



Review Article

Electrocatalytic selective oxidation of ethylene glycol: A concise review of catalyst development and reaction mechanism with comparison to thermocatalytic oxidation process

Ji Qi¹, Ziyang An¹, Chuang Li¹, Xiao Chen¹, Wenzhen Li² and Changhai Liang¹**Abstract**

As an important water and seawater degradable plastic monomer, glycolic acid can be synthesized by selective oxidation of ethylene glycol. This review recapitulates recent advances in electrocatalytic ethylene glycol oxidation reaction (EGOR) from the aspects of catalytic performance and reaction mechanism. For catalytic performance evaluation, target product yield and space-time yield are correlated and analyzed for electrocatalytic and thermocatalytic EGOR systems. To elucidate the rationale behind the electrocatalytic selective oxidation of ethylene glycol, previous works using *in situ* Fourier transform infrared spectroscopy, online differential electrochemical mass spectrometry, ion chromatography, and theoretical calculations to investigate EGOR are systematically reviewed. Finally, the advantages of electrocatalytic EGOR are summarized by comparing electrocatalytic and thermocatalytic processes.

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Keywords

Ethylene glycol oxidation, Glycolic acid, Reaction mechanism, Electrocatalytic process, Thermocatalytic process.

Introduction

A promising way to solve the ‘white pollution’ problem is to develop biodegradable plastics, preferentially from

renewable resources. As an important chemical feedstock, ethylene glycol (EG) is currently produced from fossil fuels [1], with an annual global production capacity of 41.8 million metric tons (2019), and can be potentially produced from renewable biomass in the long run [2,3], or even from waste CO₂ [4,5]. Owing to its two relatively active primary hydroxyl groups, EG can be selectively oxidized to a range of chemicals including glycolic acid, glyoxylic acid, oxalic acid, and formic acid. Formed by selectively oxidizing one primary hydroxyl group of EG, glycolic acid is a key precursor to the synthesis of water and seawater degradable polymers such as poly(glycolic acid) (PGA) and poly(lactic-co-glycolic acid). Glycolic acid can be directly converted into PGA via polycondensation, whereas it could also first dimerize into glycolide, followed by ring-opening polymerization into PGA [6]. Meanwhile, glycolic acid may copolymerize with lactic acid to produce poly(lactic-co-glycolic acid), a kind of seawater and freshwater biodegradable polymer [7]. Because the degradation of such polymers releases carbon dioxide, the ultimate goal of the one-time plastic industry is to produce seawater and freshwater biodegradable polymers with biomass or carbon dioxide as starting feedstocks to achieve net-zero carbon emission. Selective oxidation of EG to glycolic acid is one of the potential pathways within such a blueprint.

One of the classic ways to produce glycolic acid is carbonylation of formaldehyde with carbon monoxide. This process requires a high pressure of up to 100 MPa and a reaction temperature of up to 400 °C, partially because carbon monoxide as the reactant has limited solubility in the solvent (e.g. sulfolane). Selective oxidation of EG to glycolic acid is a relatively safe and environmentally friendly alternative to this conventional process.

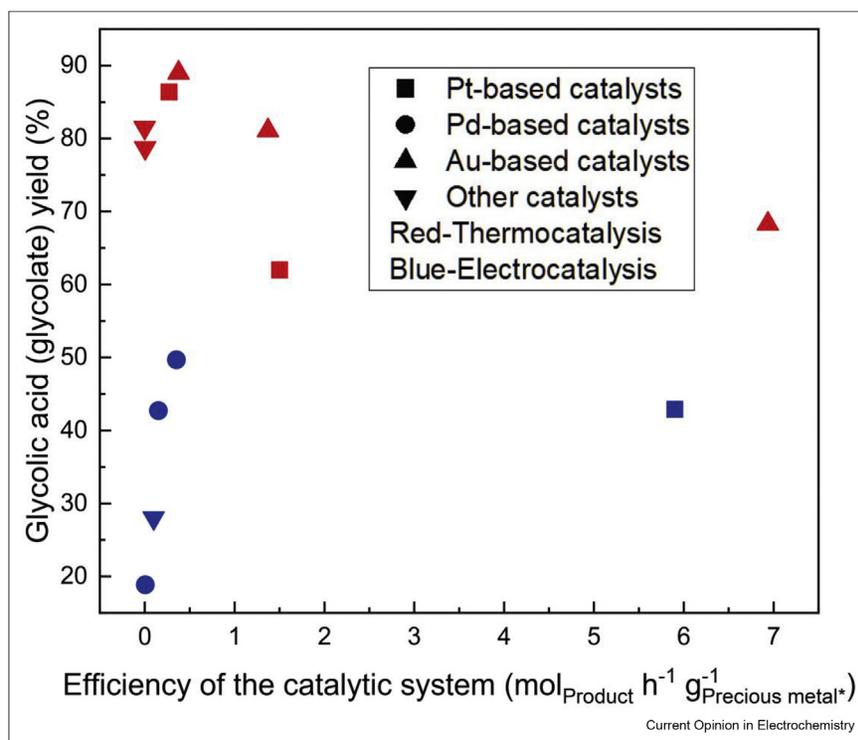
State-of-the-art technology on ethylene glycol oxidation to glycolic acid (or glycolate)

If the whole reaction system including the reactor and catalytic material is to be evaluated, the two important

core indicators for electrocatalysis and thermocatalysis systems are the yield of the target product and the efficiency of the reaction system (space-time yield), which will directly affect the atomic economy and the final overall cost of the reaction system. As summarized in Figure 1, the catalytic performance of Au-based and Pt-based catalysts is generally higher than Pd and other metal-based catalysts for the selective oxidation of EG to glycolic acid, which can be synthesized via both thermocatalytic [8,9,12–16] and electrocatalytic [10,11,17,18] routes. Several representative and pioneer research works are discussed below. Prati and Rossi [14] achieved an EG conversion of 90.2% and a glycolic acid selectivity of 89.9% in a thermocatalytic reactor using carbon-supported gold as the catalyst. Griffin et al. [12] studied the catalytic activity of the bimetallic PdAu catalyst in a similar reaction system, confirming that the bimetallic catalyst had higher turnover frequency (TOF, 600 h^{-1} at 10% conversion). With density functional theory (DFT) calculations, the authors found that the rate enhancement on the PdAu surfaces compared with Pd was likely owing to a reduction

in coverage of strongly bound adsorbates, whereas the enhancement over Au was likely owing to the reduction in the activation barrier of C–H scission. Investigated by Xin et al. [11], a direct ethylene glycol fuel cell (DEGFC) with the Pt/C anode catalyst could generate target product and electricity simultaneously, achieving a glycolate yield of 76.1% and a peak power density of 71.0 mW cm^{-2} . The reaction network of electrocatalytic EG oxidation was also proposed in this work based on the sequence of different products detected by an online sample collection system. Marchionni et al. [18] obtained 55.5% EG conversion and 89.5% glycolate selectivity with a Pd/C anode catalyst in a DEGFC setup. With Rh-based metal–organic compound deposited onto large-surface area carbon support as the anode catalyst in this system, Bellini et al. [17] further reported 38% EG conversion and 100% glycolic acid selectivity. Heterogenization of homogeneous catalysis was adopted because it enlarged the average distance between each metal atom, thus enabling these atoms function as relatively independent active sites.

Figure 1



State-of-the-art performance of electrocatalytic (blue color) and thermocatalytic (red color) systems for selective oxidation of ethylene glycol to glycolic acid (glycolate). Efficiency of catalytic system (space-time yield) versus glycolic acid (glycolate) yield is exhibited with respect to Pt-based catalysts [8–11], Pd-based catalysts [10,12], Au-based catalysts [11–14], and other catalysts [15–17]. *Efficiency of the catalytic system is calculated based on the weight of precious metal used except for the case of Cu/CNF (carbon nanofiber) catalytic system [16], the efficiency of which is calculated based on the weight of copper.



Aggregation states (a) aqueous, (l) liquid, and (g) gaseous.

No matter with thermocatalytic or electrocatalytic methods, most of the above-mentioned studies used oxygen as the oxidant (eqn. (1)) so that water as the by-product would undermine the atom economy of the whole catalytic process. To avoid this, Haasterecht et al. [16] used water instead of gaseous oxygen as oxygen source for ethylene glycol oxidation reaction (EGOR), achieving 78.7% yield to glycolate with hydrogen as a cogenerated valuable product. With copper supported on carbon nanofiber as catalysts, this work reported a successful achievement in selective catalytic oxidation of a primary hydroxy group of EG on a nonprecious metal catalyst at 150 °C. Zhan et al. [15] adopted a homogeneous catalysis system for EGOR with $\text{Cp}^*\text{Ir}(\text{bpyO})\text{OH}^-$ as the catalyst, achieving 81% yield glycolic acid with hydrogen cogeneration. This reaction has taken full advantage of the hydrogen atoms from both EG and water molecules to generate hydrogen gas (eqn. (2)). Because the theoretical atom economy of this reaction is close to 100% (concerning neutralization of acid and base), selective oxidation of EG to glycolic acid with hydrogen cogeneration makes EGOR meet the criteria of green chemistry.



Aggregation states (l) liquid and (g) gaseous.

Reaction mechanism of electrocatalytic ethylene glycol oxidation reaction

To comprehend the mechanisms behind the electrocatalytic selective oxidation of EG, previous researchers have used *in situ* Fourier transform infrared spectroscopy (FTIR) [2,19–31], online differential electrochemical mass spectrometry [22,23,32], ion chromatography [27], and theoretical calculations [33–36]. These studies have provided some clues on how to increase the yield of glycolic acid, as described in the following.

First, the relationship between the catalytically active sites and the cleavage of the carbon–carbon bond was explored. If the target product is glycolic acid, C–C bond cleavage should be minimized, whereas the

catalyst should have the ability to oxidize adsorbed CO to avoid poisoning. Therefore, it is necessary to assess the level of carbon monoxide coverage on the catalyst surface at various applied potentials and pH conditions using *in situ* FTIR. In 1990, Leung and Weaver found the poisoning effect of $-\text{CO}_{\text{ad}}$ was owing to the dissociative adsorption of EG on the Pt catalyst surface. Responsible for the carbon–carbon bond breaking, the dissociative adsorption requires the adjacent metal active sites to adsorb the carbon atoms of C_2 species [29]. Consequently, the electrocatalytic active sites with strong carbon adsorption capability cannot be too dense, to reduce the possibility of the carbon atoms' dissociative adsorption that results in carbon–carbon bond cleavage. In concert with this conclusion, Lima et al. found that the presence of Ru metal was not conducive to the cleavage of carbon–carbon bond over the Pt-based catalyst from the viewpoint of EG dissociation adsorption. Instead, Ru may accelerate the transformation of CO in the adsorbed state [26]. In contrast, Freitas et al. [37] have experimentally demonstrated that the addition of Ir contributed to the cleavage of C–C bonds, whereas Tang et al. [19] reported that the addition of Pd contributed to the dissociative adsorption of EG over Pt. These two instances suggest that carbon–carbon bond scission may be promoted if the second kind of active

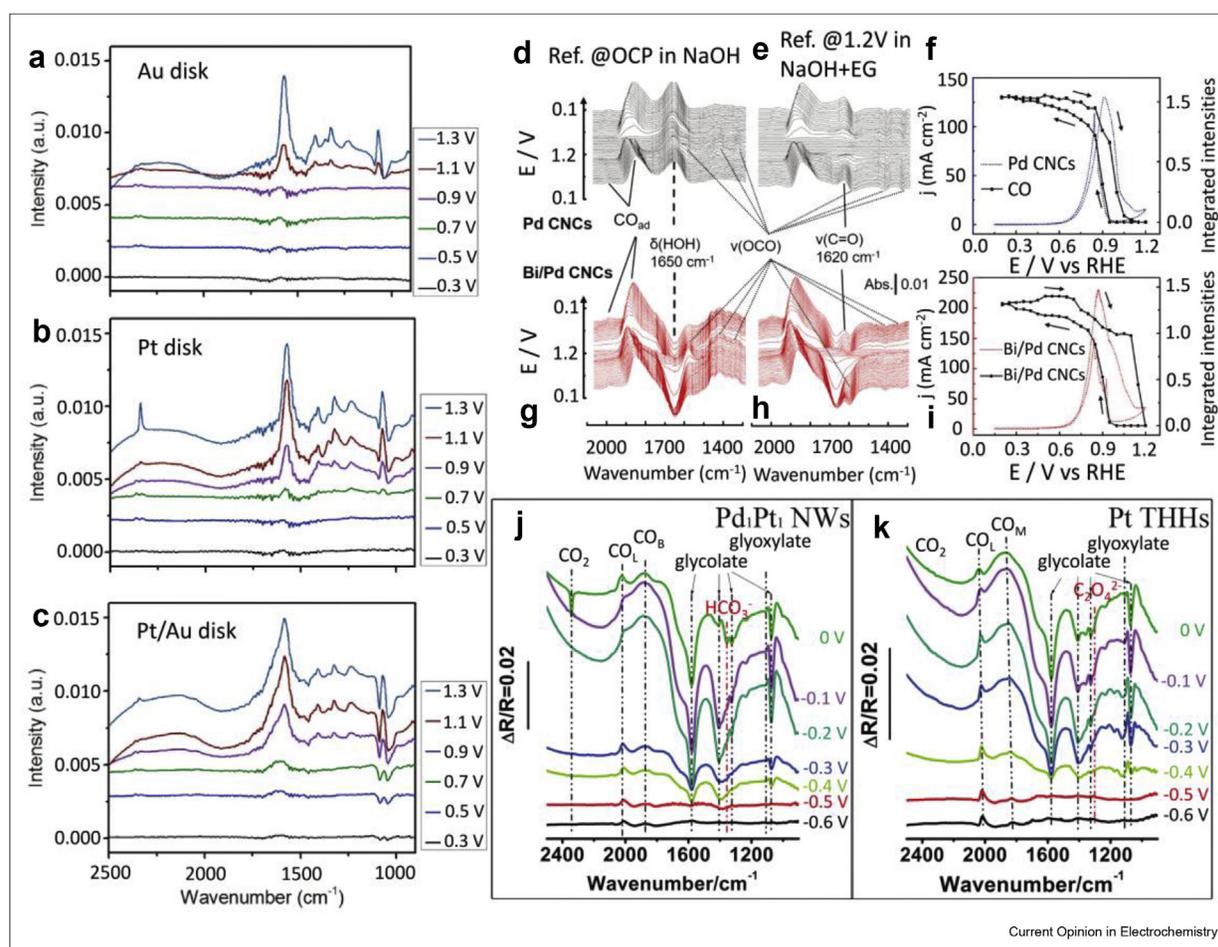
site has strong adsorption and catalytic oxidation capability toward EG.

Second, research efforts were focused on clarifying the relationship between the applied potential and reaction products. In general, it is more desirable to complete oxidation of EG to CO_2 for a DEGFC application, whereas glycolic acid is the targeted valuable product for degradable polymer synthesis. Confirming the existence of glycolaldehyde, glycolic acid, and oxalic acid as EGOR products in the acidic environment by *in-situ* FTIR, Dailey et al. [27] observed that the amount of carbon dioxide product increased with the applied anodic potential. Nevertheless, Falase et al. [25] found that the vibrational absorption peak of carbon dioxide can be produced at a lower overpotential, revealing that for classical monometallic catalysts, the formation of C_1

products may not be completely avoided even under relatively low applied potential. By monitoring the CO₂ vibration band at 2341 cm⁻¹ with *in-situ* FTIR (Figure 2 A–C), Mahoney et al. [21] concluded that Au electrocatalysts in alkaline media are not prone to break the CC bond in EG and instead provide OH_{ads} covered surface on which a deprotonated EG may react, whereas the Pt surface is able to break the CC bond in EG at high overpotentials. Meanwhile, high potential could accelerate the reaction process when the applied potential is lower than the catalyst oxidation potential. Fortunately, Schnaidt et al. demonstrated that the incomplete oxidation of EG is the favorable pathway over the Pt

electrocatalyst at low temperature, whereas complete oxidation to CO₂ had <10% current efficiency. The formation of glycolaldehyde and glycolic acid (at potentials of 0.3–0.5 V and ≥0.6 V vs reversible hydrogen electrode (RHE)) can be reflected by the appearance of bands related to the adsorption of 2-hydroxyacetyl and glycolic acid species [23]. Similarly, Wang et al. [2] demonstrated that although Pd or PdBi may cleave the CC bond of EG with *in-situ* FTIR (Figure 2 d–i), Faradaic efficiency of glycolate is still as high as 76% and 55% on Pd and PdBi catalysts, respectively. By alloying Pt with Pd as catalysts, C₂ and C₁ pathways also coexist for EGOR (Figure 2 J,K), as reported by Tang et al. [19]. To

Figure 2



Investigation of electrocatalytic EGOR mechanism with In-situ infrared spectroscopy. *In-situ* FTIR spectra of the (a) Au, (b) Pt, and (c) Pt/Au disk electrode during EGOR. Spectra were acquired in 0.1 M KOH and 0.2 M EG purged in N₂, whereas the potential was scanned at 1 mV s⁻¹. All potentials are referred to the RHE. *In-situ* attenuated total reflectance surface enhanced infrared absorption spectroscopy (ATR-SEIRAS) spectra collected with a time resolution of 5 s on a Pd CNC electrode (d, e) and a Bi/Pd CNC electrode (g, h) in 0.5 M NaOH + 0.5 M EG solution, using a single-beam spectrum at open circuit potential at ca. 1.02 V in 0.5 M NaOH solution (d, g) and at 1.2 V in 0.5 M NaOH + 0.5 M EG solution (e, h) as the reference spectrum, respectively. Each single-beam spectrum was an average of 18 scans. Corresponding cyclic voltammograms (dotted line) of Pd CNCs (f) and Bi/Pd CNCs (i) in 0.5 M NaOH + 0.5 M EG solution at 10 mV s⁻¹, together with the potential-dependent peak intensities of CO_{ad}. SPAFTIR (single potential alteration Fourier-transform infrared spectroscopy) spectra of Pd₁Pt₁ NWs (j) and Pt THHs (k) in 0.5 M EG + 0.5 M NaOH solution with E_s varied from 0.6 to 0 V and E_R = 0.75 V. (a–c) Reprinted and adapted with permission from Mahoney et al. [21] Copyright 2016, Elsevier B.V. (d–i) Reprinted and adapted with permission from Ref. [2] Copyright 2017, American Chemical Society. (j, k) Reprinted and adapted with permission from Ref. [19] Copyright 2018, The Royal Society of Chemistry. EG, ethylene glycol; EGOR, ethylene glycol oxidation reaction; FTIR, Fourier transform infrared spectroscopy.

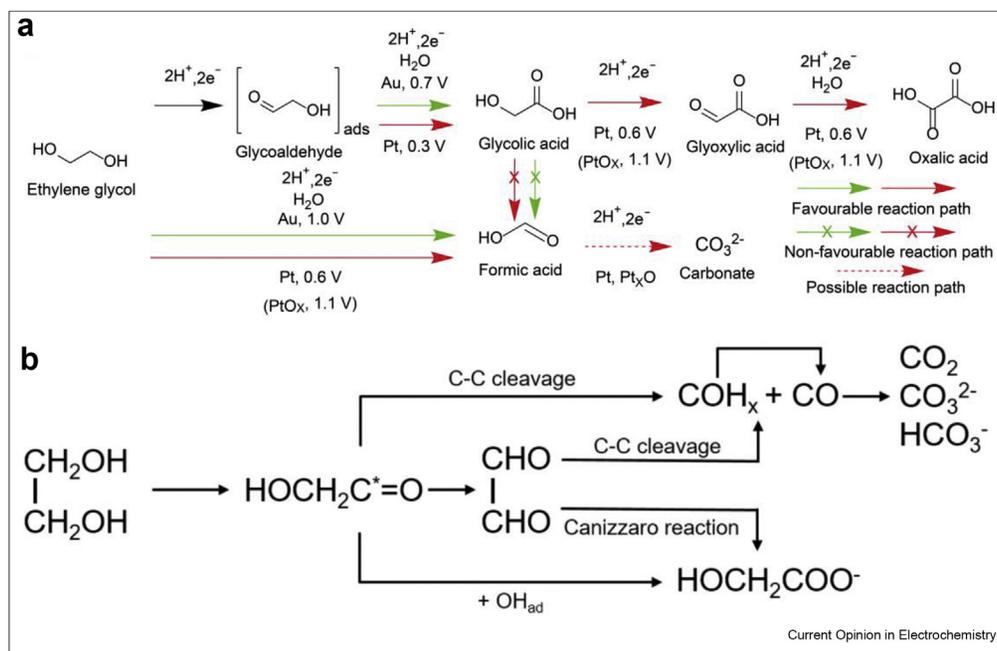
summarize the work of the several groups mentioned previously, the main EGOR products over Pt-based, Pd-based, and Au-based catalysts at low potential are C₂ chemicals, and the increase of applied voltage within a certain voltage range helps to speed up the conversion of EG to glycolic acid. Pech-Rodríguez et al. [20] further confirmed that the oxidation of glycolic acid could only occur when the potential is above 0.7 V versus RHE by *in situ* FTIR, which provided a clue to the upper voltage limit of electrocatalytic selective oxidation EG to glycolic acid. It should be noted that the main product of electro-oxidation polyols (including EG) on nickel oxide electrodes in alkaline media at higher potential (e.g. >1.5 V vs RHE) is formate, indicating C–C cleavage pathway dominates in high potentials [28].

Third, the reaction network with detailed reaction pathways was outlined based on research efforts of a few groups. Using an online sampling approach in a three-electrode setup, Xin et al. [11] examined the reaction pathways of EGOR on Au/C and Pt/C (Figure 3 A), confirming that the C–C bond breakage originates from some intermediates in the adsorbed state rather than from glycolic acid in the desorbed state. To deepen the understanding of adsorbed intermediates, Wang et al. carried out the *in-situ* FTIR study, confirming that 2-hydroxyethyl is the key intermediate for EGOR and can be further oxidized to glyoxal. Both of these

intermediates could be further converted to glycolate in an alkaline environment, whereas C–C bond fracture can also occur [2]. In the proposed reaction pathway (Figure 3 B), it is inferred that the C–C bond of EG is broken mainly via the above two C₂ adsorbents or intermediates, rather than via the re-adsorption and further oxidation of desorbed glycolate. This conclusion is similar to the previous experimental studies of glycerol [38] and echoed well with older research on the *in-situ* FTIR study of electro-oxidation of polyols on Pt, Au, and Ni electrodes [28]. In other words, the selective oxidation of EG to glycolate requires an enhanced formation rate of the adsorbed 2-hydroxyacetyl at least in the proposed reaction network or a simultaneous acceleration of 2-hydroxyacetyl and glyoxal formation. It should be further ensured that these key intermediates are mainly converted to glycolate without dissociative adsorption or consecutive oxidation to oxalate.

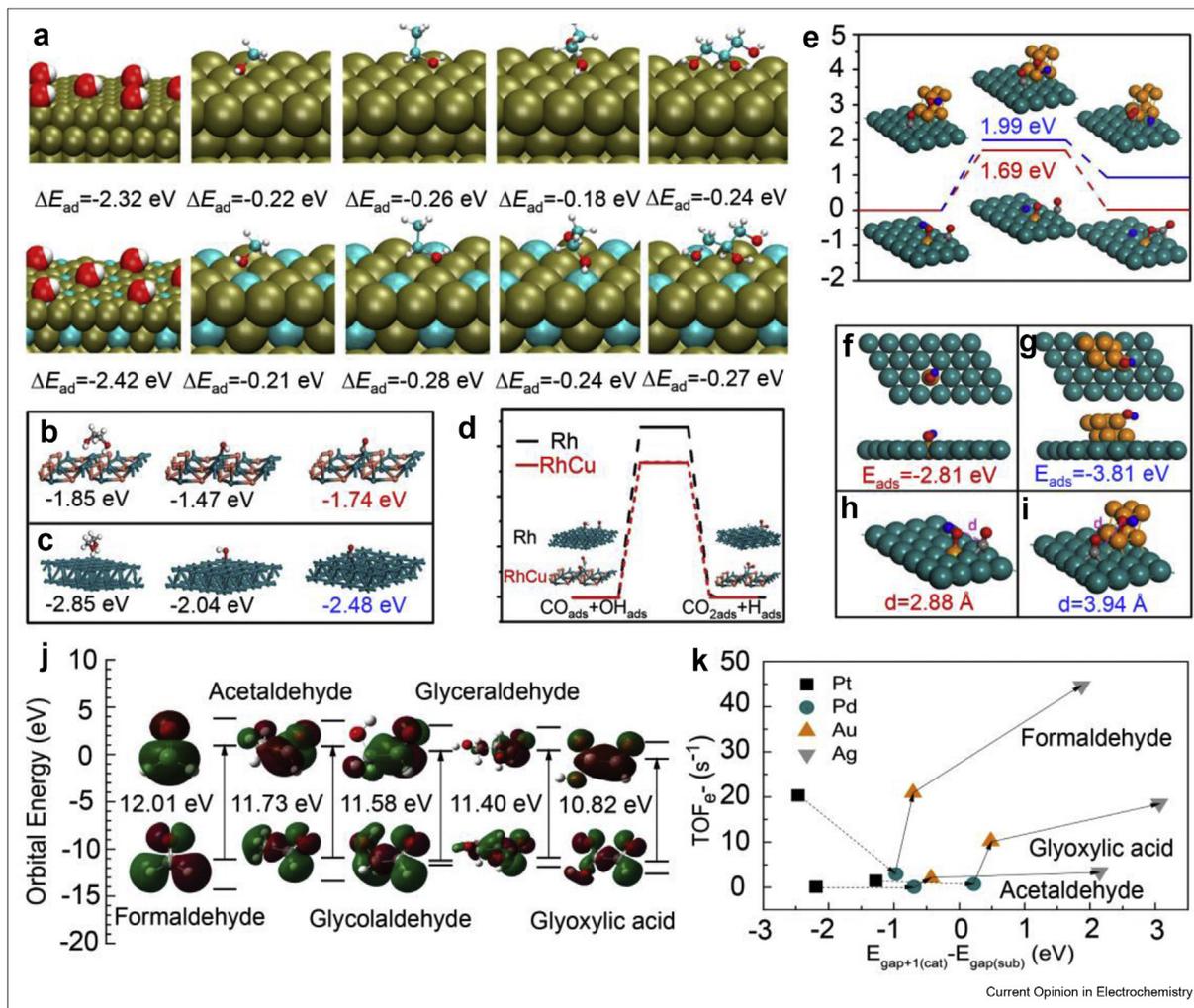
Finally, the origin of intrinsic catalytic activity promotion was investigated with theoretical calculations based on computational approaches. Previous studies have successfully used various descriptors to examine the effectiveness of active sites for EG oxidation, including adsorption energy [33–35], activation energy [34], Gibbs free energy [33], and degree of orbital energy difference matching [36], which can be defined or calculated with the following equations:

Figure 3



The reaction pathways analysis for electrocatalytic EGOR. **(a)** The proposed pathways for electrocatalytic EGOR on Au/C and Pt/C in alkaline media, the starting potentials for observed reaction paths are marked. **(b)** Reaction pathways suggested for electrocatalytic EGOR on Pd and Bi/Pd CNCs in alkaline media. **(a)** Reprinted and adapted with permission from Xin et al. [11] Copyright 2012, Elsevier B.V. **(b)** Reprinted and adapted with permission from Ref. Wang et al. [2] Copyright 2017, American Chemical Society. EGOR, ethylene glycol oxidation reaction.

Figure 4



Theoretical calculations for ethylene glycol oxidation and intermediate oxidation over different electrocatalysts. **(a)** Optimized structures of hydroxyl, methanol, ethanol, ethylene glycol, and glycerol adsorbed on Pd(111) and Pd₃Cu(111) surfaces as calculated using density functional theory. **(b, c)** Adsorption energies of ethylene glycol, hydroxyl, and CO species on Rh(111) and RhCu(111) surfaces, and **(d)** the reaction energy barrier of the oxidation of CO_{ads} assisted by OH_{ads} to form CO₂ Rh(111) and RhCu(111) surfaces. **(e)** Reaction energy diagram of CO_{ads} oxidation via L-H mechanism on Ru₁@Pt plane and Ru₈@Pt plane. The binding energies of adsorbed OH on **(f)** Ru₁@Pt plane and **(g)** Ru₈@Pt plane. The distance of adsorbates (CO_{ads} and OH_{ads}) sitting at nearest energy-favorable positions on **(h)** Ru₁@Pt plane and **(i)** Ru₈@Pt plane. **(j)** Calculated orbital energy diagram of HOMO-1, HOMO, LUMO, and LUMO+1 for different aldehydes with frontier HOMO-LUMO gaps ($E_{\text{gap(sub)}}$) as orbital energy differences. **(k)** TOF_{e⁻} (at 0.6 V vs RHE) as a function of orbital energy difference matching represented by $E_{\text{gap+1(cat)}} - E_{\text{gap(sub)}}$. Experimental points of the same substrate are linked with arrows. **(a)** Reprinted and adapted with permission from Serov et al. [35]; Copyright 2016, Elsevier B.V. **(b-d)** Reprinted and adapted with permission from Qiao et al. [33]; Copyright 2021, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim **(e-i)** Reprinted and adapted with permission from Wang et al. [34] Copyright 2019, Elsevier B.V. **(j-k)** Reprinted and adapted with permission from Qi et al. [36] Copyright 2016, Elsevier B.V.

$$\Delta E_{\text{adsorption}} = E_{\text{active phase surface/adsorbate}} - E_{\text{bare active phase surface}} - E_{\text{structure to be adsorbed}} \quad (3)$$

Where $\Delta E_{\text{adsorption}}$ is the adsorption energy of an adsorbate onto the active phase surface, $E_{\text{active phase surface/adsorbate}}$, $E_{\text{bare active phase surface}}$, and $E_{\text{structure to be adsorbed}}$ are the total energy of the active phase surface and the adsorbate, the bare surface, the structure to be adsorbed, respectively

$$\Delta E_{\text{activation energy}} = E_{\text{transition state}} - E_{\text{initial state}} \quad (4)$$

where $\Delta E_{\text{activation energy}}$ is the activation energy of an elementary reaction step, $E_{\text{transition state}}$ and $E_{\text{initial state}}$ are the total energy of the transition state and initial state.

$$\Delta G = \Delta E_{\text{DFT}} + \Delta E_{\text{ZPE}} - T\Delta S \quad (5)$$

where ΔG is Gibbs free energy change, ΔE_{DFT} is total energy change calculated with density functional theory (DFT), ΔE_{ZPE} is zero-point energy change, ΔS is the entropy change, and ΔG can be further affected by the pH value and applied potential.

$$\Delta E_{\text{degree of orbital energy difference matching}} = E_{\text{gap}+1(\text{cat})} - E_{\text{gap}(\text{sub})} \quad (6)$$

where $\Delta E_{\text{degree of orbital energy difference matching}}$ is the matching degree of orbital energy differences, $E_{\text{gap}+1(\text{cat})}$ and $E_{\text{gap}(\text{sub})}$ are the highest occupied molecular orbital (HOMO) - lowest unoccupied molecular orbital (LUMO) gaps of the anode catalyst and substrate as orbital energy differences.

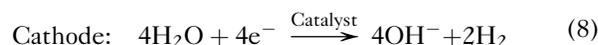
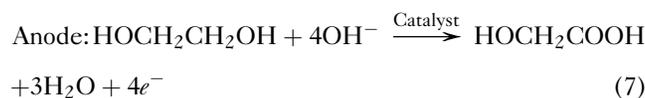
With DFT (Figure 4 A), Serov et al. calculated the adsorption energy of hydroxyl group adsorbed on Pd(111) and Pd₃Cu(111) surfaces to be -2.32 eV and -2.42 eV, respectively, providing theoretical support on that the addition of copper contributes to the adsorption of OH⁻. Because the OH⁻ species are involved in various steps of the elementary reactions, the energetically enhanced adsorption of them shall be favorable to TOF of the catalytic sites for EGOR [35]. As shown in (Figure 4 D), Qiao et al. [33] computed the free energy barrier of oxidation of CO_{ads} into CO₂ on RhCu surface (0.27 eV) and Rh surface (0.34 eV), showing that CO may readily desorb from RhCu alloy surface with a higher reaction rate. CO species exhibit adsorption energies of -1.47 eV and -2.48 eV on RhCu and Rh surfaces (Figure 4 B,C), respectively, inferring that RhCu nanoboxes are more CO-tolerant than commercial Rh nanocrystals. Wang et al. determined the bond breaking of O–H in adsorbed OH_{ads} to be about 1.69 eV and 1.99 eV on the Ru₁@Pt plane and Ru₈@Pt plane, respectively (Figure 4 E). The energy barrier declines by 0.30 eV, implying that surface alloying favors CO_{ad} oxidation/removal [34]. Compared with Ru₈@Pt plane, Ru₁@Pt plane can release OH_{ad} easier for subsequent CO_{ad} oxidation (Figure 4 F, G) with closer OH_{ad} and CO_{ad} distance (Figure 4H, I). Qi et al. analyzed HOMO–1, HOMO, LUMO, and LUMO+1 orbital energy diagrams for various aldehydes (EGOR intermediates) using frontier HOMO–LUMO gaps ($E_{\text{gap}(\text{sub})}$) as orbital energy differences (Figure 4 J). According to the correlation between the degree of orbital energy matching and TOF_c⁻ for aldehyde oxidation (Figure 4 K), the Ag catalyst has the highest TOF_c⁻ owing to the positive degree of orbital energy matching which is slightly higher than 0 [36].

Comparison of electrocatalytic and thermocatalytic ethylene glycol oxidation reaction

In a thermocatalytic EGOR process that selectively produces glycolate [12–14,39,40], one of the major by-

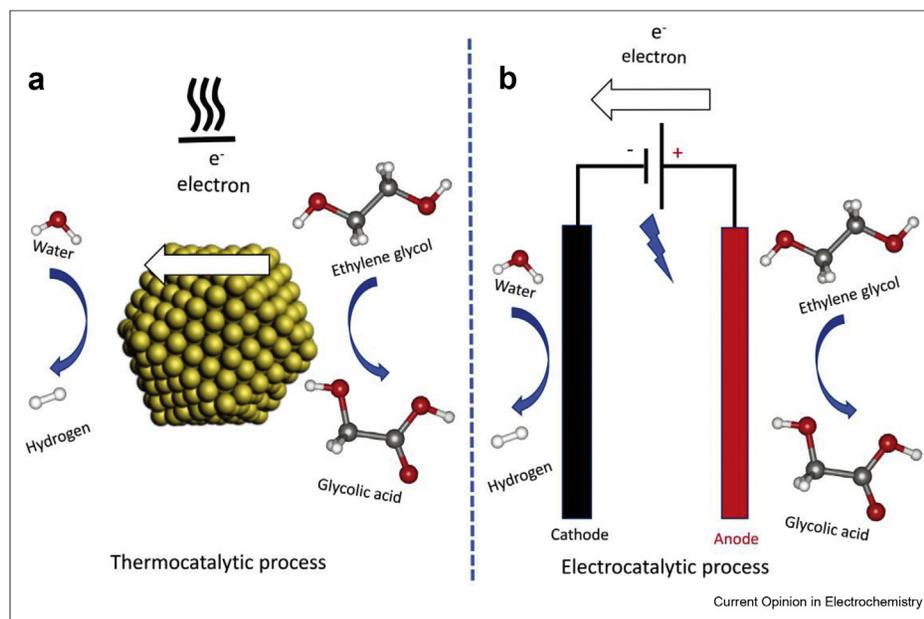
products is water because oxygen is used as the oxidant. To make the glycolic acid production process more economically feasible toward industry-scale production, it is reasonable to thermocatalytically or electrocatalytically couple the EGOR with the water reduction to generate hydrogen (H₂). In this way, H₂ gas can be cogenerated with glycolic acid. From the hydrogen production viewpoint, the above-mentioned process is more energy-efficient than traditional water splitting, because EGOR requires lower potential and proceeds more facile than water oxidation reaction. Moreover, the electrocatalytic material participating in the reaction process is in the form of solid electrodes (similar to a fixed catalyst bed), which simplifies the separation of the reaction products and the catalyst.

Based on the previous discussions, both thermocatalytic and electrocatalytic processes can realize the selective oxidation of EG [9,11]. Figure 5 demonstrated thermocatalytic and electrocatalytic processes of selective EG oxidation to glycolic acid with hydrogen cogeneration. The catalysts for thermocatalytic reaction not only function as active phase for both ethylene glycol oxidation and water reduction simultaneously but also act as an electron transport channel that conducts the electrons released from EG to water molecule. For the electrocatalytic process, the selective EG oxidation to glycolic acid is catalyzed by the anode electrocatalyst, whereas the water reduction reaction is catalyzed by the cathode electrocatalyst. The electrons transfer from the anode to cathode via an external circuit. From the energy point of view, the difference between the two is that the main energy source overcoming reaction energy barrier is heat or electric energy (except for high-temperature electrochemistry). From the reaction point of view, the thermocatalytic redox process occurs on active sites relatively close to each other, so interactions may occur between the intermediates and products of the oxidation reaction and the reduction reaction. The electrocatalytic process could separate the two half-reactions of oxidation (eqn. (7)) and reduction (eqn. (8)) in relatively independent regions.



This difference makes electrocatalysis have the following features: 1) it may avoid the direct interaction between oxidation reaction and reduction reaction intermediates and products; 2) it can also lower the energy consumption of the total reaction via selecting different active sites that are most suitable for EGOR and the reduction

Figure 5



Schematic illustration of (a) thermocatalytic and (b) electrocatalytic ethylene glycol selective oxidation to glycolic acid with hydrogen cogeneration.

reaction; 3) some half-reactions with high energy consumption or poor economic feasibility can be replaced with other half-reactions to construct some redox reaction pairs that are not easily realized by thermocatalysis alone; 4) if the total reaction is a spontaneous reaction with sufficiently negative Gibbs free energy, the reactor could release electric energy during reaction, converting chemical energy into electrical energy.

Conclusions

Electrocatalytic EG oxidation to glycolic acid is undeniably an attractive alternative to its thermocatalytic counterpart. 20–30 years ago, the major barriers of electrocatalytic EGOR were the low activity of the electrochemical system. There were studies on electrocatalytic EGOR that did not deliberately pursue the selective oxidation to glycolic acid as the target product. Thus, early studies focused on enhancing the activity of the EGOR electrocatalyst and investigating the possible product distribution. Nowadays, although the electrocatalytic EGOR using fuel cell-typed reactor with oxygen as the oxidant has achieved some improvements, the electrocatalytic selective oxidation of EG to glycolic acid using water molecules as the oxygen source only reach limited results with no competitive yields and space-time yields reported in the published articles. It is still challenging to maintain the high selectivity of glycolic acid (>90%) at high EG conversion (e.g. >90%). In addition, the space-time yield of hydrogen generation and the whole system's energy consumption should be thoroughly assessed and effectively improved. Such

existing limitation is to be challenged in the future research of electrocatalytic EG selective oxidation process, which places higher demands on the design of both electrochemical reactors and catalytic materials.

In detail, future research should be concentrated on promoting the activity of catalytic materials, boosting selectivity to glycolic acid (glycolate), and deepening the understanding of the reaction mechanisms. The intrinsic activity (TOF) catalyzing EGOR, the electrochemically active surface area, conductivity, and hydrophilicity of the catalytic materials should be raised concurrently by rational catalyst design to boost the activity of the electrocatalysts. After examining the full EGOR reaction network, it is vital to combine the active sites that favor the primary reaction pathways with those that suppress the side reaction pathways, thereby maximizing the selectivity to glycolic acid (glycolate). Moreover, *in-situ* studies should be combined with theoretical calculations to offer deeper insights into the reaction mechanisms.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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