Recent advances in single atom catalysts for the electrochemical carbon dioxide reduction reaction

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The electrochemical carbon dioxide reduction reaction (CO2RR) offers a promising solution to mitigate carbon emission and at the same time generate valuable carbonaceous chemicals/fuels. Single atom catalysts (SACs) are encouraging to catalyze the electrochemical CO2RR due to the tunable electronic structure of the central metal atoms, which can regulate the adsorption energy of reactants and reaction intermediates. Moreover, SACs form a bridge between homogeneous and heterogeneous catalysts, providing an ideal platform to explore the reaction mechanism of electrochemical reactions. In this review, we first discuss the strategies for promoting the CO2RR performance, including suppression of the hydrogen evolution reaction (HER), generation of C1 products and formation of C2+ products. Then, we summarize the recent developments in regulating the structure of SACs toward the CO2RR based on the above aspects. Finally, several issues regarding the development of SACs for the CO2RR are raised and possible solutions are provided.

1. Introduction

Excessive emission of CO2 resulting from overconsumption of fossil fuels causes the green-house effect. The CO2RR not only provides a solution to reduce CO2 concentration in the atmosphere, but also is able to simultaneously produce valuable carbonaceous chemicals/fuels. 1,2 Electrocatalytic reduction of CO2 driven by renewable electricity is environmentally friendly, and has become a hotspot in the field of CO2 conversion. The CO2RR involves very complex reactions, coupled with multiple proton and electron transfer steps, 3 which can convert CO2 into carbon monoxide (CO), methane (CH4), formic acid (HCOOH), methanol (CH3OH), ethylene (C2H4), ethanol (C2H5OH), etc:

\[
\begin{align*}
\text{CO}_2 + 2\text{H}^+ + 2e^- &\rightarrow \text{HCOOH} \\
\text{CO}_2 + 2\text{H}^+ + 2e^- &\rightarrow \text{CO} + \text{H}_2\text{O} \\
\text{CO}_2 + 6\text{H}^+ + 6e^- &\rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O} \\
\text{CO}_2 + 8\text{H}^+ + 8e^- &\rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \\
2\text{CO}_2 + 12\text{H}^+ + 12e^- &\rightarrow \text{C}_2\text{H}_4 + 4\text{H}_2\text{O} \\
2\text{CO}_2 + 12\text{H}^+ + 12e^- &\rightarrow \text{C}_2\text{H}_5\text{OH} + 3\text{H}_2\text{O}
\end{align*}
\]

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Many catalysts have been explored to break the robust C=O bond, such as sulfides,\textsuperscript{4,6} phosphides,\textsuperscript{7,8} oxides,\textsuperscript{3-15} and so on. However, the performance of the CO\textsubscript{2}RR is still unsatisfactory, showing low activity and poor product selectivity,\textsuperscript{14,15} especially for liquid C\textsubscript{2+} products. Therefore, developing highly active catalysts with good selectivity and stability is crucial for promoting this clean energy conversion technology.\textsuperscript{16-18}

Since Qiao et al.\textsuperscript{19} developed the Pt\textsubscript{1}/FeO\textsubscript{0.5} single atom catalyst (SAC) in 2011, SACs have received considerable attention. SACs usually consist of a metal center coordinated with non-metal elements (such as Mo, Fe, Co, Ni, Cu, and Zn), noble metal (Pd, Ag and Ir) and p-block (Sn, Sb and Bi) elements (Fig. 1). Most of the reported SACs electrocatalysts for the CO\textsubscript{2}RR. The determining factor for product selectivity is still under controversy. Therefore, to clearly elucidate the structure–activity relationship in the CO\textsubscript{2}RR and further develop SACs with higher product selectivity, especially for C\textsubscript{2+} products, a systematic review of previous studies of SACs in the CO\textsubscript{2}RR is urgently needed. Fig. 2 shows the development of SAC-based electrocatalysts for the CO\textsubscript{2}RR.

In this review, the strategies to enhance the CO\textsubscript{2}RR performance are first outlined, including the suppression of the HER, and the generation of C\textsubscript{1} products and C\textsubscript{2+} products. Then, recent advances in promoting CO\textsubscript{2}RR performance using SACs are summarized. Finally, some challenges in this field are proposed and possible solutions are provided at the end.

2. Strategies to improve the CO\textsubscript{2}RR

2.1. Suppression of the HER

The HER is the main side reaction competing with the CO\textsubscript{2}RR. The HER can proceed via two mechanisms, the Volmer–Heyrovsky and the Volmer–Tafel mechanism.\textsuperscript{34-36} In the Volmer step, a proton from the electrolyte reacts with an electron to form an adsorbed hydrogen on the catalyst surface (H\textsuperscript{*}). If the second step is the Heyrovsky reaction, the H\textsuperscript{*} will directly react with a proton and another electron to generate H\textsubscript{2}. If the Tafel reaction happens, another proton combines with another electron to form a second H\textsuperscript{*}, which will couple with the first H\textsuperscript{*} to generate H\textsubscript{2}.

\begin{align}
H^+ + e^- & \rightarrow \text{H}^* \text{ Volmer} \\
\text{H}^* + \text{H}^+ + e^- & \rightarrow \text{H}_2 \text{ Heyrovsky} \\
\text{H}^* + \text{H}^* & \rightarrow \text{H}_2 \text{ Tafel}
\end{align}

The Tafel route requires two adjacent active sites to adsorb two H\textsuperscript{*}, which is difficult in the case of SACs. So, the Heyrovsky mechanism is more plausible for the HER on SACs. Previous studies have shown that the activation energy of the Heyrovsky

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step is typically two times that of the Tafel step. Consequently, the HER can be considerably suppressed on SACs compared to their nanoparticle counterparts. A similar principle is also applicable to the CO$_2$RR, where the Heyrovsky mechanism is more plausible.

\[ \text{CO}_2 + \text{H}^+ + e^- \rightarrow \text{COOH}^* \]  
\[ \text{COOH}^* + \text{H}^+ \rightarrow \text{CO} + \text{H}_2\text{O} \text{ Tafel} \] (10)

\[ \text{COOH}^* + \text{H}^+ + e^- \rightarrow \text{CO} + \text{H}_2\text{O} \text{ Heyrovsky} \] (11)

\[ \Delta G_1 = (\Delta G_1(\text{COOH})) - (\Delta G_1(\text{CHO})). \]

The difference between the thermodynamic limiting potentials ($U_L(\text{CO}_2) - U_L(\text{H}_2)$) is a descriptor to indicate the selectivity of the CO$_2$RR ($U_L(\text{CO}_2)$ and $U_L(\text{H}_2)$ are the thermodynamic limiting potentials for the CO$_2$RR and HER, respectively). The larger the value, the higher the selectivity of CO.

The HER is the main side reaction competing with the CO$_2$RR, which needs to be suppressed so as to improve the selectivity of the CO$_2$RR. Jung et al. calculated the adsorption

![Figure 3](image-url)

Fig. 3 (a) Free energy change of the first protonation step in the CO$_2$RR and HER on various SACs. Catalysts below the dotted parity line are CO$_2$RR selective. Reproduced with permission from ref. 7. Copyright (2017) The Royal Society of Chemistry. (b) CO faradaic efficiency of Fe$_x$/Au compared with Au NPs, at different applied cathodic potentials. Reproduced with permission from ref. 37. Copyright (2020) American Chemical Society. (c) Calculated DOS for NiI-NCNT@Ni and NiI-NCNT@Ni$_9$Cu. (d) The calculated free-energy diagram of the HER on the (111) surface of Ni@C, Ni$_2$Cu@C, NiCu@C, and Ni=--N$_4$ sites. Reproduced with permission from ref. 38. Copyright (2020) Wiley-VCH. (e) $E_{\text{CCO}}$ of Ni/Fe--N--C, Ni--N--C and Fe--N--C at various applied potentials. (f) Difference in limiting potentials for the CO$_2$RR and HER for different catalysts. Reproduced with permission from ref. 39. Copyright (2019) Wiley-VCH.
energy of H (ΔG(H*)), *COOH and *OCHO [ΔG(*COOH/*OCHO)] and found that most SACs possess a ΔG(H*) larger than the ΔG(*COOH/*OCHO), suggesting that the CO2RR was more favorable than the HER on most SACs (Fig. 3a).7 Although the HER is intrinsically unfavorable on SACs, the selectivity towards CO2RR products still needs to be further improved. Yao et al. reported that by introducing Fe atoms into Au nanoparticles (Au NPs), the HER could be effectively suppressed, which greatly enhanced the CO faradaic efficiency (FE) in the CO2RR.37 Furthermore, the introduced Fe atoms bound with O atoms in CO2, while the nearby Au atoms bound with C atoms in CO2. Such a synergistic effect boosted the performance of Fe/Au (Fig. 3b). Other metal elements have also been studied to constrain the HER in SACs. Liu et al. introduced Cu into Ni SAC to form Ni(II)-NCNT@Ni9Cu to tune the adsorption energy of H*. Electrochemical results showed that Ni(II)-NCNT@Ni9Cu delivered a specific current density of −32.87 mA cm−2 and a TOF of 1962 h−1 at an overpotential of 620 mV for generating CO with 97% FeCO. DFT calculations found that the d-band center was upshifted from −1.520 eV to −1.438 eV after the introduction of Cu, which strengthened the adsorption of H* and thus further impeded the HER (Fig. 3c and d).18 The HER dominates at high overpotentials in single Fe atom catalysts. Zhao et al. introduced single Ni atoms into Fe-SAC and found that the adsorption energy of H*99 suppressed the HER and thus promote FeCO (Fig. 3e and f).

Another issue in the electrochemical CO2RR is that the solubility of CO2 in aqueous electrolyte is typically low (34 mM),68 and the reactant diffusion limitation restricts the reaction rate of the CO2RR particularly at high overpotentials, while the HER becomes more competitive. To tackle this challenge, many strategies have been developed, such as increasing the device pressure,31 lowering the reaction temperature,42 adopting a flow-cell device,43 and using a solid electrolyte.44

2.2. Generation of C1 products
C1 products from the CO2RR include CO, HCOO−, CH3OH, and CH4. Fig. 4 lists the possible pathways for the C1 products. To reduce CO2 to CO, *COOH is first generated on the catalyst’s surface via a proton coupled electron transfer (PCET) step, followed by *CO formation through dehydrogenation of *COOH, which is finally desorbed from the catalyst to release CO.45 If the catalyst adsorbs *CO very strongly, the catalytically active sites will be poisoned and the HER becomes dominant. If the catalyst adsorbs *CO loosely, *CO will be desorbed from the catalyst surface to generate CO. Only when the catalytic surface adsorbs *CO neither too strongly nor too weakly, further reduction reaction can take place. HCOO− is formed via the *OCHO intermediate, which has a medium adsorption energy.46 *OCHO can be bound to the catalyst surface via one or two oxygen atoms. As there are no neighbouring active sites, *OCHO is more likely to bind to the SAC via only one O atom as shown in Fig. 4. Both *CHO and *COH pathways are able to produce CH4, forming *CHOH and then *CH3OH and finally branching into two routes (CH3OH and CH4).47–51 *C is formed via dehydroxylation of *CHOH and constitutes another pathway to generate CH4. Carbon deposition covered on the copper catalyst after the CO2RR confirmed the existence of *C. Furthermore, *CH3O formed via protonation of *CHO is an important intermediate for CH4 and CH3OH.52–56 It is worth mentioning that the energy barriers for both pathways (*CH3OH and *CH3O) to produce CH3OH are high, making CH3OH generation rather difficult.

2.3. Generation of C2 products
C2 products from the CO2RR include C2H4, C2H5OH, C2H6, CH3COOH, C2H6O, etc. Several protonation and electron transfer steps engage in the formation of C2 products, making the reactions very sophisticated. As many possible pathways are capable of generating the same product, this leads to controversy about the reaction mechanisms.

![Fig. 4](image-url) The possible CO2RR pathways for C1 products.
Fig. 5 shows the possible CO$_2$RR pathways for C$_2$ products. In the first route, CH$_2$CHO* acts as an important intermediate to produce C$_2$H$_4$ and CH$_2$CH$_2$OH, which can branch into two pathways. One transforms to *C$_2$H$_2$O$_2$ which dissociates and releases C$_2$H$_4$. The other forms CH$_3$CHO* which is further reduced to generate CH$_3$CH$_2$OH. It is noteworthy that the calculated energy barrier for CH$_2$CHO* → CH$_3$CH$_2$OH is 0.2 eV, which is higher than that for CH$_2$CHO* → *O + C$_2$H$_4$, explaining the higher selectivity for C$_2$H$_4$ than for C$_2$H$_2$OH among different C$_2$ products. In the second route, starting from *CO, CH$_2$OHCH$_2$OH can be formed through CO insertion into *CHO coupled with several protonation and electron transfer steps. *CHO can also undergo another pathway to produce CH$_4$. The pathway towards CH$_4$ production has a lower energy barrier than that towards CH$_2$OHCH$_2$OH production, disclosing that very little CH$_2$OHCH$_2$OH can be detected. In the third route, *CH$_3$, originating from *CO, serves as an important intermediate to produce CH$_3$COOH and C$_2$H$_4$. As discussed above, the C$_2$ pathways involve two close active sites to adsorb intermediates, which are severely limited in SACs. Consequently, very few groups have reported the generation of C$_2$ products on SACs via the CO$_2$RR.

3. SACs for the CO$_2$RR

3.1. Advantages of SACs

Compared with traditional catalysts, the metal single atom sites in SACs locate at the catalyst’s surface. Such an attribute makes SACs possess maximum atom utilization efficiency and thus exhibit excellent catalytic performance. Furthermore, the metal centers in SACs can be influenced by the near-range coordination environment and long-range interactions. Therefore, the electronic structure of SACs is tunable, which helps to improve the selectivity of the CO$_2$RR. Also, SACs are ideal models for exploring the structure-activity relationship because of their homogeneous atomically-dispersed metal active centers.

3.2. CO$_2$ to CO

Various strategies have been developed to promote the catalytic performance of SACs for the CO$_2$RR to CO, including regulation of the center metal atom and manipulation of the coordination environment of the center metal atom. Recently, great achievements have been made in the production of CO from CO$_2$ on SACs. But, for commercial applications, further improvements in intrinsic catalytic activity and stability are needed. In this section, the developed strategies to promote the production of CO on SACs via the CO$_2$RR are summarized.

3.2.1. Modulation of the metal atomic center for boosting CO$_2$ reduction to CO. SACs with different metal centers possess different d-band centers, which determine their catalytic performance in the CO$_2$RR. Typically, the higher the d-band center is, the stronger the SAC binds with the intermediates. Jiang et al. synthesized various SACs implanted in N-doped carbon (M$_1$-N-C; M = Fe, Co, Ni, and Cu) by calcining metal–organic frameworks (MOF). Aberration-corrected high-angle annular dark field scanning transmission electron microscopy (HAADF-STEM) images showed sparsely distributed bright dots, and Fourier transformed extended X-ray absorption fine structure (FT-EXAFS) spectra confirmed the absence of M–M bonds in all SACs, indicating that the metal atoms were atomically dispersed. In the N K-edge near-edge X-ray absorption fine structure (NEXAFS) spectra, a peak was found broadened and split into a doublet (a1 and a2), revealing that the metal atoms were stabilized by pyridinic N. EXAFS fitting results further showed that the metal centers in all SACs were coordinated with four pyridinic N atoms. Besides, all SACs possessed a similar N content and metal loading amount (about 4.94 at% and 1.75 wt%, respectively). Electrochemical results exhibited that Ni$_1$-N-C had the best activity and selectivity towards CO production, followed by Fe$_1$-N-C, Co$_1$-N-C, and Cu$_1$-N-C. Specifically, the TOF and CO partial current density of Ni$_1$-N-C reached 11 315 h$^{-1}$ and 27 mA cm$^{-2}$, respectively, at −0.8 V.
vs. RHE. Ni$_1$-N-C displayed a much smaller Tafel slope (98 mV per decade) than the other SACs (104 mV per decade for Fe$_1$-N-C, 142 mV per decade for Co$_1$-N-C, and 118 mV per decade for Cu$_1$-N-C). Additionally, Ni$_1$-N-C also showed long-term durability at −0.8 V vs. RHE for 10 h without obvious attenuation in terms of current density and FE CO. Density functional theory (DFT) calculations were performed to explain the differences among these SACs. As stated above, all SACs have similar structural parameters except for the metal centers, and offer an ideal model to study the role of metal atomic centers in CO$_2$RR performance. The calculated free energy diagram revealed that the formation of *COOH was the rate-determining step (RDS) for all SACs. Ni$_1$-N-C and Fe$_1$-N-C had a similar energy barrier for *COOH formation, lower than that of Co$_1$-N-C and Cu$_1$-N-C. Besides, the energy barrier for CO desorption on Ni$_1$-N-C was lower than that on Fe$_1$-N-C, suggesting favorable CO release from Ni$_1$-N-C (Fig. 6a). The $U_l$(CO$_2$) − $U_l$(H$_2$) values for Ni$_1$-N-C, Fe$_1$-N-C, Co$_1$-N-C and Cu$_1$-N-C are −1.19 eV, −1.55 eV, −1.98 eV, and −2.33 eV, respectively. The most positive value of $U_l$(CO$_2$) − $U_l$(H$_2$) for Ni$_1$-N-C supported the conclusion that Ni$_1$-N-C had the highest selectivity towards CO production (Fig. 6b). Peter et al. also prepared a series of transition metal SACs (Fe-N-C, Co-N-C, Ni-N-C, Cu-N-C, and Mn-N-C) and studied their CO$_2$RR performance. The results demonstrated that Fe-N-C produced the most CO at low overpotentials, while Ni-N-C produced the most CO at high overpotentials (Fig. 6c). Fe-N-C, Mn-N-C, and Co-N-C all bind to CO* very strongly such that desorption of CO becomes the RDS for these SACs. Ni-N-C and Cu-N-C display a weak binding to *COOH and thus they require higher overpotentials to initiate the CO$_2$RR. Interestingly, a small amount of CH$_4$ was detected in the CO$_2$RR catalyzed on Fe-N-C and Mn-N-C due to their strong adsorption towards CO*, indicating their potential for producing CH$_4$ (Fig. 6d). Other studies also attained a similar consensus that the Ni SAC possessed the highest activity and selectivity for the CO$_2$RR to CO among different SACs.\(^\text{69-73}\)
3.2.2. Effect of coordination number on CO2 reduction to CO. Typically, in SACs, the metal atomic center is coordinated with four non-metal atoms. However, this structure does not always give the best CO2RR activity. Regulating the coordination number in SACs offers an effective strategy to tune the adsorption energy of reaction intermediates and thus their catalytic performance. Generally, the lower the coordination number, the stronger the adsorption of intermediates on SACs. Li et al. prepared Co-N2, Co-N3, and Co-N4 by calcining Co/Zn zeolite imidazolate frameworks (ZIFs) at different temperatures. Since N species become volatile at high temperature, Co-N2, Co-N3, and Co-N4 could be obtained at 1000 °C, 900 °C, and 800 °C. The atomically dispersed Co atoms could be directly observed by HAADF-STEM. EXAFS confirmed the existence of Co-N bonds (at around 1.4 Å) and the absence of Co-Co bonds. The intensity of the Co-N peak for Co-N2 was found much lower than that for Co-N3 and Co-N4, indicating lower coordination around the Co center in Co-N2. EXAFS fitting gave the Co-N coordination number in these Co-SACs of 2.2, 3.1, and 4.1, respectively. Electrochemical measurements showed that Co-N2 had the highest activity to reduce CO2 to CO (Fig. 6e). Co-N3, Co-N-N3, and Co-N4 have similar structural parameters except the Co-N coordination number, and provide an ideal platform to elucidate the influence of coordination number on CO2RR performance. DFT calculations disclosed that the endergonic CO2−* formation was the RDS for these Co-SACs. Owing to the higher d-band center of Co-N3 (−0.81 eV) than that of Co-N2 (−1.06 eV), Co-N2 had a lower energy barrier than Co-N3 to form COO−*+. The enhanced CO2RR activity on Co-N2 (Fig. 6f). Additionally, the authors further measured the OH− adsorption strength to simulate the binding affinity of COO−* as COO−* was unstable in the electrolyte. Co-N2 showed a more negative OH− adsorption peak, verifying its stronger adsorption to COO−*. Considering the higher catalytic activity of Co-N4 towards the HER, the enhanced CO2RR performance of Co-N2 could also be related to the increase in U1(CO2)−U1(H2). This work indicated that lower coordination number in SACs would enhance the adsorption of CO2RR intermediates. Li et al. performed DFT calculations to study Ni SACs with different coordination numbers (NiN4: x = 1–4) toward catalyzing the CO2RR. The results show that the RDS for all studied NiN SACs is the formation of COOH* as an endergonic step. NiN has the lowest coordination number and thus possesses the smallest energy barrier to generate the COOH* intermediate, justifying its highest CO2RR activity (Fig. 6g). Zhang et al. synthesized Mn-N3 and Mn-N4 catalysts and measured their CO2RR performance. The Mn-N3 catalyst delivered a 98.8% CO FE with a CO partial current density of 14 mA cm−2 at an overpotential of 0.44 V. In situ X-ray absorption spectroscopy showed that Mn-N3 facilitated the formation of COOH*, which is the RDS. DFT calculation gave an energy barrier of 0.24 eV for Mn-N3 and 0.91 eV for Mn-N4 (Fig. 6i). Local density of states (LDOS) revealed that the d-band centers of Mn-N3 and Mn-N4 were located at −2.50 eV and −4.93 eV, respectively (Fig. 6h). Other researchers also reached a similar conclusion that the lower coordination number in SACs indeed strengthened the adsorption of CO2RR intermediates.

3.2.3. Effect of the coordinated nitrogen type on CO2 reduction to CO. Four types of nitrogen atoms exist in SACs, namely pyridinic, pyrrolic, graphitic and oxidized N. The metal centers in SACs could be bonded with pyridinic N or pyrrolic N. The d-band center for pyridinic-N coordinated metal sites is lower than that for pyridinic-N coordinated metal sites and thus pyridinic-N coordinated metal sites bind to the CO2RR intermediates more weakly. Hu et al. prepared Fe-N-C coordinated with pyridinic N and Fe2+-N-C coordinated with pyridinic N using different pyrolysis precursors. Fe2+-N-C could reduce CO2 to CO with a CO partial current density of 94 mA cm−2 at an overpotential of 340 mV. No catalytic performance decay was observed in 12 hours of continuous reaction. Operando X-ray absorption spectroscopy verified the true active sites of Fe3+-ions coordinated with pyridinic N atoms and the +3 oxidation state of Fe was maintained during the reaction (Fig. 7a). Furthermore, electrochemical measurements indicated that the faster CO2 activation and weaker CO adsorption were responsible for the superior catalytic activity of Fe3+-N-C. Other research groups also regarded M-pyrrolic N as the active center for the CO2RR. Wang et al. constructed Co(n)CPY (Co atoms coordinated with four pyridinic N atoms) and Co-porphine (Co atoms coordinated with four pyrrolic N atoms) and found that Co(n)CPY showed better CO2RR activity than Co-porphine. DFT calculations suggested that the formation of COOH* was the RDS, in which Co(n)CPY had a lower energy barrier (Fig. 7b). Bader charge analysis showed that the Co atoms in Co(n)CPY could get more electrons from the ligand compared with the case in Co-porphine (Fig. 7c). Projected density of states (PDOS) demonstrated that the dxy orbital of Co(n)CPY was closer to the Fermi level before the reaction and had a larger overlap with the 2p orbital of COOH after the reaction, substantiating the enhancement of COOH* adsorption in Co(n)CPY. Other research studies also reached the same conclusion that M-pyridinic N species served as the reaction sites in catalyzing the CO2RR. Since the controversy about which type of M–N species is the active site(s) in the CO2RR still remains, more attention has to be paid on this research hotspot.

3.2.4. Effect of heteroatoms on CO2 reduction to CO. Heteroatom doping could induce electron transfer between the metal atomic center and the surrounding non-metal atoms, leading to the distinct electronic structure and hence the electrocatalytic performance. Liu et al. synthesized a S doped Ni-SAC (Ni–N2S) and Ni–N4 and studied their CO2RR mechanisms. The CO2RR onset potential of Ni–N2S was 100 mV lower than that of Ni–N4. Operando XAS showed that the valence state of Ni atoms in Ni SACs was +1, serving as the true active sites. Moreover, the Ni2+ sites were identified as having strong interactions with CO2, where electrons were transferred from Ni2+ to the C 2p orbital in CO2 to generate CO3−, facilitating the CO2 activation and further reduction (Fig. 7d). Consequently, the catalyst achieved a specific current of 350 A gcatalyst−1 and a TOF of 14 800 h−1 at an overpotential of 0.61 V with 97% FEco. The authors also proposed the activation process of CO2 on the Ni(i) active center and its structural evolution during the CO2RR (Fig. 7d). Cl doping in a Mn-SAC was reported by Zhang et al. to improve the CO2RR activity. Mn-SACs usually displayed poor selectivity towards CO production because of their too strong adsorption for CO*, making CO release rather difficult. After
Fig. 7  (a) The first derivative of the XANES spectra for Fe$^{3+}$-N-C and Fe$^{2+}$-N-C as dry powder (black) and on a glassy carbon electrode at the open circuit potential (OCP) (blue), −0.1 V (light blue), −0.2 V (green), −0.3 V (dark green), −0.4 V (dark blue), −0.5 V (red), and −0.6 V (pink) versus RHE, with Fe$_2$O$_3$ (blue dashed), Fe$^{3+}$TPPCl (green dashed), FeO (pink dashed), and Fe foil (orange dashed) references. Reproduced with permission from ref. 84. Copyright (2019) the American Association for the Advancement of Science. (b) Free energy profiles of Co(ii)CPY/graphene and Co-porphine/graphene. (c) Bader charge of Co and N atoms. Reproduced with permission from ref. 87. Copyright (2020) Wiley-VCH. (d) Structural evolution of the active sites in electrochemical CO$_2$ reduction. Reproduced with permission from ref. 92. Copyright (2018) Springer Nature. (e) Calculated free energy of the CO$_2$RR. (f) Calculated free energy of hydrogen adsorption. Reproduced with permission from ref. 93. Copyright (2019) Springer Nature.
introducing Cl into the Mn-SAC ((Cl, N)-Mn/G), the selectivity towards CO was significantly increased from 17% to 97% with the partial current density for CO production exhibiting an 11-fold increase. PDOS revealed that the d-band center of (Cl, N)-Mn/G was lower than that of MnN4, weakening the CO* adsorption and thus improving the CO selectivity. The free energy diagram further supported this conclusion. Specifically, the energy barrier of the RDS (desorption of CO*) decreased from 1.64 eV for MnN4 to 0.65 eV for (Cl, N)-Mn/G (Fig. 7e). Moreover, the energy barrier for H2 generation increased from 0.11 eV for MnN4 to 0.92 eV for (Cl, N)-Mn/G, implying that the HER was largely suppressed (Fig. 7f).93

3.2.5. Effect of dual metal atoms on CO2 reduction to CO.
Although much progress has been made in the CO2RR to produce CO using SACs, their performance could be further improved through constructing dual metal atomic sites. Gong et al. demonstrated an example of neighboring Zn and Co monomers (ZnCoNC) for enhancing CO production in the CO2RR.94 ZnCoNC displayed a CO FE of 93.2% at −0.5 V vs. RHE in 30 h. XANES confirmed the interaction between Zn and Co. According to the free energy diagram, after introducing Co into the Zn-SAC, the formation of COOH* (the RDS for the Zn-SAC) changed from endergonic to exergonic (Fig. 8a), which enhanced the adsorption of COOH* and thus promoted CO production. Zhao et al. synthesized a Ni–Fe dual-metal-atom catalyst (NiFe-N-C).95 Electrochemical study disclosed that NiFe-N-C possessed higher activity and selectivity than Ni-N-C and Fe-N-C in the CO2RR (Fig. 8b and c).
energy diagram showed that the energy barrier for COOH* formation (RDS) was much lower in NiFe-N-C than in Ni-N-C. Therefore, Fe doping could strengthen the binding affinity of Ni atoms for COOH*. It is worth mentioning that two mechanisms are possible for enhancing the CO2RR performance in dual metal atom catalysts. One is that only one metal site acts as the active center, and the introduction of the second metal atom regulates the electronic structure of the first metal site. The other is that both metal sites serve as the active centers for adsorbing reaction intermediates and engage in the reaction. To date, the reported examples belong to the former mechanism. If the reaction could follow the latter mechanism on dual metal atom catalysts, the scaling relationship might be broken, which provides another possibility to tune the CO2RR performance.

3.2.6. Effect of surrounding functional groups on CO2 reduction to CO. The charge state of the metal atomic center determines its intrinsic catalytic activity. Therefore, introducing functional groups (electron-withdrawing or electron-donating) into SACs offers an effective strategy to manipulate their CO2RR performance. Huang et al. prepared CoPc/G, amino functionalized CoPc/G (amino-CoPc/G), and nitro functionalized CoPc/G (nitro-CoPc/G) and studied the effect of electron-withdrawing/electron-donating groups in SACs on the CO2RR activity (Fig. 8e).96 Electrochemical measurements showed that nitro-CoPc/G possessed the highest activity and selectivity for generating CO. DFT calculations revealed that formation of *CO2 was the RDS, where nitro-CoPc/G had the lowest energy barrier. After the introduction of the electron-withdrawing nitro group, the electron density around the Co site decreased. Also, the d_z^2 orbital was upshifted and became less affected by other lower energy level orbitals, like d_xy. Another important descriptor was also found, that is, the larger the energy difference between the d_z^2 and d_xy orbital, the smaller the energy.
barrier to form *CO2− (Fig. 8f). Wang et al. introduced an electron-withdrawing cyano group into CoPc/CNT (CoPc-CN/ CNT) and found that both activity and CO selectivity increased obviously (Fig. 8d). The electron-withdrawing cyano group could prompt the generation of Co(i), which was regarded as the active site for the CO2RR. The enhanced Co(II)/Co(I) redox transition at more positive potentials in CoPc-CN/CNT supported this proposal. Moreover, the cyano group also reduced the affinity of the Co site for CO*, facilitating the release of CO.

In addition to the nitro group and cyano group, a trimethyl ammonium group (CoPc2) was also introduced into CoPc1 (Fig. 8g). After such a modification, the CoPc2 showed high selectivity towards CO production, while the CO partial current density increased substantially.

3.3. HCOOH

It is reported that SACs with a p-block metal (Sn, Sb) center are able to catalyze the CO2RR to produce formic acid or formate. Xie et al. synthesized SnN4C2 and found that it could reduce CO2 to formate at a very low onset overpotential of 60 mV and with a high TOF of 11 930 h−1 at −1.14 V vs. RHE. Moreover, its activity did not decay during 200 h of continuous reaction. DFT calculations revealed that electrons were transferred from Sn atoms to graphene, making Sn atoms positively charged. Fourier transformed infrared spectroscopy (FTIR) spectra and Gibbs free energy calculations confirmed that Sn5+ could facilitate CO2 activation and protonation through stabilizing CO2−* and HCOO−* (Fig. 9a). Wei et al. constructed a NiSn atomic pair (NiSn-APC) and also achieved a good performance in the CO2RR to formate. NiSn-APC produced HCOOH with a high TOF of 4752 h−1 and formate productivity of 36.7 mol h−1 gSn−1 at −1.02 V vs. RHE. In situ attenuated total reflection-infrared (ATR-IR) spectra and theoretical calculations confirmed the electron redistribution on Sn, which is induced by the adjacent Ni atoms. Moreover, ΔG (HCOOH) (−0.05 eV) was much smaller than ΔG (COOH−) (1.36 eV), explaining its high selectivity towards formate production. Sb-N4 (Sb@dv-Gr) reported by Li’s group also displayed a good CO2RR performance. Sb@dv-Gr produced formate with a FE of 94% at −0.8 V vs. RHE. In situ XAFS and DFT calculations confirmed that the positively charged Sb5−N4 was the origin of the high catalytic activity. Sb@dv-Gr possessed a ΔG (HCOOH) (0.21 eV) smaller than ΔG (COOH−) (1.00 eV) and ΔG (H+) (0.81 eV), implying that formate production was more favorable than CO and H2 (Fig. 9b). Xie et al. reported that Mo atoms supported on N doped graphene (Mo@NG) could also efficiently reduce CO2 to produce HCOOH. Mo@NG produced HCOOH with a high FE, twice as that of NiG, and achieved a formate yield of 747 mmol gcat−1 h−1 (Fig. 9c).

3.4. CH3OH

CH3OH is a high value-added product in the CO2RR. However, as discussed above, both CO2RR pathways to generate CH3OH (*CH3OH and *CH3O) possess very high energy barriers and thus its production remains a big challenge. Wang et al. immobilized cobalt phthalocyanine (CoPc) onto carbon nanotubes (CNTs), denoted as CoPc/CNT. CoPc/CNT was found to be able to reduce CO2 to CH3OH with a FE of 44% and a partial current density greater than 10 mA cm−2 at −0.94 V vs. RHE. But the catalytic activity of CoPc/CNT quickly decayed after 1 h of electrochemical reaction. To enhance the stability, an amino functional group was introduced into CoPc/CNT to form CoPc-NH2/CNT, whose stability was greatly improved. In addition to experiments, theoretical studies have also been conducted to prompt the discovery of potential catalysts to reduce CO2 to CH3OH. Cai et al. anchored Co, Rh, and Ir atoms onto porphyrin-like graphene. First, the structural stability of the SACs was confirmed from the strong hybridization between metal d-orbitals and N 2p-orbitals. Then, the energy barriers for the CO2RR to CH3OH were calculated. CoN4/graphene was found most promising among the three studied catalysts for CH3OH generation with a RDS energy barrier of only 0.59 eV. Jung et al. conducted DFT calculations to predict a series of transition metal SACs on graphene with single and double vacancies. They figured out that Ni and Pt SACs with double vacancies (Ni@dv-Gr, Pt@dv-Gr) were promising to reduce CO2 to CH3OH. Taking Pt@dv-Gr as an example, CO* was adsorbed on one Pt atom via the top-on adsorption configuration, while bulk Pt adsorbed CO* via two Pt atoms adopting the bridge adsorption mode. As a result, bulk Pt adsorbed CO* so strongly that the transformation of CO* to *CHO – an important intermediate for CH4OH formation became rather difficult. In contrast, Pt@dv-Gr had a much smaller energy barrier for this step and held the premise for CH3OH production (Fig. 9d). He et al. developed a simple method to prepare a Cu-SAC on through-hole carbon nanofibers (Cu SAs/TCNFs). The Cu SAs/ TCNFs (Cu-N4) could generate methanol with a FE of 44%. DFT calculations found that the energy barrier for COOH* formation was much larger than that for CHOH* formation on Cu-N4, which effectively suppressed the CO production. Moreover, Cu-N4 could adsorb CO* more strongly than Ni-N4, which allowed CO* to be further reduced (Fig. 9e). Additionally, the energy barrier to form C* from COH* by an important step towards CH3OH was calculated to be 1.88 eV, which is much larger than that to form CH3OH (Fig. 9f). Therefore, CH3OH was more favorable than CH4 in the CO2RR. In summary, the mechanism of the CO2RR to form CH3OH on SACs was nearly completely based on DFT calculation. The lack of understanding of the structural characteristics poses a big challenge for designing efficient SACs for reducing CO2 to CH3OH.

3.5. CH4

CH4 is another important product in the CO2RR, which undergoes an 8e− transfer process. Strong adsorption affinity of metal sites for the CO* intermediate is required for generating CH4. Xin et al. reported Zn–N4 that could stably reduce CO2 to CH4 with a FE of 85% and a partial current density of −31.8 mA cm−2 at −1.8 V vs. the saturated calomel electrode (SCE) (Fig. 10a–c). DFT calculations showed that Zn atoms tended to bond with O atoms to form *OCHO (ΔG (OCHO) = 0.46 eV) rather than with C atoms to form COOH* (ΔG (COOH) = 1.2 eV) (Fig. 10d). Furthermore, surface-enhanced infrared
absorption spectroscopy enabled direct observation of the existence of *OCH₃ and *OCH₂. Zheng et al. deposited Cu atoms on CeO₂ nanorods (Cu-CeO₂), where Cu atoms were stabilized by three oxygen vacancies. Cu-CeO₂ could reduce CO₂ into CH₄ with a FE of 58% (Fig. 10e and f).¹⁰⁷ Theoretical calculations revealed that the synergistic effect between atomic dispersion of Cu and multiple surrounding oxygen vacancies as well as the contribution from the CeO₂ framework expedited CO₂ adsorption and activation.

3.6. C₂⁺

Generation of C₂⁺ products in the CO₂RR requires C–C coupling, which possesses a high energy barrier and is difficult to take place in SACs. Cu nanoparticles have been shown as an excellent catalyst to reduce CO₂ to form C₂⁺ products, while this is not the case for Cu SACs due to the lack of neighbouring active sites to allow for C–C coupling. Fontecave et al. reported that a Cu SAC (Cu₀.₅NC) could reduce CO₂ to ethanol with a FE of 43% at −1.2 V vs. RHE in 0.1 M CsHCO₃ solution.¹⁰⁸ A higher FEethanol (~66%) could be achieved using CO as the feed gas, suggesting that CO²⁺ might be the important intermediate to form ethanol. Operando XAS analysis showed that the initial isolated Cu atoms would aggregate and form Cu NPs during the CO₂RR, acting as the true active sites. Interestingly, Cu atoms could be recovered after the reaction, indicating that such a transition was reversible. Xu et al. also observed a similar phenomenon where Cu atoms transformed into Cu n clusters (n = 3 and 4) during the electrochemical reaction and then returned back to their initial state after the reaction.¹⁰⁹ Chen

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**Fig. 10** (a) Polarization curves for MNC, Zn powder, and SA-Zn/MNC. (b) FEs for the electrochemical CO₂RR to CH₄ at different applied potentials. (c) CO₂RR pathway for single Zn atoms to produce CH₄. (d) The most stable structure. The red and pink balls represent O and H atoms, respectively. Reproduced with permission from ref. 106. Copyright (2020) American Chemical Society. (e) Faradaic efficiencies (bars, left y-axis) and the deep reduction product current density (jdrp, red curve, right y-axis) of Cu–CeO₂-4%. The red column represents CH₄. (f) Effect of oxygen vacancies on the CO₂RR. Reproduced with permission from ref. 107. Copyright (2018) American Chemical Society.
et al. designed a Cu SAC loaded on N-doped porous carbon (Cu-SA/NPC) to reduce CO₂ into C₂ products. Cu-SA/NPC produced acetone with a FE of 36.7% and a yield of 336.1 μg h⁻¹ at −0.36 V vs. RHE. Theoretical calculations pointed out that Cu coordinated with four pyrrolic N atoms was the true active center, which decreased the energy barrier of CO₂ activation and C–C coupling. Also, the most possible pathway to form acetone was proposed: CO₂ → COOH* → CO* → COCO* → COCOH* → COC* → COCH* → COCH₂* → COCH₃* → COOCCH₃* → COOCHCOCH₃* → CCOCH₃* → CH₃COCH₃ → CH₂COCH₂ → CH₂COCH₃ (Fig. 11a). Zheng et al. regulated the population of Cu–N₂ sites on NC (Cu-N-C) by controlling the pyrolysis temperature [800 °C and 900 °C], where Cu-N-C-800 contained 4.9 mol% metal atoms and Cu-N-C-900 had 2.4 mol% metal atoms. Adjacent Cu–N₂ sites existed among the densely distributed Cu-N₄ in Cu-N-C-800, enabling C–C coupling for C₂H₄ formation with a FE of 24.8% at −1.4 V vs. RHE (Fig. 11b). DFT calculations disclosed that Cu–N₂ bound with CO* more strongly (−1.17 eV) than Cu–N₄ (−0.19 eV), which was favorable for CO* to participate in the further reaction. Moreover, the adjacent Cu–N₂ sites possessed a much lower energy barrier for C–C coupling (0.14 eV) than the isolated Cu–N₂ (1.38 eV). Cu-N-C-900 with fewer neighboring Cu–N₂ sites generated much less C₂H₄, substantiating the important role of the adjacent Cu–N₂ sites in C–C coupling. Qiao et al. came up with a novel dual active center mechanism to produce C₂ products in the CO₂RR, where Cu atoms bound with reaction intermediates having carbon as the anchoring atom (*COOH, *CO, and *CHO) and C atoms on C₃N₄ bound with reaction intermediates having oxygen as the anchoring atom (*OCH₃, *OCH₂, *O, and *OH) (Fig. 11c). The detection of various C₂ products validated the reaction mechanism, though the selectivity of C₂ products was low (Fig. 11d).

Tandem catalysis provides another efficient strategy to produce C₂ products via the CO₂RR, in which plenty of CO* is first generated on one type of active site and it diffuses to the other type of active site, and then gets further reduced to produce C₂ products. Grätzel et al. fabricated a Cu₂O–Ag tandem catalyst. CO* was first produced on the Ag sites and then underwent C–C coupling on the Cu sites to generate C₂H₄. Operando Raman spectroscopy allowed direct observation of the enhanced coverage of CH-containing intermediates (Fig. 12a). Consequently, the partial current density of C₂H₄ reached −18.1 mA cm⁻² at −1.05 V vs. RHE on the CuAg catalyst, while it was −5.8 mA cm⁻² on the Cu catalyst. A similar tandem catalyst was demonstrated using Ni SAC as the CO generator. By optimizing the loading amount of Ni-N-C, the Cu/Ni-N-C tandem electrode could reduce CO₂ into C₂.
products at a high production efficiency (80% FE) and rate (over 500 mA cm\(^{-2}\)) (Fig. 13a–c). Therefore, the tandem catalysis strategy not only efficiently promoted the C\(_2\) product faradaic efficiency, but also substantially enhanced the reaction rate. Wang et al. reported that CoPc@Zn-N-C was able to reduce CO\(_2\) to CH\(_4\) via a two-step tandem reaction. CO was first generated on CoPc, and then it was further reduced to CH\(_4\) on the Zn-N\(_4\) site. DFT calculations disclosed that CoPc not only engaged in the first step to produce CO but also took part in the next step, where it increased the availability of H\(^+\) over nearby N sites in Zn-N\(_4\) and thus benefited CH\(_4\) formation (Fig. 12b). The above studies highlighted that multiple sites are essential for multi-electron product formation in the CO\(_2\)RR, in which the multiple sites can be adjacent single atom sites, or metal atoms and coordination atoms.

The mechanism of the CO\(_2\)RR to C\(_2\) products on Cu-based catalysts is still controversial due to the multiple electron transfer and dynamic structural transformation in the reaction. The above-mentioned challenges are also present for Cu-N-C SACs. A few studies reported that C\(_2\) could be produced by Cu-N-C SACs due to the strong adsorption of CO\(_2\) reduction intermediates on Cu atoms, which is favorable for the C-C coupling. For example, some groups showed that C\(_2\) formation was catalyzed by small Cu nanoparticles or clusters in Cu-N-C SACs, which came from aggregation of Cu single atoms under negative bias. But others reported that Cu single atoms were stable in the CO\(_2\)RR, and the formation of the C\(_2\) products was on the dual active sites (Cu and N in Cu-N-C SACs). Based on the reported results, the stability of Cu-N-C SACs in the CO\(_2\)RR seems to be related to the synthesis method and electrochemical reaction environment, which is directly correlated to the binding strength of Cu single atoms with the substrate. Therefore, it is crucial to develop novel strategies to enhance the binding strength between the central metal atom and the substrate for further studying the reaction mechanism of the CO\(_2\)RR to C\(_2\) products on SACs. Right now, besides the Cu-N-C SAC, there are no other reported SACs capable of reducing CO\(_2\) to form C\(_2\) products. As Zn and Co could strongly adsorb CO\(_2\)RR intermediates, combining Zn and Co together to develop a Zn and Co diatomic catalyst might facilitate the reduction of CO\(_2\) to form C\(_2\) products.

SACs supported on metals belong to single-atom alloys and some reviews have already summarized their progress. Here, we focus on SACs supported on carbon-based substrates. Besides carbon, other substrates have also been used to support metal single atoms. For example, Li et al. deposited Ag single atoms on MnO\(_2\) and found that Ag single atoms in Ag\(_{1}\)/MnO\(_2\) had a higher electronic density close to the Fermi level than Ag.
nanoparticles, which enabled them to reduce CO₂ to CO with a FE of 95.7% at −0.85 V vs. RHE. Sun et al. reported that Sn single atoms supported on oxygen-deficient CuO could reduce CO₂ to ethylene with a FE of 48.5%, resulting from the lowered CO dimerization energy due to Sn doping. The CO₂RR is limited by the scaling relationship. Hybridizing d-orbitals of transition metals with p-orbitals of main group elements or metal carbides or nitrides offers a promising strategy to break the scaling relationship. Jung et al. inserted a series of single metal atoms into the surface defect sites of TiC, denoted as M@d-TiC, and Ir@d-TiC was found to display a very low overpotential of only −0.09 V to reduce CO₂ to produce CH₄. pDOS revealed that the lack of sigma-type bonding interaction between *CO and single Ir atoms in Ir@d-TiC resulted in an appreciable decrease in the limiting potential. Inspired by these studies, substrates beyond carbon deserve more attention to be studied.

4. Summary and outlook
To sum up, in this review, we introduced the theoretical considerations to guide the design of CO₂RR catalysts in terms of HER suppression, generation of C₁ products and formation of C₂+ products, which were later supported by experiments (Table 1 summarizes the products beyond CO using SACs in the CO₂RR). Although much progress has been made in this field,
many challenges still remain. In the following we list the main issues and offer our solutions to address these obstacles.

(1) Most of the SACs are prepared at high temperatures (>800 °C), which makes the synthesis uncontrollable. 121–123 As a result, the construction of SACs with a precise coordination environment is difficult to realize. Up to now, the coordination number is solely determined by EXAFS. However, EXAFS can only give the average structure124–126 of SACs instead of the local structure. The high similarity of the M–C, M–N, and M–O bonds makes it hard to exactly figure out the coordination structure and the coordination number. Also, even if SACs possess the same coordination number, many possible models exist. For example, for the M-SAC with a coordination number of 3, the structure can be M–N3, M–N2–C, or M–N2–V. Moreover, these species can be located in plane or at the edges. The above uncertainty leads to the divergence in the electronic structure of SACs instead of the local structure. However, EXAFS can only give the average structure, which makes it difficult to figure out the true structure and coupling in situ techniques together with the rapid developing computational methods are conducive to elucidating the underlying reaction mechanisms155,156 (Fig. 14).

(4) Most of the SACs are in the form of powder, and show unsatisfactory performance in real devices. 157–163 Particularly, the solubility of CO2 is low in aqueous solution (34 mM) and the CO2 mass diffusion limitation dominates the CO2RR particularly at high current densities. Hybridizing SACs with a gas diffusion support or designing monolithic SAC electrodes has the potential to tackle this challenge. Moreover, flow cells and membrane electrode assembly cells have been developed rapidly, which assists in further improving CO2RR performance to meet the industry requirement. 162–167

**Author contributions**

J. Z., H. B. Y., and B. L. conceived the topic and structure of the article. All authors reviewed and contributed to this paper.

**Conflicts of interest**

There are no conflicts to declare.

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