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Review Article

Plastic waste upcycling through electrocatalysis

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The widespread use and chemical durability of plastics have contributed to the escalating issue of white pollution. Among various mitigation strategies, recycling waste plastics stands out as one of the most effective and sustainable solutions. Electrochemical methods, featuring mild operating conditions, tunable reaction selectivity, and low carbon emissions, have emerged as promising approaches for plastic recycling. This mini review offers a concise summary of recent advances in the electrocatalytic conversion of plastic waste. We highlight key strategies that involve the selective electrooxidation of monomers derived from plastic hydrolysis, the coupling of anodic and cathodic reactions to increase energy efficiency, and the incorporation of heteroatoms to expand the functionality of target products. We conclude by discussing emerging approaches for non-hydrolyzable plastics and the integration of electrocatalysis with complementary methods for broader applicability and scalable circular recycling.

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Introduction

Plastic pollution has become a global environmental crisis driven by the massive and growing consumption of plastic products [1–5]. To date, over 8 billion tons of plastic have been produced worldwide, with annual production exceeding 300 million tons and showing no signs of slowing. However, only 6–26 % of plastic waste is recycled, while the vast majority accumulates in landfills, waterways, and ecosystems [6]. This challenge is rooted in the large-scale use of disposable plastics, inefficient recycling infrastructure, and chemical stability of the plastics themselves. Most plastics are derived from polymerization reactions that produce robust molecular structures that are further reinforced by additives such as plasticizers and stabilizers, making them highly resistant to degradation. As a result, plastic waste can persist in the environment for centuries [7,8].

Currently, the dominant strategies for plastic waste management include incineration and landfilling, all of which pose serious environmental and health risks [9,10]. Incineration releases toxic gases and carcinogens (*e.g.*, dioxins) and contributes to air and soil pollution. Landfilling consumes valuable land and allows microplastics and hazardous chemicals to leach into soil and groundwater [11–13]. Common plastic recycling methods include mechanical recycling [14], chemical recycling, pyrolysis, biodegradation, and solvent-based separation/purification. Figure 1a illustrates the advantages and disadvantages of each recycling approach. These limitations underscore the urgent need for cleaner, more efficient recycling technologies that support a circular economy.

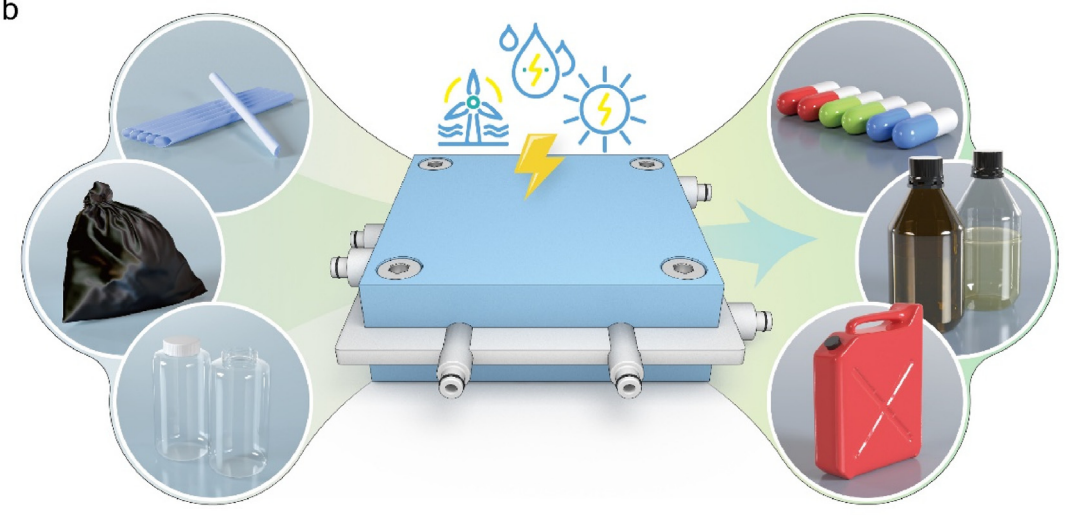
Electrocatalysis has recently emerged as a promising route for plastic waste valorization [15–17]. By harnessing renewable electricity (*e.g.*, solar, wind and hydro), electrocatalytic systems enable molecular transformations under mild conditions, offering a sustainable alternative to conventional thermal processes [18–20]. Through the rational design of catalysts and reactor systems, these approaches allow for precise control over reaction pathways and selectivity, which are key advantages for upcycling plastic waste into valuable chemicals and fuels [21] (Figure 1b). Nevertheless, the chemical inertness and poor aqueous solubility of most plastics present challenges for direct electroconversion [22]. Furthermore, the diverse and often proprietary additives in plastics pose challenges for systematic studies, as their compositions are typically undisclosed. Reported evidence suggests that these additives can induce catalyst deactivation [23], making direct catalytic conversion of waste plastics inherently difficult. To address this, modified catalytic systems or feedstock pretreatment strategies are required to minimize additive–catalyst interactions [24]. Thus, effective pretreatment strategies are essential for enhancing the reactivity and accessibility of plastic substrates [25]. This short review highlights recent advances in electrocatalytic plastic waste conversion, focusing on strategies for monomer upgrading, integrated redox systems, and heteroatom

Figure 1

a

Recycling Method	Advantage	Disadvantage
Mechanical Recycling	- Low cost - Well-established infrastructure - Maintains polymer structure	- Limited to clean, single-type plastics - Quality degradation after cycles - Cannot remove additives
Chemical Recycling	- Handles mixed/contaminated waste - Produces virgin-quality materials - Broad plastic compatibility	- High energy requirements - Expensive catalysts needed - Potential toxic byproducts
Pyrolysis	- Processes complex mixtures - Creates fuel/wax products - No sorting required	- High temperature (400-800°C) - Complex product purification - Significant carbon emissions
Biodegradation	- Environmentally benign - Complete mineralization possible - Mild conditions	- Extremely slow (months-years) - Limited to specific plastics - Microbial sensitivity
Solvent Purification	- Preserves polymer quality - Effective additive removal - Precise separation	- Hazardous solvent use - High operational costs - Scaling challenges

b



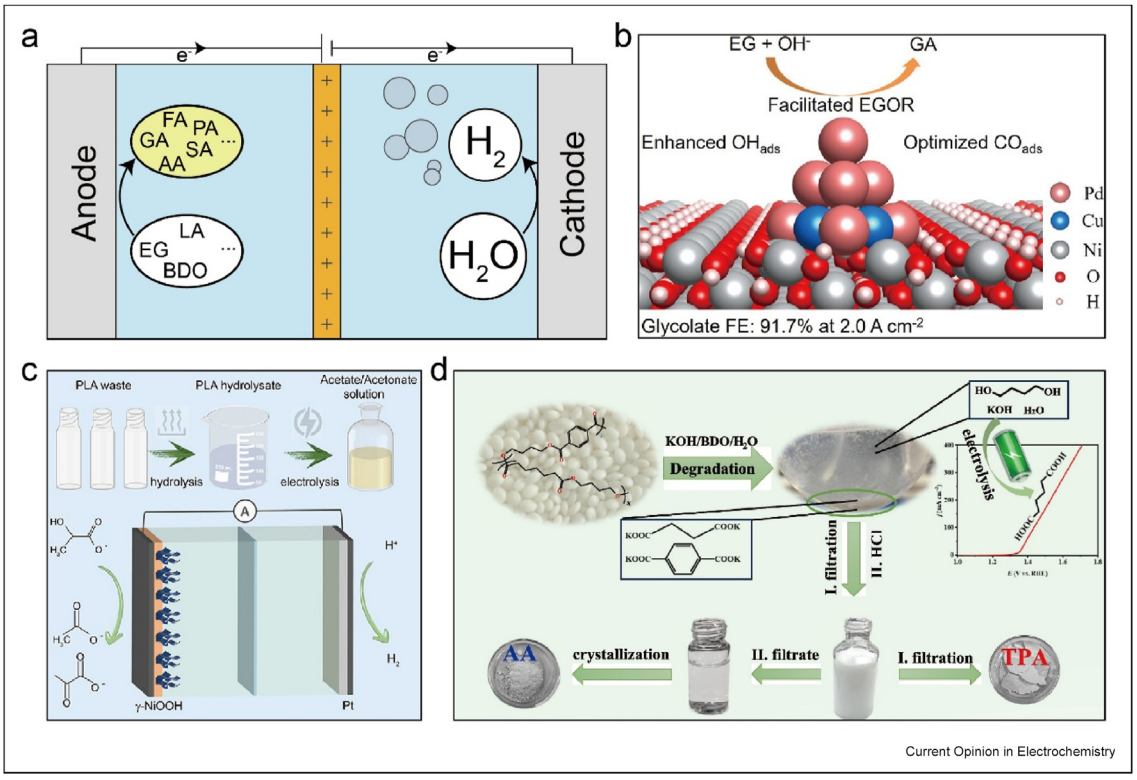
(a) A comparison table of different plastic recycling methods with their advantages and disadvantages. **(b)** Scheme of electrocatalysis of transforming waste plastics into high-value products.

incorporation, along with prospects for developing scalable and efficient upcycling technologies.

Electrocatalytic upgrading of hydrolysis-derived monomers

For hydrolyzable polyesters such as polyethylene terephthalate (PET), polylactic acid (PLA), poly (butylene succinate) (PBS), and poly (butyleneadipate-co-terephthalate) (PBAT), electrocatalytic valorization typically begins with depolymerization into constituent monomers, followed by electrooxidation into higher-value products [26–30] (Figure 2a). These monomers are typically water-soluble and chemically tractable, making them suitable for aqueous-phase electrocatalysis under mild conditions [31,32]. However, the

Figure 2



(a) Scheme of electrocatalysis for the transformation of monomers to high-value products. **(b)** Scheme of the Pt@Ni(OH)$_{2-x}$ catalyst facilitating the oxidation of EG to GA. **(c)** Scheme of electroreforming PLA to acetate and acetonate. **(d)** Hydrolysis process of PBAT and product separation.

electrooxidation of small organics involves complex, multi-electron pathways that require careful tuning of the catalyst structure, electrolyte environment, and applied potential to achieve high selectivity and efficiency.

PET, the most extensively used polyester, can be efficiently depolymerized into two monomeric units: terephthalic acid (TPA) and ethylene glycol (EG). Among these materials, EG, in particular, has emerged as a promising substrate for electrocatalytic upcycling because of its simple molecular structure, high reactivity, and compatibility with aqueous-phase oxidation [33–35]. Its key oxidation products, formic acid (FA) and glycolic acid (GA), are important industrial feedstocks with broad applications in fine chemicals, pharmaceuticals, and textiles. Electrocatalysis enables the controlled transformation of EG into these value-added compounds under mild conditions, with the product distribution governed by the cleavage of the C–C bond [36–38]. Achieving selective conversion requires precise control over the catalyst surface properties and applied potential. For instance, a Pt@Ni(OH)$_{2-x}$ catalyst (Figure 2b) has demonstrated potential-dependent selectivity, favoring FA at lower voltages (0.9 V, 95 % yield, 355.1 mA cm^{-2}) and GA at higher voltages (1.6 V, 92 % yield, comparable current density) [39]. This tunable selectivity highlights the potential of catalyst engineering to unlock multiple value streams from a single feedstock.

PLA, a biodegradable polyester derived from renewable resources, has seen growing adoption in packaging and consumer goods. Despite its green origins, current disposal methods rely largely on slow and low-value biodegradation, often resulting in CO_2 release. Electrocatalysis presents a more efficient and value-driven route. Chen et al. [40] developed a Ni_3P/NF catalyst that selectively oxidizes PLA-derived lactic acid to acetic acid (AA, >80 % selectivity) and pyruvic acid with ~100 % Faradaic efficiency (FE) (Figure 2e). The *in-situ* formed γ-NiOOH phase ensures high activity and stability, maintaining >90 % FE for 100 h at 100 mA cm^{-2} in flow systems, demonstrating industrial potential. Lan et al. [41] report the electrooxidation of waste PLA to acetate at a high current density of 100 mA cm^{-2} with high Faraday efficiency (95 %) and excellent stability (>100 h) over a nickel selenide nanosheet catalyst.

For more complex co-polyesters such as PBS, PBAT, and polybutylene terephthalate (PBT), hydrolysis yields a mixture of aliphatic monomers such as 1,4-butanediol (BDO). Efficient conversion of these monomers into multifunctional platform molecules such as succinic acid (SA) offers significant economic and environmental benefits [42,43]. Pang et al. [44] developed an efficient alkali-assisted PBAT depolymerization method, achieving >99 % BDO recovery in 1 h without neutralization steps (Figure 2d). Their integrated system used a NiOOH/foam catalyst to electrochemically upgrade BDO to SA (97.6 % FE at 1.43 V *vs.* RHE), demonstrating improved atom economy and process simplicity.

Overall, electrocatalytic oxidation of hydrolysis-derived monomers enables controlled C—C and C—H bond activation under mild conditions, allowing selective access to C_1—C_3 oxygenates and expanding the chemical utility of polyester waste. Future work should focus on enhancing product selectivity, improving catalyst stability in complex feedstocks, and coupling anodic oxidation with value-generating cathodic reactions to improve system efficiency.

Integrated anodic–cathodic systems for coupled electrocatalytic valorization

While the selective electrooxidation of plastic-derived monomers provides a valuable route for converting polyester waste into chemicals such as formic acid, glycolic acid, and succinic acid, its energy efficiency remains limited when it is used in isolation. To advance electrocatalytic plastic upcycling toward scalable and economically viable systems, recent efforts have shifted toward integrating anodic oxidation with cathodic reduction reactions, such as oxygen reduction reaction (ORR) [45], CO_2 reduction reaction (CO_2RR) [46,47], and nitrate reduction reaction (NO_3RR) [48,49]. This paired-electrode approach not only improves the overall energy economy but also enables simultaneous valorization of two waste streams, significantly amplifying system productivity [50—52]. The integration of well-matched anodic and cathodic half-reactions offers several advantages. Thermodynamically, combining reactions with compatible redox potentials reduces the cell voltage required to drive the process. Kinetically, balanced electron flow between the electrodes enhances system stability and FE. Economically, the concurrent generation of high-value products at both electrodes provides an opportunity for double resource utilization, making the system more attractive for industrial deployment.

Several studies have demonstrated the viability and versatility of this strategy, using PET-derived monomers as representative model substrates. One notable example [53] involves the coupling of PET-derived ethylene glycol oxidation with the two-electron oxygen reduction reaction (ORR) (Figure 3a). Using a selenized NiMn-MOF catalyst for EG oxidation and a B/N-doped onion-like carbon catalyst for two-electron ORR, the system achieved Faradaic efficiencies of 93.0 % for formate and 97.5 % for H_2O_2, operating at only 0.927 V and sustaining current densities as high as 400 mA cm^{-2}. This configuration outperformed conventional H_2O_2 electrosynthesis systems, illustrating how paired reactions can transform plastic waste and produce industrially relevant oxidants simultaneously. Another example [54] paired the anodic oxidation of 1,4-butanediol derived from polybutylene succinate hydrolysates with the cathodic conversion of biomass-derived maleic acid, enabling the co-production of succinic acid at both electrodes (Figure 3b). A Cr^{3+}-doped $Ni(OH)_2$ catalyst accelerated the rate-limiting Ni^{2+}/Ni^{3+} redox transition, resulting in a succinic acid productivity of 3.02 g h^{-1} and an apparent FE of 181.5 %. Researchers have also developed a CO_2-assisted precipitation method to recover high-purity succinic acid, further enhancing process integration and economic viability.

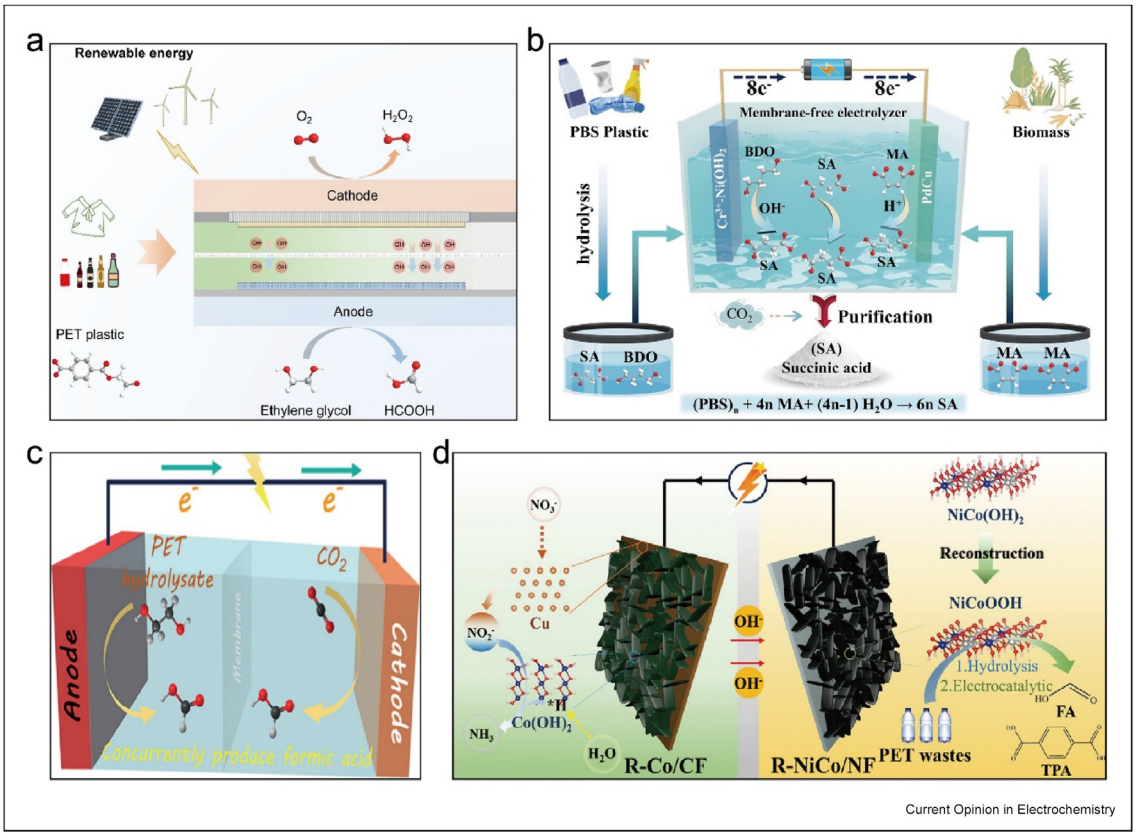
An alternative strategy demonstrated the coupling of PET hydrolysate oxidation with CO_2 electroreduction, enabling the simultaneous production of formic acid at both electrodes [55] (Figure 3c). By utilizing $NiCo_2O_4$ nanowires as the anodic catalyst and SnO_2 nanosheets at the cathode, the system achieved Faradaic efficiencies of 90 % and 82 %, respectively, while operating at a low cell voltage of 1.55 V. This energy-efficient configuration not only addresses plastic and CO_2 waste simultaneously but also yields an estimated $557 net revenue per ton of PET processed, emphasizing its industrial relevance. In another study [56], PET upcycling was paired with nitrate reduction for ammonia production (Figure 3d). By employing transition metal-based electrodes reconstructed *in-situ*, the system achieved Faradaic efficiencies of 98.2 % for formic acid and 96.2 % for ammonia while reducing the cell voltage by 202 mV compared with standard nitrate reduction systems. Techno-economic analysis revealed energy savings of 2.8×10^5 kWh and revenue generation of approximately $6,900 per ton of ammonia produced, offering a dual solution for wastewater treatment and plastic waste valorization.

While the integration of cathodic reactions offers dual advantages of reducing overall cell potential (minimizing energy input) and potentially improving product selectivity through engineered pathways, the scope of chemically distinct products remains constrained within this framework.

Heteroatom incorporation for functionalized product synthesis

Building on the development of electrocatalytic plastic upcycling strategies, recent research has further

Figure 3



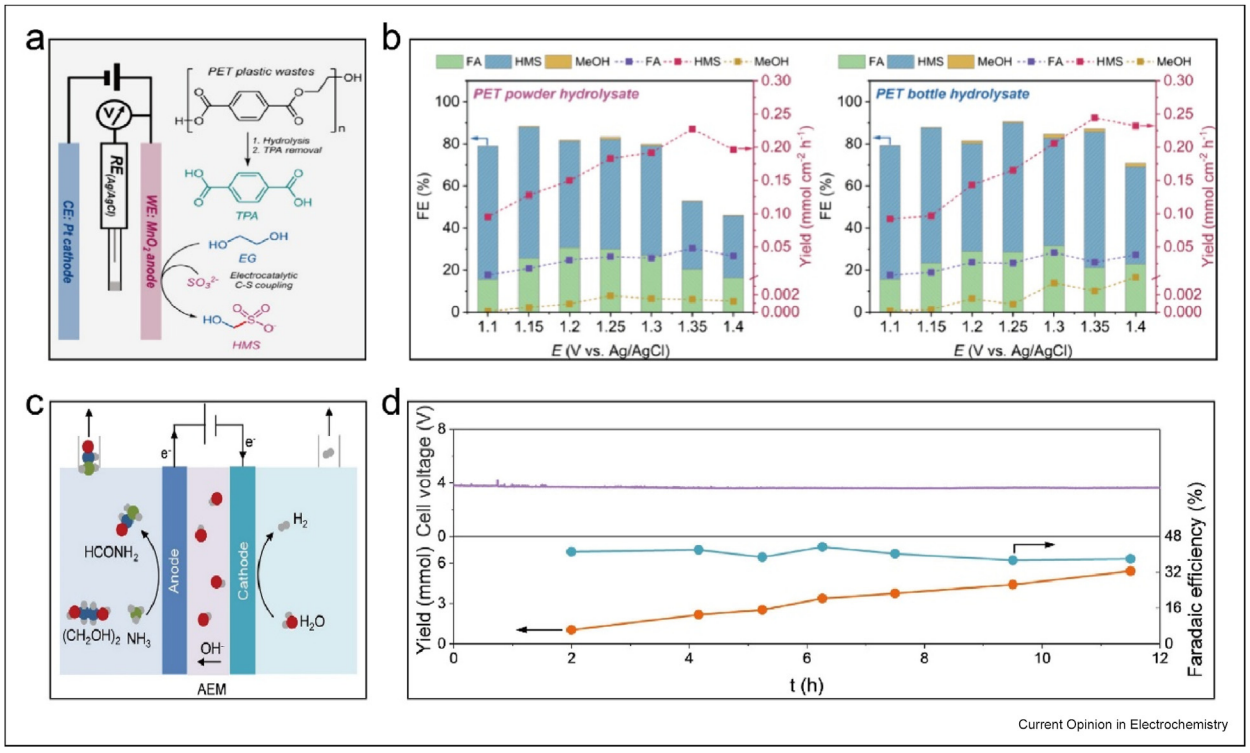
(a) Schematic illustration of the electrolysis system coupling ORR-to-H_2O_2 with PET upcycling. **(b)** Scheme of the SA anode/cathode co-production system. **(c)** Scheme of the electrolysis system coupling the CO_2RR with PET upcycling. **(d)** Schematic illustration of a dual-electrode coupled system for the electrochemical upgrading of waste pollutants (nitrate and PET).

expanded the functional scope of electrocatalytic transformations by incorporating heteroatoms such as sulfur, nitrogen and oxygen into plastic-derived intermediates [57–59]. These C–S, C–N or C–O coupling strategies not only diversify the product portfolio but also enable access to high-value functionalized chemicals with broad industrial applications. As in the previous sections, the PET-derived monomers continue to serve as model substrates.

Kang et al. [60] demonstrated a pioneering approach that couples PET-derived EG oxidation with C–S bond formation, enabling the synthesis of organosulfur compounds such as hydroxymethanesulfonate (HMS) (Figure 4a). Using an amorphous MnO_2 catalyst prepared *via* electrodeposition, the reaction was conducted under near-neutral conditions (0.1 M K_2SO_4), a notable departure from traditional alkaline systems. The key to this strategy lies in capturing electrophilic intermediates (*e.g.*, $*CH_2OH$) generated during EG oxidation and coupling them with sulfur–based nucleophiles (SO_3^{2-}/HSO_3^-) sourced from industrial wastewater. The system achieved a FE of up to 70 %, and mechanistic insights from density functional theory calculations and *in-situ* characterization revealed that the amorphous MnO_2 catalyst substantially lowered the energy barriers for both C–C bond cleavage and C–S bond formation. Importantly, the approach was validated using post-consumer PET bottles as the feedstock, achieving a 65 % HMS yield within 2 h, and techno-economic analysis confirmed its feasibility for real-world applications (Figure 4b).

Similarly, Shi et al. [61] reported an electrocatalytic method to convert PET-derived EG and other biomass-based polyols (*e.g.*, glycerol and glucose) into formamide, a nitrogen-containing platform molecule (Figure 4c). The system employed a cost-effective WO_3 catalyst to oxidize polyols into aldehyde intermediates, such as glycolaldehyde and formaldehyde. These reactive species were subsequently aminated through C–N bond formation with nitrogen radicals ($\bullet NH_2$) generated from ammonia electrooxidation. Operating under ambient conditions in a flow electrolyzer, the system delivered a formamide productivity of 537.7 μmol cm^{-2} h^{-1} and a FE of 43.2 % at 100 mA cm^{-2}. The reaction maintained

Figure 4



(a) Scheme of electrocatalytic conversion of PET plastic wastes to HMS. **(b)** Products FE and yield with PET powder and PET bottle hydrolysates as substrates. **(c)** Schematic illustration of the membrane electrode-based flow electrolyzer used to construct C–N bonds and eventually produce formamide. **(d)** Continuous synthesis of formamide at a current density of 100 mA cm^{-2} with a flow rate of 60 mL min^{-1}.

performance over 12 h of continuous operation, ultimately producing 5.4 mmol (244.6 mg) of formamide (Figure 4d). This approach was also extended to a wide range of C_3–C_6 polyols, highlighting its broad applicability and high carbon atom efficiency. Moreover, the successful transformation of commercial PET bottle waste into nitrogen-functionalized products highlights the potential for electrocatalysis to bridge plastic and biomass valorization pathways within a single process platform.

Heteroatom incorporation expands electrocatalytic monomer oxidation beyond oxygenates, enabling selective C–S and C–N bond formation under mild conditions. Optimizing the reaction environment will be key to improving selectivity and scaling functionalized plastic upcycling.

Outlook and conclusion

Electrocatalytic upcycling shows promise for hydrolyzable plastics like PET, but is limited to depolymerizable polymers. Most commercial plastics (PE, PP, *etc.*) contain inert C–C backbones resistant to hydrolysis and electrochemical activation, hindering universal plastic valorization. Future research should develop strategies to directly activate intact polymer chains, including: Catalysts for C–C/C–H bond cleavage under mild aqueous conditions; Solutions for solid-state limitations (solubility, mass transfer); Hybrid thermo-electrochemical and tandem catalytic approaches [62–65]; Combined chemical/electrochemical activation. For example, Pichler et al. [66] demonstrated a chemical–photo/electrocatalytic strategy to realize the transformation from PE to ethylene and propylene. Furthermore, polyolefins can be pyrolyzed to produce carbon dioxide, which can then be electrochemically converted into higher-value chemicals [67]. The field is transitioning from degradation to value-added conversion of plastics into chemicals and fuels [68].

Meanwhile, to enable the practical application of electrocatalytic plastic waste treatment, scale-up experiments and techno-economic analyses are essential. Although some studies have reported catalyst scale-up and economic assessments [69–71], further research and design of electrolyzer components are necessary to achieve stable operation under industrial conditions.

Looking ahead, key priorities include designing multifunctional electrocatalysts with enhanced selectivity and durability, developing reactor systems tailored for

heterogeneous polymer interfaces, and incorporating renewable energy sources for sustainable operation. Integrating electrocatalysis with other technologies, such as biocatalysis, photochemistry, or mechanochemical pretreatment, may further enhance system performance and product scope.

Declaration of competing interest

The authors declare no conflict of interest.

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Data availability

No data was used for the research described in the article.

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** of outstanding interest

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