the degradation of pharmaceuticals such as diclofenac and ibuprofen [58]. Nevertheless, these approaches are often associated with high energy consumption, and the thermal decomposition of organic components can release gaseous by-products, raising concerns about potential secondary pollution [44].

2.2. Modified Hummers' Method and Related Oxidative Exfoliation

Modified Hummers' method, employing strong oxidizing systems such as $KMnO_4/H_2SO_4/HNO_3$, has been widely applied to oxidize battery-derived graphite into graphene oxide (GO) [59]. During oxidation, oxygen-containing functional groups including carboxyl (–COOH), hydroxyl (–OH), and epoxy (–C–O–C–) are introduced, endowing GO with hydrophilicity, abundant active sites, and a layered structure. These features of construction enable pollutant removal through π–π stacking, hydrogen bonding, and electrostatic adsorption [60, 61]. For instance, GO prepared from spent dry battery graphite achieved 98.8% removal of azithromycin within 15 min, while GO derived from Zn–C batteries demonstrated a

Table 1: Representative pollutants in e-waste and associated human health risks.

Pollutant	Source	Health Hazards	Ref.
Ba	Electron tubes, fluorescent lamps, spark plugs, cathode ray tubes (CRTs)	Breathing issues, muscular tremor	[27, 28]
Pb	Lead-acid batteries, fluorescent tubes, cable sheathing, transistors, light emitting diodes (LEDs), CRTs, printed circuit boards (PCBs)	Neurotoxicity, anaemia, hypertension and accumulation of reproductive toxicity	[29, 30]
Cr(VI)	Plastic and computer housings, cabling, hard disks, anti-corrosion layers in electronics, magnetic tapes	DNA damage, permanent ocular impairment, carcinogenicity	[31, 32]
BFRs	Flame-retardant additives in PCBs, plastic casings of monitors, insulation of wires, connectors	Endocrine disruption, neurodevelopmental disorders, reproductive toxicity	[33]
Cd	PCBs, CRTs, pigments in plastics, semiconductors, Ni–Cd batteries	Lung cancer, renal dysfunction, bone demineralization	[34, 35]
Hg	Batteries, Liquid crystal display (LCDs), switches, lamps, thermostats, relays	Severe neurotoxicity, kidney dysfunction, immune suppression	[36, 37]
Be	Power supply boxes, thermal interface materials, X-ray tubes, connectors	Skin sensitization, chronic beryllium disease	[27, 30]
Br	PCBs, casings of TVs, PVC cables insulation	Neurotoxicity, depression, eye and skin irritation, endocrine disruption,	[38]
Sb	CRT glass, plastic housings, solder alloys, semiconductor	Carcinogen, pneumoconiosis, skin and mucous irritation	[39, 40]
Sr	CRTs, rechargeable batteries	Cancer, mineralization, haematological disorders	[41]
CN^-	PCB etching solutions, electroplating wastewater	Cyanide poisoning, respiratory failure, central nervous system collapse	[42]
Li	Batteries (phones, laptops), CRTs, PCBs, portable electronics	Diarrhea, Gastrointestinal irritation, kidney problems, neurological symptoms	[43, 44]
Ni	Ni–MH and Ni–Cd batteries, semiconductors, CRTs, PCBs, capacitors	Allergic reactions, bronchitis, lung cancer, cardiovascular toxicity	[45]
Zn	Zn–Mn batteries, PCBs, luminous objects	Gastrointestinal irritation (nausea, cramps), the reduction of immunity	[46, 47]
Co	Li–Co oxide batteries, cutting tools, alloy components	Pulmonary disease, reproductive toxicity, thyroid disruption	[48, 49]
CFCs	Refrigerators, freezers, foaming agents	Skin cancer, cataracts, immune suppression	[50]
PVC	Monitor casings, keyboards, flexible connectors, tubing, cables	Respiratory irritation, endocrine disruption	[51, 52]
Dioxins	PVC cables, plastic casings, PCB components	Immunotoxicity, endocrine disruption, carcinogenicity	[37, 51]
Americium	Smoke detectors, industrial sensors, nuclear instrumentation	Carcinogenic	[52, 53]

maximum adsorption capacity of 419 mg/g for CIP [62]. Nevertheless, this method relies on strong acids and oxidants, which are environmentally unfriendly and may pose risks of secondary contamination.

2.3. Green Reduction Assisted by Biomass

GO can be further reduced to reduced graphene oxide (rGO) using plant extracts (e.g., polyphenols, flavonoids, vitamin C) as green reducing agents [63-65]. These natural reductants remove or partially reduce oxygen-containing groups on GO while potentially introducing heteroatom doping (e.g., N, S). This environmentally friendly approach avoids the use of toxic chemicals such as hydrazine and often imparts antibacterial activity and eco-compatibility. For example, GO reduced with Tinospora cordifolia extract yielded G-rGO, which removed 94.85% of methylene blue (MB) with an adsorption capacity of 58.81 mg/g, and exhibited antibacterial activity against S. aureus and E. coli [66].

2.4. Wet-chemical Functionalization

Wet-chemically functionalized materials derived from e-waste are often synthesized via precipitation, hydrothermal synthesis, or sol–gel processes, enabling the deposition or reduction of metal ions and precious metals onto solid carriers [40, 53]. The key advantages of these synthesis routes include particle size control, morphology tuning, and surface functionalization, making

Table 2: Representative examples of e-waste-derived catalyst for wastewater purification.

Method	Precursors	Temperature	Advantages	Limitations	Ref.
Thermal treatment and chemical activation	PCB powder, LCD glass, toner waste	250 to 800 °C	Forms aluminosilicate; high SSA; strong ion-exchange and catalysis activity	High energy input, possible toxic gases releasing and limited morphology control	[9, 54, 56]
Modified Hummers' method and related oxidative exfoliation	Waste battery graphite rods/powders	Ambient to 50 °C	Producing GO with –OH, –COOH, –C–O–C, high hydrophilicity and more active sites	Using strong acids/oxidants and certain environmental concerns	[59-61]
Green reduction with biomass	GO from spent batteries and plant extracts	60 to 95 °C	Eco-friendly, avoiding toxic reductants and introducing N/S doping, antibacterial activity	Weaker reduction ability and possible variability from biomass source	[63-65]
Wet-chemical functionalization	$LiFePO_4$ cathode, PCB leachate, CPU leachate	120 to 200 °C	Precise morphology control, multifunctionality and precious metals recovery	Too much synthesis steps and requiring chemical reagents	[54, 67, 70]
Precious metal recovery and reuse	CPU leachate, PCB leachate	Room temperature to 150 °C	Simultaneous metal recovery and catalyst preparation with high catalytic activity	using acidsto leach and high cost of frameworks (e.g., MOFs, PAFs)	[71-73]
Direct reuse as electrodes	ITO glass, capacitors, graphite rods	Ambient	Simple, low-cost, conductive and enabling electrochemical and bioelectrochemical coupling	Limited stability; fouling and metal leaching risks	[9, 68]

it particularly suitable for developing AOP catalysts. For example, $Fe_5(PO_4)_4(OH)_3{\cdot}2H_2O$ (FPOH) was prepared via hydrothermal treatment of spent $LiFePO_4$ cathodes, showing dual functionality in adsorbing Pb^{2+} and degrading dyes via Fenton-like reactions [67].

2.5. Precious Metal Recovery and Reuse

Precious metal recovery and reuse from e-waste offers a dual benefit. Valuable metals such as Au and Pd can be recovered from CPUs or PCB leachates [55] and subsequently immobilized onto porous frameworks (e.g., MOFs, PAFs, or hybrid networks) to form highly active catalysts [56, 57]. These catalysts efficiently activate PMS or reduce nitroaromatics; for example, the AuNP@iPAF catalyst achieves continuous-flow hydrogenation of nitroaromatics within just 10 seconds, exhibiting activity far superior to conventional AuNP systems [58]. Nevertheless, the high cost and environmental burden associated with acid leaching and framework precursor preparation remain significant challenges.

2.6. Direct Reuse as Electrodes

Conductive components from e-waste (e.g., ITO glass, capacitors, graphite rods) can be directly reused as electrodes without extensive modification [9, 68]. The primary mechanisms include anodic oxidation to generate ·OH, cathodic reduction to produce H_2O_2 or O_2^-, and electro-bio synergy to accelerate microbial degradation. For example, waste fan capacitors (WFCs) used directly as microbial fuel cell cathodes achieved 87.3% COD removal, with a peak power density of 278.9 mW/m^2, while simultaneously facilitating the removal of heavy metals such as Cu, Fe, and Co [69]. Although direct reuse of e-waste components as electrodes offers the advantage of low cost and minimal processing, it also carries potential risks, such as electrode instability due to scaling and the possible dissolution of residual heavy metals into the treated water.

3. PRACTICAL APPLICATIONS OF ELECTRONIC WASTE-DERIVED MATERIALS IN WASTEWATER TREATMENT

3.1. Photocatalysis / AOPs with E-waste-derived Materials for Contaminant Removal

For photocatalysis and AOPs in wastewater treatment using EDMs, the fundamental pathway involves the generation and reaction of photogenerated electron–hole pairs [54, 74, 75]. When semiconductors are irradiated with light, photoexcited holes (h^+) can directly oxidize water or hydroxide ions to form hydroxyl radicals (·OH), while electrons (e^-) reduce dissolved oxygen to yield superoxide radicals ($\cdot O_2^-$), which can subsequently transform into O_2, H_2O_2, and other reactive oxygen species (ROS) [76-84]. These ROS are highly oxidative and can non-selectively attack a broad spectrum of organic contaminants. However, because electron–hole recombination readily occurs, strategies have been developed to enhance charge separation, such as constructing heterogeneous junctions. Coupling g-C_3N_4 with Fe_2O_3 or WO_3, for instance, can form type-II or Z-scheme heterostructures that facilitate the persistent generation of active species under visible light irradiation

Table 3: Representative examples of e-waste-derived catalyst for wastewater purification.

Catalyst	Source	Target Pollutant	Main ROS/Oxidant	Removal Efficiency	Ref.
g-C_3N_4/Fe_2O_3	Waste printer toner	Methyl orange, textile wastewater	h^+, ·OH, $·O_2^-$	MO: 99% in 90 min (k = 4.92 × 10^{-2} min^{-1}), TE: 97% in 60 min (k = 5.05 × 10^{-2} min^{-1})	[96]
mpg-C_3N_4–WO_3	Waste tungsten wire	MB	·OH, $·O_2^-$	92% MB degradation under photocatalyst = 100 mg/L, $[MB]_0$ = 10 mg/L, pH=8 in 120 min, stable after 10 cycles	[85]
CuPd/C	CPU leachate	4-NP	·OH, $SO_4^{·-}$/5 mM PMS ($KHSO_5^-$)	92.4% removal of 10 mg/L 4-NP within 15 min via $SO_4^{·-}$ and ·OH activation, 78.2% removal at 50 mg/L 4-NP under the same conditions	[94]
CuAu/C	CPU leachate	4-NP	·OH, $SO_4^{·-}$/5 mM PMS ($KHSO_5^-$)	87.6% removal of 10 mg/L 4-NP within 15 min via $SO_4^{·-}$ and ·OH activation, 62.8% removal at 50 mg/L 4-NP under the same conditions	[94]
PCS-PAA	CPU leachate	Au	-	An adsorption capacity of 647 mg/g for Au (III) was achieved within 30 min	[95]
PCS-PAA loaded with Au	CPU leachate	4-NP	-	Reducing 4-NP to 4-aminophenol with high activity under visible light	[95]
FPOH composite	Spent $LiFePO_4$ cathode	Pb^{2+}, MB	·OH/5 mL H_2O_2	43.203 mg/g Pb^{2+} adsorption and MB effective degradation in 12 h	[67]
ZFO-CN	Spent Zn–Mn batteries	BPA	$^1O_2$, h^+/0.5 mM PMS	>97.7% BPA degradation under visible light in 60 min	[97]
NC-PCB	WPCBs	Diclofenac, Ibuprofen, TOC	·OH/H_2O_2	86% DCF, 66% IBP in 30 min, TOC 61% (DCF), 50% (IBP) in 60 min, >80% reusability	[58]
C-CPB	WPCBs	Diclofenac, Ibuprofen, TOC	·OH/H_2O_2	61% DCF, 65.7% IBP in 30 min, TOC 45% (DCF), 43% (IBP) in 60 min	[58]
SnO_2 NPs	WPCBs	MB, EY, Mixed dyes	·OH, $·O_2^-$	MB: 97.1% in 360 min (k = 0.0104 min^{-1}), EY: around 100% in 50 min (k = 0.0796 min^{-1}), Mixed dyes: MB 95% (180 min), EY 100% (60 min), k = 0.0153 (MB), 0.1103 (EY) min^{-1}	[98]
Thiourea-functionalized magnetic core stirring bar	PCB leachate	4-NP	-	Adsorption capacity 224.97 mg/g Au (III), 4-NP reduction k = 2.394 min^{-1}	[99]
Au@iPAF-7	CPU leachate	4-NP	-	Complete conversion to amines in 10 s, >98% selectivity	[100]
Au@iPAF-7	CPU leachate	Nitroaromatics	-	99% conversion rates of these nitroarenes catalyzed by Au@iPAF-7 and high selectivity	[100]

[85]. Beyond photocatalysis, Fenton and Fenton-like processes further expand the radical generation pathways [86, 87]. Transition metals such as Fe and Cu can cyclically activate H_2O_2 to continuously produce ·OH, while under near-neutral conditions these metal sites can also activate peroxymonosulfate (PMS, HSO_5^-) to produce sulfate radicals ($SO_4^{·-}$). Compared with ·OH, $SO_4^{·-}$ possess higher oxidation potentials (2.5–3.1 V) and better selectivity, enabling more efficient degradation of recalcitrant pharmaceutical compounds [88, 89]. Noble metals provide another enhancement route via surface plasmon resonance [90]. Nanoparticles of Au, Pd, and others can significantly improve light absorption and carrier migration, while simultaneously serving as electron sinks to suppress recombination [91]. Moreover, they may promote PMS activation through non-radical pathways, yielding singlet oxygen ($^1O_2$) or surface-bound complexes, maintaining high degradation efficiency and minimizing undesired side reactions. A further modification strategy is the integration of adsorption with photocatalysis [92]. Carbonaceous materials such as graphene, activated carbon, and porous carbons can pre-concentrate organic dyes or pharmaceuticals at the catalyst surface, where they are subsequently degraded by in situ generated ·OH and $·O_2^-$ [93]. This synergy between initial adsorption and subsequent photocatalytic oxidation enhances degradation efficiency while minimizing the release and toxicity of intermediate products.

Representative applications of EDMs in photocatalysis and AOPs demonstrate their great potential in waste-water remediation (Table **3**). Noble metal-based catalysts derived from e-waste have also shown remarkable versatility. Chen *et al*. recovered gold and palladium from CPUs and immobilized them on MOF@graphene foam to

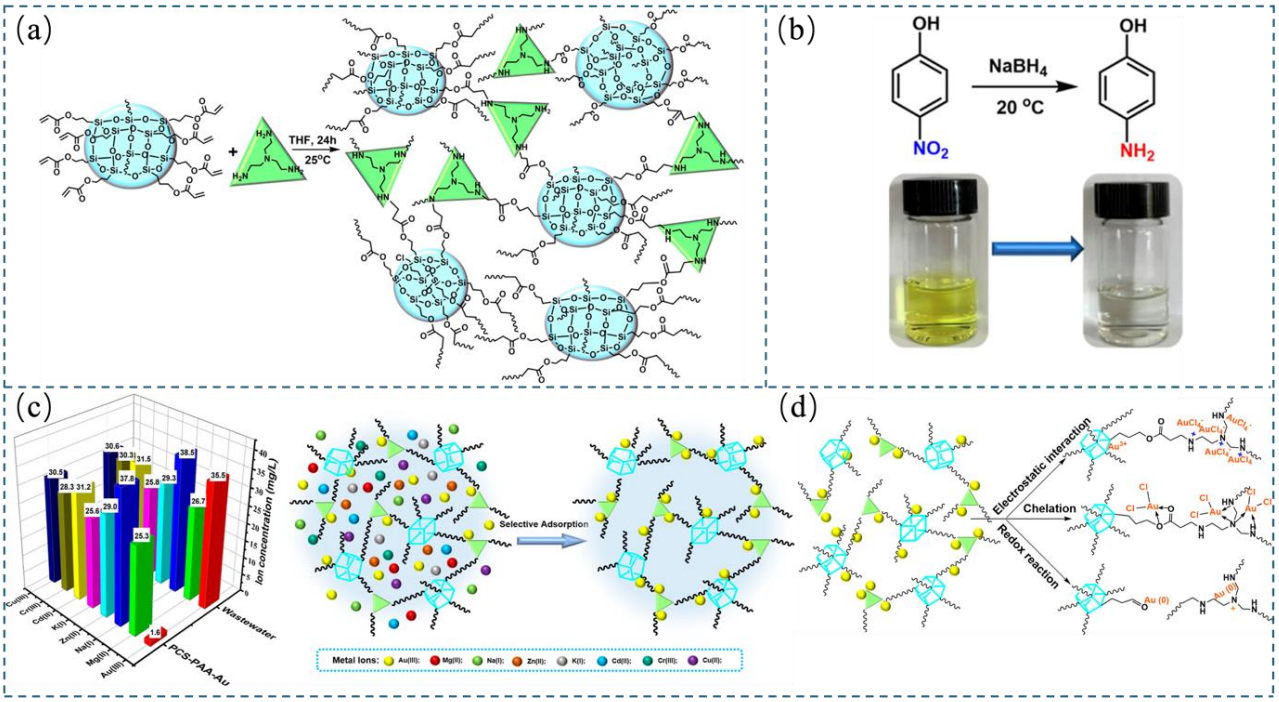

Figure 2: (a) Synthesis process of the amine-functionalized SQ-based network via the Amine–Ene Reaction. (b) Photographs of the reaction mixture before and after the reduction of 4-NP. (c) Effect of different metal ions on the selective adsorption of PCS-PAA toward Au (III). (d) Proposed adsorption mechanism of Au (III) on PCS-PAA [95].

prepare a 3D functional MOF@graphene foams hybrids, which achieved over 90% recovery of Au and Pd and also efficiently activated PMS to degrade 4-NP through $SO_4^{\cdot-}$ and ·OH radicals [94]. Similarly, amine-functionalized silsesquioxane (SQ) hybrid networks (PCS-PAA) were developed to capture Au(III) from CPU leachates and simultaneously reduce them into catalytically active gold nanoparticles (PCS-PAA loaded with Au), which served as electron traps to suppress charge recombination and promoted 4-nitrophenol reduction to 4-aminophenol with high catalytic activity (Figure **2**(a-d)) [95]. A major research focus also has been on solar-driven photocatalytic heterojunctions. For example, Babar *et al*. reported a g-C_3N_4–Fe_2O_3 heterojunction photocatalyst synthesized from waste printer toner, where the coupling structure effectively promoted charge separation and enhanced visible-light absorption, enabling nearly complete degradation of methyl orange and textile effluents [96]. Similarly, Shinde and colleagues constructed a Z-scheme heterojunction by coupling WO_3, converted from waste tungsten wires, with mpg-C_3N_4, which achieved more than 90% degradation of MB while maintaining excellent stability over ten cycles (Figure **3**(a)) [85]. In addition to heterojunction systems, Fenton and Fenton-like processes have also been widely investigated using e-waste-derived catalysts. An early study reported that FPOH composites obtained via hydrothermal treatment of spent $LiFePO_4$ cathodes exhibited dual functionality, with strong adsorption of Pb(II) and effective degradation of MB through Fenton-like activation of H_2O_2 [67]. Similarly, a $ZnFe_2O_4$/g-C_3N_4 (ZFO-CN) S-scheme heterojunction photocatalyst was synthesized by calcining melamine with Fe and Zn resources derived from spent alkaline Zn–Mn batteries. Under visible light irradiation, ZFO-CN could activate PMS (HSO_5^-) to generate h^+ and $^1O_2$ as the dominant reactive species, thereby degrading the endocrine disruptor BPA with a removal efficiency of 97.7% within 60 min, accompanied by a TOC removal of 75.1% [97]. Likewise, Cu-rich heterogeneous catalysts derived from uncarbonized and carbonized PCB fractions prepared by air calcination or N_2 pyrolysis were able to activate H_2O_2 for the removal of pharmaceuticals such as diclofenac, ibuprofen and TOC. The removal efficiencies for diclofenac and ibuprofen were 86% and 66% within 30 min respectively, while the corresponding TOC removals reached 61% and 50% after 60 min for non-carbonized catalyst (NC-PCB) [58]. Importantly, the catalysts exhibited good reusability, maintaining degradation efficiencies above 80% over multiple cycles. Meanwhile, SnO_2 nanoparticles (<50 nm) were also successfully synthesized by recovering tin from waste printed circuit boards (Figure **3**(b)) [98]. These SnO_2 nanoparticles exhibited excellent photocatalytic performance under natural sunlight, efficiently degrading both the cationic dye MB and the anionic dye eosin Y

(EY). Notably, the degradation of EY occurred at amarkedly faster rate than that of MB, with complete removal of EY achieved within 60 minutes, whereas MB reached 95% degradation after 180 minutes. Chen *et al*. developed thiourea-functionalized magnetic stir bars from PCB leachates, which selectively adsorbed Au(III) with a capacity of 224.97 mg/g and subsequently the adsorbed Au(III) is directly converted into Au(0) in situ to be applied on the reduction of 4-NP with a rate constant of 2.394 min^{-1}, integrating precious-metal recovery with catalytic reuse [99]. Apart from that, Ma and co-workers synthesized AuNP@iPAF catalysts by adsorbing and reducing Au(III) with porous aromatic frameworks (iPAF-7) (Figure **3**(c-j)) [100]. These catalysts enabled the complete conversion of nitroaromatics into aromatic amines within 10 seconds, exhibiting activities far exceeding those of conventional AuNP catalysts.

3.2. Pollutant Adsorption via e-wastes-derived Materials

Adsorption is a surface-driven process that occurs via interactions between pollutants in the liquid phase and solid adsorbents [101-104]. The mechanism of adsorption is multifaceted, and its efficiency strongly depends on the physical and chemical characteristics of both adsorbents and contaminants. In EDMs, adsorption can be understood through a layered progression [105-108], ranging from weak to strong interactions, from physical to chemical processes, and from non-specific to highly selective mechanisms. The physical mechanisms (mainly van der Waals forces and pore filling) represent the most basic and universal form of adsorption, though they generally exhibit poor selectivity [109]. These mechanisms rely on the specific surface area and porosity of the materials, which determine the accessibility and accommodation of pollutants. Typical examples include waste polyurethane foam (PUF) and waste glass powders, where adsorption is primarily governed by pore structure [110, 111]. When charged functional groups are present on the surface, oppositely charged pollutants can be removed through electrostatic attraction. For instance, –COOH or –OH groups on GO can dissociate in aqueous solutions to generate negative charges, which strongly adsorb cationic dyes (e.g., MB, RB4) and heavy metal ions (e.g., Cu^{2+}, Pb^{2+}). For organic molecules containing aromatic rings and amino or hydroxyl groups (such as antibiotics and dyes), adsorption is often reinforced by hydrogen bonding and π–π stacking interactions [107]. Beyond these mechanisms, ion exchange offers more stability than simple electrostatic adsorption and enables reusability [112, 113]. Also, materials for ion exchange can be regenerated through acid washing, making them suitable for repeated use. Finally, the strongest interactions are observed through surface complexation/coordination, which provides highly specific and chemically robust binding [114]. In functionalized adsorbents such as amidoxime-modified ABS plastics or GO enriched with hydroxyl and amino groups, toxic metal ions including Cr(VI), As(V), and Hg(II) can coordinate with –OH, –C=O, $–NH_2$, and similar functional groups [115, 116]. This mechanism ensures high selectivity and adsorption capacity, particularly for highly toxic pollutants. Representative e-waste-derived adsorbents for adsorption are concluded in Table **4**.

In practical applications, adsorbents derived from e-waste have exhibited multifunctional properties for the removal of diverse pollutants. For the removal of heavy metals and metalloids, non-metallic fractions of waste PCBs, when activated with KOH, are transformed into aluminosilicate-like porous structures that have been widely employed as efficient ion-exchange adsorbents. For these adsorbents, weakly bound cations such as Ca^{2+} or K^{+} participate in ion-exchange reactions that effectively remove Cd^{2+} [117], Cu^{2+}, Pb^{2+}, and Zn^{2+} [57], with efficiencies often surpassing those of commercial ion-exchange resins. More recent studies have further functionalized PCB-derived adsorbents, enabling simultaneous removal of 90% As(V) and 76% F^{-} in binary systems [118]. Polymer composites and geopolymers synthesized from non-metallic PCB fractions have been shown to act as stable carriers for catalytic or adsorption–oxidation processes, while simultaneously mitigating environmental concerns associated with residual heavy metals also [119]. For organic dyes, the performance of e-waste-derived adsorbents spans a broad range, from relatively low-cost but less efficient options, such as PUF that achieve only 37% removal of MB and mercury [110], to silica-enriched glass powders obtained from LCD waste that achieve nearly 99% removal of MB [111], and finally to highly engineered functional adsorbents, such as amidoxime-modified ABS plastics, which exhibit extremely high adsorption capacities (around 595 mg/g for MB) and the additional ability to reduce toxic Cr(VI) [116]. For antibiotics and pharmaceuticals, graphene-based adsorbents synthesized from spent batteries have been extensively investigated. For instance, GO prepared from Zn–C batteries achieved almost 99% removal of CIP with a maximum adsorption capacity of 419 mg/g (Figure **4**(a-c)) [62], while GO derived from spent dry batteries removed 98.8% of azithromycin and maintained stable performance over nine reuse cycles (Figure **4**(d-g)) [120]. Functionalized composite materials, such as SDS-

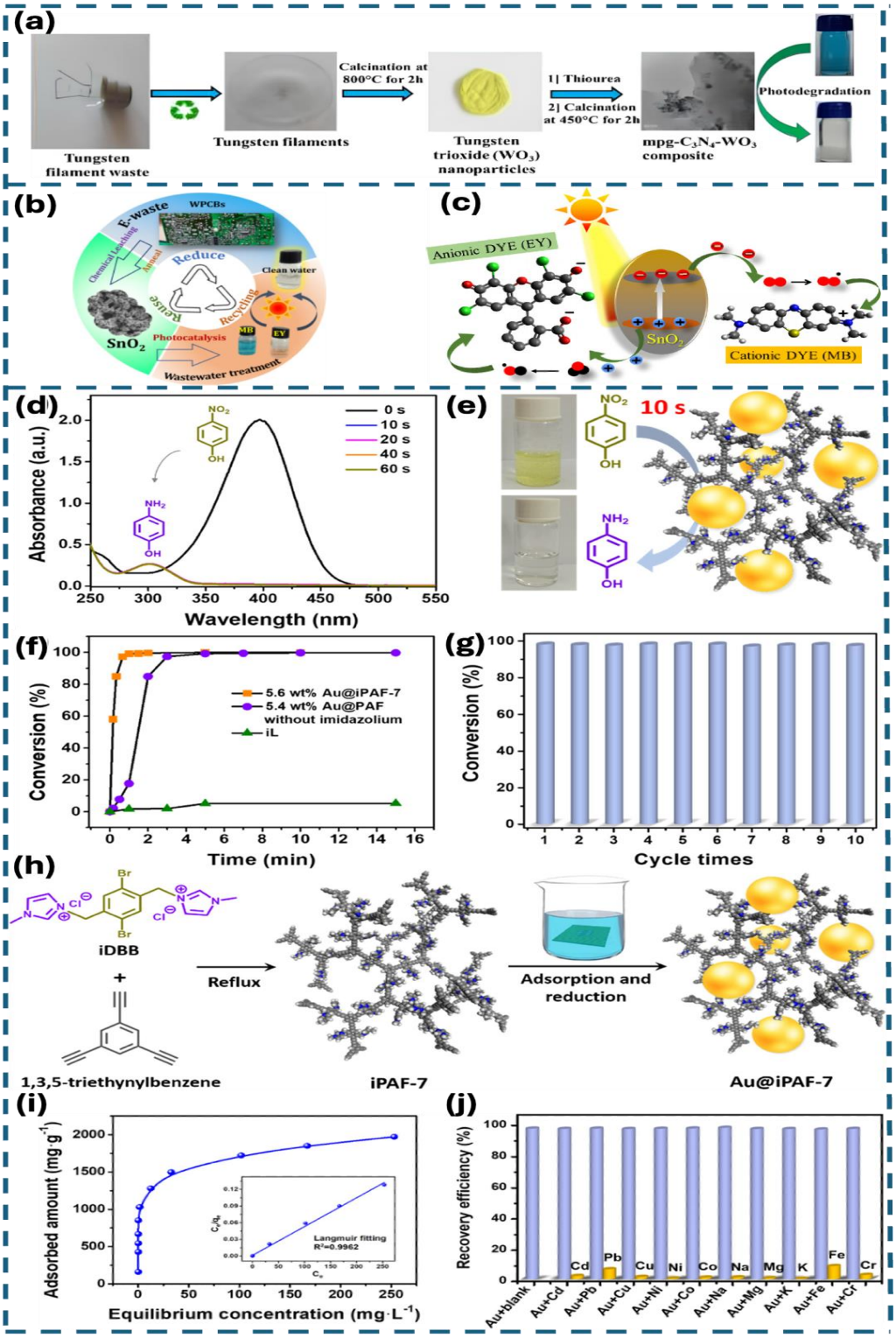

Figure 3: (a) The synthesis process of mpg-C_3N_4–WO_3 and its application in photodegradation [85]. (b) The conversion pathway from e-waste sources to functional SnO_2 materials for wastewater treatment [98]. (c) Photodegradation of MB and EY using the synthesised SnO_2 materials. (d) Time-dependent UV–vis spectra of the reduction of 4-NP with $NaBH_4$ in the presence of Au@iPAF-7. (e) The colour changes of the 4-NP solution before and after the reduction, observed 10 s after adding Au@iPAF-7. (f) Comparison of catalytic conversion rates of 4-NP under identical conditions using 5.6 wt% Au@iPAF-7, 5.4 wt% Au@PAF without imidazolium, and neat imidazolium-based ionic liquid. (g) Catalytic conversion efficiency of 4-NP over Au@iPAF-7 during ten consecutive cycles. (h) The synthesis procedure of iPAF-7 and Au@iPAF-7. (i) Adsorption isotherm of Au(III) on iPAF-7; inset shows the Langmuir adsorption isotherm fitting. (j) Selectively adsorpting Au(III) on iPAF-7 [100].

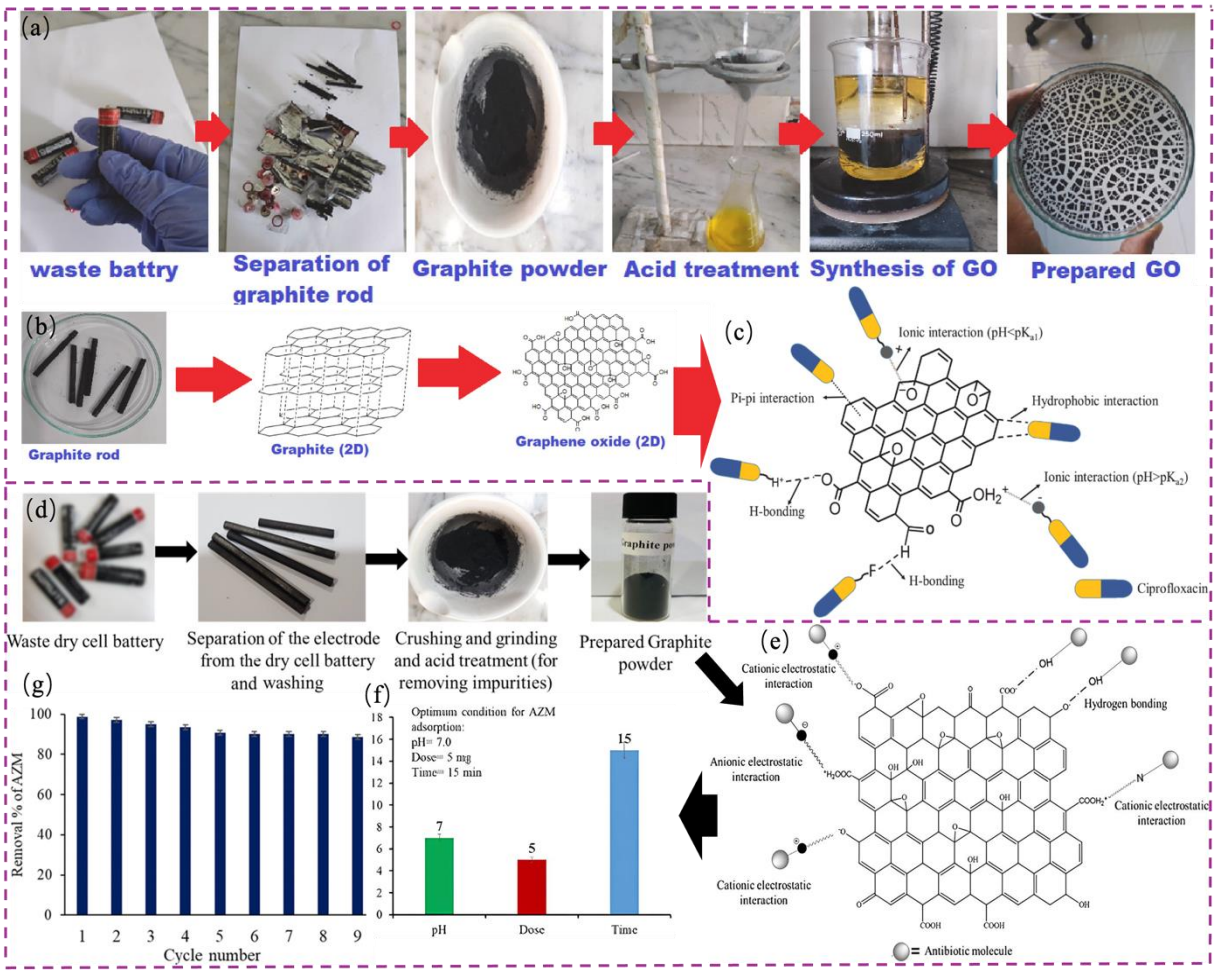

Figure 4: (a) Preparation process of GO from spent Zn–C batteries. (b) Structure of the graphite rod. (c) Proposed mechanism for CIP removal using GO [62]. (d) Synthetic process of GO derived from spent dry batteries. (e) Morphological structure of the graphite rod and possible removal mechanism for AZM. (f) Determination of optimal adsorption conditions for AZM. (g) Reusability performance of GO for AZM removal over nine cycles [120].

modified GO, have demonstrated excellent performance in removing moxifloxacin (about 98% removal, approximately 40 mg/g) (Figure **5**(b-d)) [115], while green reduced graphene oxide (GrGO), obtained via biomass-assisted reduction of battery-derived GO, has shown removal efficiencies of 97–98% against tetracycline antibiotics (TEC, OTC, CTC) (Figure **5**(e-f)) [121]. A similar G-rGO adsorbent was synthesized using *Tinospora cordifolia* plant extract as a reducing agent, by mixing it in a suspension of GO. The resulting G-rGO achieved 94.85% removal efficiency of MB with an adsorption capacity of 58.81 mg/g, and also exhibited antibacterial activity against Staphylococcus aureus (Gram-positive) and Escherichia coli (Gram-negative) (Figure **5**(a)) [66]. These studies highlight various modifications of carbon materials derived from spent batteries, all within the common GO/rGO framework, can be tailored to target different classes of antibiotics, illustrating the universal roles of π–π interactions and hydrogen bonding in antibiotic adsorption. Even for oils and other hydrophobic pollutants, e-waste-derived adsorbents have also proven to be effective. For instance, refrigerator-derived PUF demonstrated an oil uptake capacity of 7–10 g of oil per gram of adsorbent, outperforming several commercial sorbents for leakage control [122]. Valorization of glass-based e-waste has also contributed to adsorption ability. Tsai *et al*. demonstrated that TFT-LCD glass waste can be converted into mesoporous aluminosilicates with high surface area, capable of effectively adsorbing heavy metals such as Cu^{2+}, Zn^{2+}, and Ni^{2+} from electroplating wastewater, preventing electron–hole recombination by removing charge-carrier poisons [123]. Overall, EDMs have progressed from simple porous adsorbents with limited selectivity to advanced functionalized materials with high capacity and strong selectivity, enabling them to address the complexity of modern wastewater contaminants.

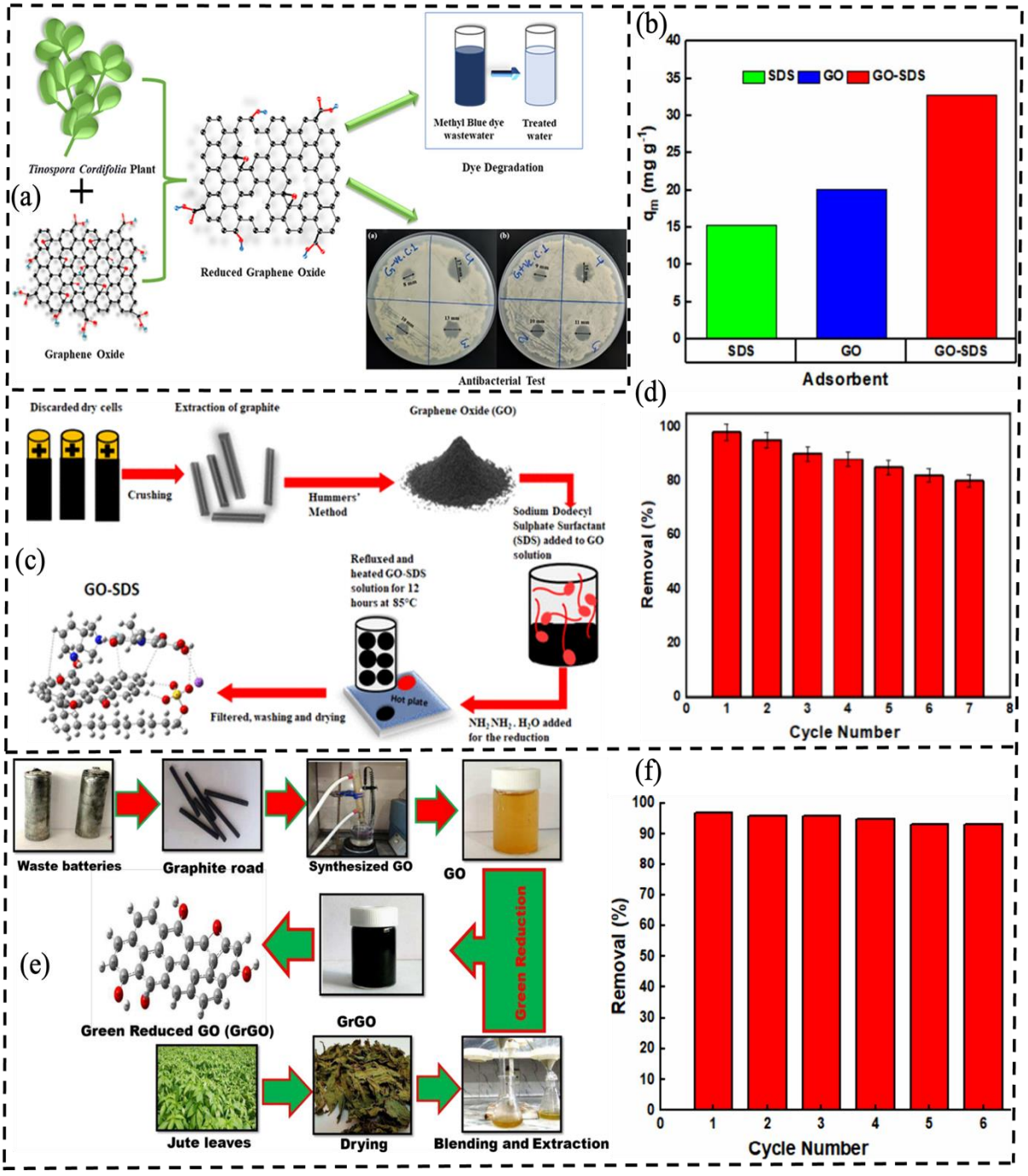

Figure 5: (a) Green synthesis of reduced GO using *Tinospora cordifolia* plant extract, applied for MB degradation and exhibiting antibacterial activity [66]. (b) Comparison of adsorption capacities among SDS, GO, and GO-SDS adsorbents. (c) Preparation process of SDS-modified GO (GO-SDS) derived from spent dry batteries. (d) Removal efficiency of moxifloxacin (MFX) over multiple reuse cycles [115]. (e) Synthesis route of green reduced GO (GrGO) from spent batteries using jute leaves as a reducing agent. (f) Stable removal efficiency of tetracyclines maintained across six reuse cycles [121].

3.3. Electrochemical / Bioelectrochemical System Application

For the reuse of spent electronic materials, the primary mechanism lies in their application as electrodes or conductive fillers to drive pollutant removal through electrochemical processes [9, 124]. Under an applied electric field, these electrodes can generate reactive species such as ·OH, $\cdot O_2^-$, and H_2O_2, which possess strong oxidizing capabilities and degrade organic contaminants in wastewater. In addition to direct electrochemical oxidation, the conductivity and surface

Table 4: Representative examples of e-waste-derived adsorbents for wastewater purification.

Adsorbent	Source	Target Pollutant	Adsorption Capacity	Ref.
KOH-activated non-metallic PCB (aluminosilicate-like)	Waste printed circuit boards	Cd^{2+}	Cd^{2+}: 2.1 mmol/g	[117]
KOH-activated non-metallic PCB (aluminosilicate-like)	Waste printed circuit boards	Cu^{2+}, Pb^{2+}, Zn^{2+}	Cu^{2+}: 2.9 mmol/g, Pb^{2+}: 3.4 mmol/g, Zn^{2+}: 2.0 mmol/g	[57]
Functionalized PCB-derived adsorbent	Waste printed circuit boards	As(V), F^-	90% As(V), 76% F^-removal	[118]
PUF	Refrigerator waste	MB, Hg	37% MB and mercury removal	[110]
LCD-derived glass powder (SiO_2-rich)	LCD waste	MB	around 99% MB removal	[111]
Amidoxime-modified ABS plastic	ABS plastics (e-waste housing)	MB, Cr(VI)	MB ≈ 595 mg/g, Cr(VI) reduction	[116]
GO from Zn–C batteries	Spent Zn–C batteries	CIP	CIP qm ≈ 419 mg/g (about 99% removal)	[62]
GO from spent dry batteries	Spent dry batteries	Azithromycin (AZM)	98.8% removal, reusable 9 cycles	[120]
SDS-modified GO composite	Spent battery-derived GO	Moxifloxacin (MFX)	98% removal, adsorption capacity: 40 mg/g	[115]
GrGO	Battery-derived GO	Tetracyclines (TEC, OTC, CTC)	97–98% removal	[121]
Green rGO (Tinospora cordifolia reduction)	Battery-derived GO	MB, antibacterial activity	94.85% MB removal, 58.81 mg/g;	[66]
Refrigerator-derived PUF	Refrigerator	Oil and hydrophobic pollutants	7–10 g oil per g adsorbent	[122]
Mesoporous aluminosilicate composite	TFT-LCD glass waste	Cu^{2+}, Zn^{2+}, Ni^{2+}	64.5, 34.0 and 23.1 mg/g for Cu^{2+}, Zn^{2+}, Ni^{2+} respectively	[123]

properties of these materials facilitate biofilm formation, enhancing microbial degradation activity and enabling the coupling of electrochemical and biological processes [125]. In microbial fuel cells (MFCs), such electrodes function as electron acceptors or donors, supporting the biodegradation of organic pollutants while simultaneously recovering electrical energy, thus integrating wastewater treatment with energy recovery.

For detailed application examples (Table **5**), spent LCD electrodes (ITO conductive glass) have been reported as nematic liquid crystal electrodes (NLCEs) in electrode-enhanced biofilm reactors (EBBRs) [126]. The high conductivity of NLCEs accelerates biofilm initiation and improves the degradation efficiency of organic pollutants, achieving COD and suspended solids removal rates of approximately 71.2% and 79.3%, respectively, while dramatically reducing the start-up time. Subsequently, another study directly adopted spent LCD electrodes as cathodes to construct a bio-electroperoxone system [127]. This system enabled deep purification of pharmaceutical wastewater through the coupling of cathodically generated hydrogen peroxide with microbial metabolism, achieving 92.2% color removal, 84.7% total suspended solids reduction, 89% TOC removal, and 99.99% microbial inactivation. Importantly, the energy consumption of this coupled process was about ten times lower than that of standalone electrochemical treatment. Furthermore, WFCs have been directly reused as cathodes in single-chamber MFCs, where their conductivity supports efficient electron transfer and power generation [69]. In this system, COD, color, and total dissolved solids (TDS) removal reached 87.3%, 81.6%, and 86%, respectively, with a peak power density of 278.9 mW/m^2, while heavy metals such as Cu, Fe, and Co were simultaneously removed. Collectively, these studies highlight that spent electronic components can be not only recovered but also repurposed as functional electrodes in electrochemical and bio-electrochemical systems, achieving both pollutant removal and energy recovery simultaneously. The recovery of Pb from waste PCBs were utilized as a precursor, and ultrasound-assisted electrodeposition was applied to prepare PbO_2-coated graphite (G-PbO_2) electrodes (Figure **6**) [128]. When applied to kitchen wastewater (COD 6150 mg/L, containing oil, grease, detergents, and food residues), ultrasound promoted the generation of ·OH radicals, while the PbO_2 coating enhanced the formation of active chlorine species (Cl_2, HOCl, ClO^-), thereby improving pollutant degradation. Compared with pristine graphite, G-PbO_2 achieved 98% COD removal with an energy consumption of only 1.57 kWh/kg COD, demonstrating

Table 5: Representative examples of e-waste-derived electrodes for wastewater purification

Electrode	Source	Target Pollutant	ROS/Oxidant	Removal Efficiency	Ref.
NLCEs	LCD	Tannery wastewater	·OH, $\cdot O_2^-/H_2O_2$	COD 71.2%, SS 79.3%, accelerated biofilm start-up	[126]
LCD electrode cathodes	LCD	Pharmaceutical wastewater	Electro-oxidation + biodegradation	~90% TOC removal, 99.99% microbial inactivation	[127]
Cathode for MFC	WFCs	Sewage wastewater	Microbial electron transfer + O_2 as final acceptor	COD 87.3%, color 81.6%, TDS 86%; peak power density 278.9 mW m^{-2}, metals (Cu, Fe, Co) significantly removed	[69]
Graphite (unmodified)	Commercial graphite	Kitchen wastewater (same conditions)	·OH	COD removal: 92.6% (440 mg/L COD remained), energy consumption 3.036 kWh/kg COD, current efficiency 11.38%	[128]
G-PbO_2	WPCBs	Kitchen wastewater	·OH and active chlorine species (Cl_2, HOCl, ClO^-)	COD removal: 98% (130 mg/L COD remained), oil & grease reduced from 85 to 7 mg/L, energy consumption 1.573 kWh/kg COD, current efficiency 15.05%	[128]
CuAu/CC	CPU leachate	50 mg/L Bisphenol A	·OH, $\cdot O_2^-/ H_2O_2$	99.5% Bisphenol A removal within 120 min, 64.2% TOC removal, stable for 10 cycles with slight decline	[129]

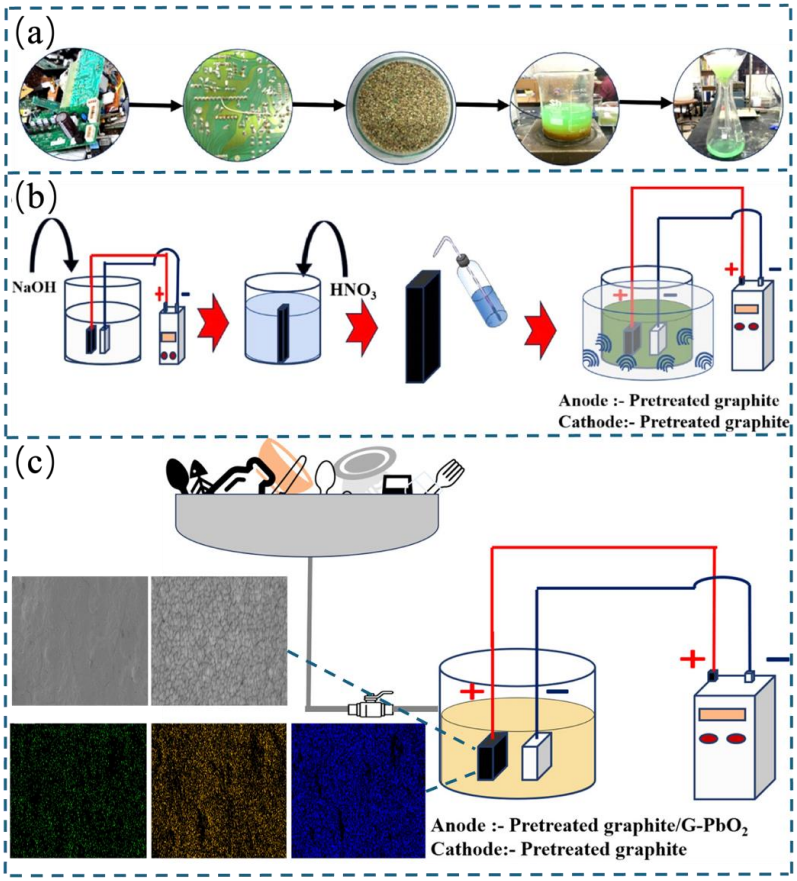

Figure 6: (a) Extraction of Pb^{2+} from WPCBs. (b) Synthesis of G-PbO_2 via ultrasound-assisted electrodeposition. (c) Electrochemical treatment process of kitchen wastewater, along with SEM image and EDS mapping of the synthesized electrode [128].

both higher efficiency and lower energy demand. Using CPU leachate as the metal source, the CuAu/CC catalyst, particularly the CuAu/CC-1 electrode, exhibited the most efficient H_2O_2 generation, producing approximately 50 mg/L after 120 min, which was markedly higher than that of CuAu/CC-2 (37.2 mg/L), CuAu/CC-3 (25.5 mg/L), CuAu/CC-4 (13.4 mg/L), and CuAu/CC-5 (8.6 mg/L) [129]. This superior H_2O_2 yield indicates enhanced oxygen reduction activity and higher H_2O_2 selectivity. As a result, continuous ·OH radical generation was facilitated, achieving 99.5% BPA removal and 64.2% TOC reduction, highlighting the excellent performance of the waste-derived CuAu bimetallic catalyst in the electro-Fenton process.

4. CONCLUSION AND PERSPECTIVE

The dramatic and rapid accumulation of e-waste underscores the urgent need for stricter supervision of manufacturers, particularly regarding the sustainable design of recoverable raw materials and electrical and electronic equipment. This review comprehensively summarizes recent achievements in advanced wastewater treatment through the transformation of electronic waste into functional materials. EDMs, including metal oxides, carbon-based materials, and hybrid composites, exhibit excellent adsorption, catalytic, and electrochemical properties, enabling both pollutant removal and valuable resource recovery. These findings demonstrate that EDMs can serve as sustainable functional materials capable of effectively replacing conventional adsorbents and catalysts, thereby promoting the circular economy and contributing to the realization of a “zero-pollution” goal.

Policies enforcing extended producer responsibility are essential to minimize e-waste generation at the source. Equally important is the promotion of public awareness programs and supportive regulations that encourage sustainable practices, thereby addressing the substantial volume of unreported and unmanaged e-waste.

From a technological perspective, calcination and chemical-assisted processes remain the dominant methods for recovering valuable materials from e-waste. However, these approaches often release secondary pollutants, such as hazardous gases or contaminated wastewater. Future research should therefore prioritize environmentally friendly, energy-efficient, and low-emission strategies that align with global zero-carbon targets.

Systematic application of life cycle assessment (LCA) is crucial for evaluating the environmental and economic impacts of electronic waste-derived materials (EDMs) in wastewater treatment. Such assessments can determine whether EDM-based technologies genuinely provide greater sustainability than conventional treatment methods. Furthermore, future research should emphasize integrating different treatment technologies, for instance, combining electrochemical systems with adsorption techniques—to simultaneously enhance contaminant removal efficiency and resource recovery. Beyond the overall sustainability assessment based on life cycle analysis (LCA), future research should focus on the following aspects:

1) Developing standardized pretreatment and synthesis procedures to ensure high-quality and durable materials derived from heterogeneous e-waste streams.
2) Evaluating the performance of EDMs under complex, real-world wastewater conditions rather than simplified laboratory systems.
3) Enhancing the stability and reusability of these materials through surface modification and structural optimization.
4) Conducting techno-economic and scale-up feasibility analyses to promote industrial implementation.
5) Investigating coupled processes, such as combining electrochemical oxidation with adsorption or photocatalysis, to achieve synergistic pollutant removal and resource recovery.

CONFLICT OF INTEREST

The authors declare that they have no known financial or non-financial conflicts of interest that could have influenced the research, authorship, or publication of this article.

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