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## A low-valent alkali metal doping strategy for enhanced performance of high-entropy oxide catalysts in reverse water–gas shift reactions

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The reverse water–gas shift (RWGS) reaction is a key pathway for catalytic CO<sub>2</sub> valorization. Emerging high-entropy oxide (HEO) systems exhibit great catalytic potential; however, their activity remains suboptimal. In this work, we developed a Li-doping strategy to modify the (Mg<sub>1</sub>Co<sub>1</sub>Ni<sub>1</sub>Cu<sub>1</sub>Zn<sub>1</sub>)O<sub>α</sub> (J14) high-entropy oxide (HEO) catalyst, yielding enhanced RWGS catalytic performance. The Li-doped catalyst exhibited a CO generation rate of 210 μmol<sub>CO</sub> g<sub>cat</sub><sup>-1</sup> s<sup>-1</sup> at 400 °C, 1.46 times higher than that of J14, with enhanced stability. Systematic characterization and experiments demonstrated that this approach effectively coordinates metal exsolution and dispersion while tailoring surface alkalinity, thereby enhancing both H<sub>2</sub> dissociation and CO<sub>2</sub> activation. Furthermore, a mechanistic shift from the redox pathway to the carbonate-associative pathway was observed. This low-valent alkali metal doping strategy offers a generalizable design principle for HEO catalysts.

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## Introduction

The rapid advancement of industrialization and economic growth has increased atmospheric CO<sub>2</sub> to unprecedented levels, causing significant environmental challenges.<sup>1,2</sup> Among potential solutions, catalytic conversion of CO<sub>2</sub> emerges as a particularly promising solution, offering the dual benefit of facilitating carbon cycle management while generating valuable chemical products.<sup>3–8</sup> Within this field, the reverse water–gas shift (RWGS) reaction plays a crucial role in CO<sub>2</sub> hydrogenation processes and serves as a fundamental step in Fischer–Tropsch synthesis.<sup>9–11</sup>

High-entropy oxides (HEOs), an emerging class of catalytic materials, demonstrate unique advantages including tailorably elemental configurations and lattice distortion-induced oxygen vacancy enrichment originating from their multi-component disordered structures.<sup>12,13</sup> Beyond conventional oxidation catalysis, recent advancements demonstrate the exceptional catalytic performance of HEOs in hydrogenation reactions.<sup>14–17</sup> Notably, these materials can function as self-sufficient exsolution hosts, without external metal loading, while exhibiting

excellent RWGS activity.<sup>18–20</sup> However, their catalytic efficacy still lags behind that of well-established Pt-, Cu-, and Mo-based systems, necessitating the development of targeted HEO modification protocols to unlock their full potential.<sup>21–25</sup>

A key approach for enhancing the RWGS activity of a catalyst is doping with alkali metals (e.g., Li, Na, K), which as evidenced by numerous studies can effectively boost catalyst basicity and consequently improve CO<sub>2</sub> adsorption capacity.<sup>26–28</sup> Additionally, within exsolution frameworks, the incorporation of low-valent cations was shown to facilitate the exsolution of metal sites.<sup>29,30</sup> This is attributed to the fact that low-valent cations induce lattice distortions, weakening host cation–oxygen bonds, and promote the generation of oxygen vacancies through charge compensation mechanisms, both of which enhance ion migration to drive the exsolution.<sup>30–33</sup> The resulting higher surface concentration of metal sites improves hydrogen accessibility, thereby enhancing overall hydrogenation activity, which is another key factor contributing to the catalytic RWGS reaction.<sup>34–36</sup> Therefore, a finely-controlled alkali metal doping strategy is promising for optimizing both CO<sub>2</sub> adsorption and H<sub>2</sub> activation, consequently boosting the catalytic performance.

In this work, we report enhanced RWGS performance through the strategic incorporation of low-valent alkali metals in HEO catalysts. This optimization achieved simultaneous improvement in catalytic activity and stability with limited CH<sub>4</sub> byproduct formation. Systematic characterization and structure–activity relationship studies revealed that moderate

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Li doping promoted metallic exsolution while tuning metallic composition and dispersion, thereby facilitating H<sub>2</sub> adsorption and dissociation. Concurrently, Li incorporation augmented oxygen vacancy formation, stabilized adsorbed oxygen species, and enhanced moderate-strength basic sites, which collectively promoted CO<sub>2</sub> adsorption and activation. Mechanistic investigations identify suppressed redox pathways with enhanced associative routes and rationalize the observed methane formation.

## Experimental

Experimental details can be found in the SI.

## Results

### Screening of alkali metal ions for doping

Spray pyrolysis was used to synthesize the (Mg<sub>1</sub>Co<sub>1</sub>Ni<sub>1</sub>Cu<sub>1</sub>Zn<sub>1</sub>)O<sub>α</sub> (named J14) high-entropy oxide (Fig. S1). Given the average +2 oxidation state of Mg, Co, Ni, Cu, and Zn in J14, monovalent cations (Li<sup>+</sup>, Na<sup>+</sup>, K<sup>+</sup>) were selected for low-valent substitution. During synthesis, equimolar quantities of these ions, relative to individual metals in J14, were incorporated to prepare modified samples (named J14+Li, J14+Na, J14+K). X-ray diffraction (XRD) analysis of J14 reveals distinct peaks at 37°, 42.9°, 62.1°, 74.5°, and 78.3°, corresponding to the (111), (200), (220), (311), and (222) crystal planes of a rock salt phase structure (Fig. S2). With the introduction of Li<sup>+</sup>, the diffraction peaks of the rock salt phase shifted to higher angles, and prominent impurity peaks at 31.8°, 34.4°, and 36.3° were assigned to the (100), (002), and (101) planes of wurtzite-type ZnO (Fig. S2). This indicates successful incorporation of Li<sup>+</sup> ions into the lattice, which induced segregation of Zn species from the J14 matrix. Therefore, we infer that the partial replacement of the Zn component by Li is promising for synthesizing samples with pure rock salt phases. In contrast, XRD patterns of J14+Na and J14+K revealed no discernible peak shifts compared to the parent structure, with weak ZnO impurity peaks (Fig. S2). Instead, distinct diffraction peaks corresponding to NaNO<sub>3</sub> and KNO<sub>3</sub> were observed, suggesting limited lattice incorporation of Na<sup>+</sup>/K<sup>+</sup> ions into J14 and incomplete thermal decomposition during synthesis. To elucidate the origins of this differentiation, a systematic analysis of constituent elements' ionic radii and crystal radii in the rock salt phase structure (hexacoordination) was conducted, and the comparative data are shown in Fig. S3. It reveals that the ionic and crystal radii of Li<sup>+</sup> (76 pm and 90 pm, respectively) approximate those of the J14 component ions (69–94.5 pm and 83–88.5 pm, respectively), whereas the radii of Na<sup>+</sup> and K<sup>+</sup> (102/116 pm and 138/152 pm) exceed feasible matching thresholds.

### Structural characterization of Li-doped J14 samples

Building on the alkali metal ion screening, we selected Li to incrementally replace Zn to synthesize a series of Li-doped J14

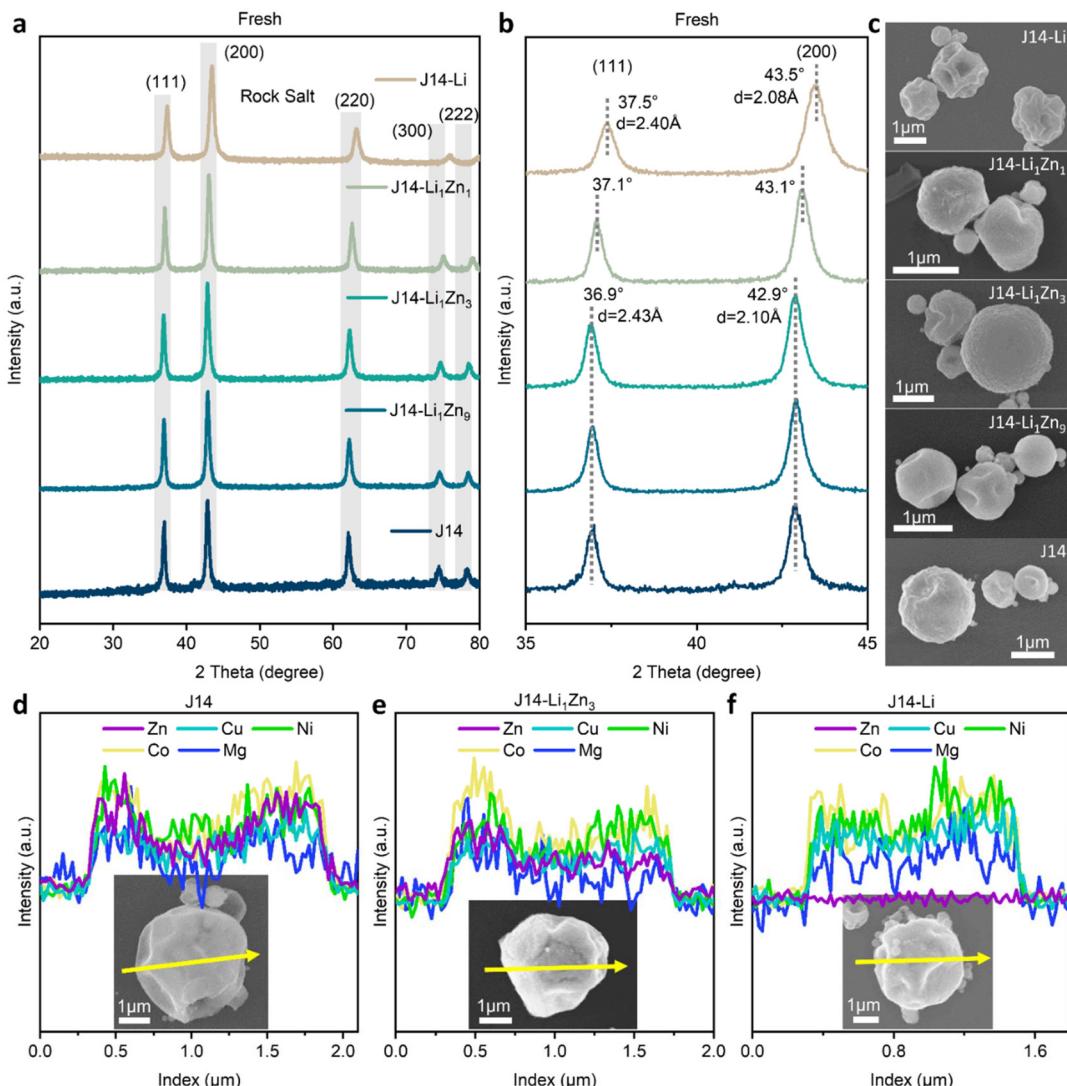
samples (denoted as J14-Li<sub>x</sub>Zn<sub>y</sub>, where x:y represents the feed ratio of Li to Zn atoms), and the accuracy of the synthesis was verified through inductively coupled plasma (ICP) analysis (Table S1). As shown in Fig. 1a, the XRD patterns exclusively exhibit the diffraction peaks of the pure rock-salt phase across all Li-doped samples, indicating that the partial substitution of Zn by Li did not disrupt the rock-salt structure. We magnified the 35°–45° region of the XRD patterns for clear resolution, covering the diffraction peaks of the (111) and (200) crystal planes of the rock salt structure located at 36.9° and 42.9°, as displayed in Fig. 1b. Compared to J14, the diffraction peaks in low-Li-doped samples (J14-Li<sub>1</sub>Zn<sub>9</sub> and J14-Li<sub>1</sub>Zn<sub>3</sub>) exhibited minimal shift. As the Li content increased, the peaks shifted to higher angles (37.1° and 43.1° in J14-Li<sub>1</sub>Zn<sub>1</sub>, 37.5° and 43.5° in J14-Li), corresponding to a decrease in interplanar spacing, indicating that Li doping induces lattice contraction.<sup>37</sup> This phenomenon could be attributed to the formation of anion vacancies caused by charge compensation mechanisms.<sup>38</sup>

The morphology of the samples was characterized by scanning electron microscopy (SEM, Fig. 1c and S4). All samples displayed irregularly shaped particles with varying sizes, but their particle size distributions did not significantly differ. This is because the particle size is predominantly determined by the droplet diameter and solution concentration, which were both rigorously maintained constant across all sample preparations. Furthermore, energy-dispersive X-ray spectroscopy (EDX) line scanning experiments were conducted on 2–3 μm diameter particles from each sample to investigate the distribution of Mg, Co, Ni, Cu, and Zn elements (Li's X-ray energy is so low that it can hardly be detected by the EDX detector). As shown in Fig. 1d, all elemental line-scanning intensity profiles in J14 exhibited consistent trends, confirming homogeneous elemental distribution. As Li replaced Zn, Zn's signal intensity progressively decreased while the other elements remained uniformly distributed (Fig. 1e, f, and S5, 6). Although Li can hardly be experimentally detected, the homogeneous distribution of Mg, Co, Ni, Cu, and Zn, coupled with the single-phase structure, strongly suggests the uniform distribution of Li. These results demonstrate the high entropy structure of the Li-doped samples.<sup>39</sup> In addition, Li doping was found to contribute to a higher specific surface area *via* the Brunauer–Emmett–Teller (BET) method (Fig. S7 and Table S2).

### The RWGS performance of the catalysts

The RWGS activity was evaluated in a fixed-bed reactor under the following conditions: reaction temperature ranging from 200 to 400 °C, weight hourly space velocity (WHSV) of 300 000 mL g<sub>cat</sub><sup>-1</sup> h<sup>-1</sup>, and pressure of 0.1 MPa. Li doping enhances CO<sub>2</sub> conversion compared to that for pristine J14 (Fig. 2a), although with a concomitant decrease in CO selectivity as Li content increased (Fig. 2b). At 400 °C, J14-Li demonstrated the highest CO<sub>2</sub> conversion (37.7%) but suffered from significantly compromised CO selectivity (<50%). In contrast, the J14-Li<sub>1</sub>Zn<sub>3</sub> sample maintained both a relatively high CO<sub>2</sub>





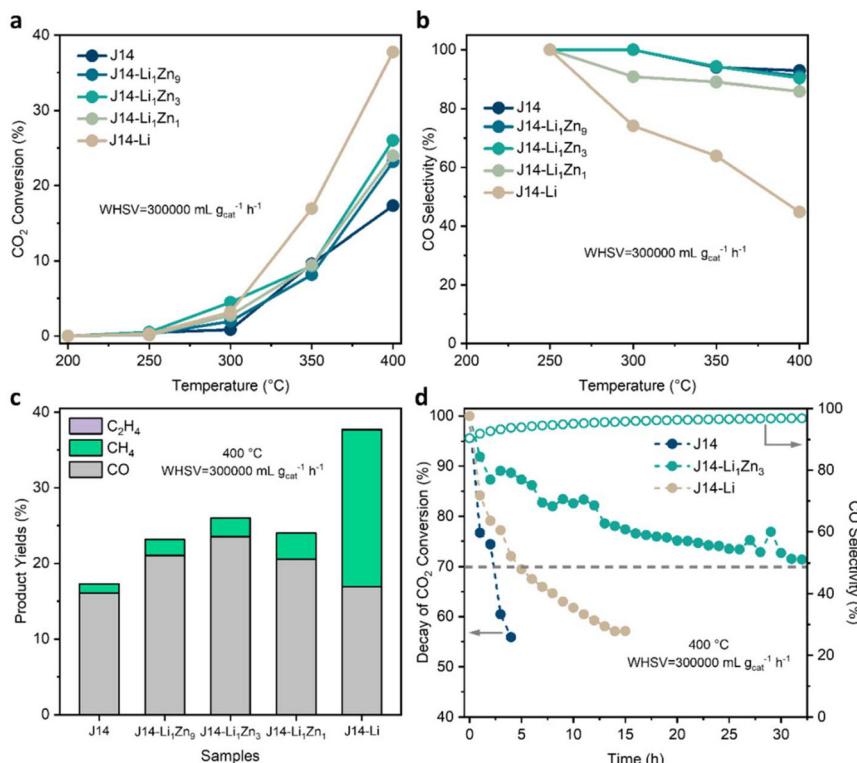
**Fig. 1** Characterization of fresh samples. (a) Overall and (b) 35°–45° magnified XRD patterns, and (c) SEM images of J14-Li, J14-Li<sub>1</sub>Zn<sub>1</sub>, J14-Li<sub>1</sub>Zn<sub>3</sub>, J14-Li<sub>1</sub>Zn<sub>9</sub>, and J14. SEM and EDX line scanning images of J14 (d), J14-Li<sub>1</sub>Zn<sub>3</sub> (e), and J14-Li (f).

conversion (26%) and excellent CO selectivity (90.4%). For better comparison, we calculated the CO formation rates for different samples (Fig. 2c). The CO yields of J14, J14-Li<sub>1</sub>Zn<sub>9</sub>, J14-Li<sub>1</sub>Zn<sub>3</sub>, J14-Li<sub>1</sub>Zn<sub>1</sub>, and J14-Li reached 16.1%, 21.1%, 23.5%, 20.6%, and 16.9%, respectively, exhibiting a volcano-shaped trend with J14-Li<sub>1</sub>Zn<sub>3</sub> demonstrating optimal catalytic performance. Here, the CO generation rate of J14-Li<sub>1</sub>Zn<sub>3</sub> reached  $210 \text{ } \mu\text{mol}_{\text{CO}} \text{ g}_{\text{cat}}^{-1} \text{ s}^{-1}$ . Based on these results, we selected J14-Li<sub>1</sub>Zn<sub>3</sub> as the primary sample for subsequent studies, using the two extreme compositions (J14 and J14-Li) as references. We subsequently evaluated their stability at 400 °C, with the decay of CO<sub>2</sub> conversion and variation in CO selectivity over time shown in Fig. 2d and S8. After 32 h of continuous operation, J14-Li<sub>1</sub>Zn<sub>3</sub> retained 70% of its initial activity, whereas J14 retained only 56% after merely 4 h, and J14-Li retained 60% after 11 h, demonstrating the superior stability of J14-Li<sub>1</sub>Zn<sub>3</sub>. Notably, their CO selectivity gradually

increased with the prolongation of reaction time. Although J14-Li exhibited the largest increase in CO selectivity, it only reached 83.2% after 15 h of catalysis, whereas that of J14-Li<sub>1</sub>Zn<sub>3</sub> reached 96.8% after 30 h. Moreover, among the state of the art non-noble and even noble metal catalysts reported recently, our J14-Li<sub>1</sub>Zn<sub>3</sub> exhibits a leading rate of CO production (Table S3).

### Structural evolution of the catalysts

The fresh catalyst samples inevitably undergo reconstruction under reactive atmospheres during catalytic evaluation, which critically governs their catalytic performance. BET analysis of the used catalysts showed that the Li-doped samples possessed consistently higher specific surface areas exceeding that of J14 (Fig. S9 and Table S2). However, notably, this property exhibited no strong correlation with catalytic performance, suggesting the key role of the catalyst structure. To investigate



**Fig. 2** RWGS performance of catalysts. The plots of CO<sub>2</sub> conversion (a) and CO selectivity (b) of J14, J14-Li<sub>1</sub>Zn<sub>9</sub>, J14-Li<sub>1</sub>Zn<sub>3</sub>, J14-Li<sub>1</sub>Zn<sub>1</sub>, and J14-Li, versus temperature. (c) Product distribution and yields of J14, J14-Li<sub>1</sub>Zn<sub>9</sub>, J14-Li<sub>1</sub>Zn<sub>3</sub>, J14-Li<sub>1</sub>Zn<sub>1</sub>, and J14-Li, at 400 °C. (d) Long-term catalytic tests of J14, J14-Li<sub>1</sub>Zn<sub>3</sub>, and J14-Li, at 400 °C. Reaction conditions: CO<sub>2</sub>/H<sub>2</sub>/Ar = 24/72/4 (v/v/v); WHSV = 300 000 mL g<sub>cat</sub><sup>-1</sup> h<sup>-1</sup>; ordinary pressure.

the fine structures of the used catalysts, we next performed a series of characterization studies, including XRD, scanning transmission electron microscopy (STEM), and energy-dispersive X-ray spectroscopy (EDX) mapping. The XRD patterns reveal that all catalysts maintained the rock salt phase structure (Fig. 3a). Additionally, two broad peaks centered at 43°–45° and 50°–52° were observed across all samples, which could be attributed to face-centered cubic (fcc) metallic phases. These emergent features intensified progressively with the increase in Li content, suggesting an increase in metal composition. For precise peak identification, the 40°–55° region was magnified (Fig. 3b). A comparative analysis revealed that the broad peaks did not correspond to any metal element. Instead, they were located at intermediate positions between Cu and Co/Ni metal. It may be caused by overlapping of diffraction peaks of these metals or the formation of alloys. Increasing Li doping induced a shift in peak positions toward Co/Ni positions, implying an increasing Co/Ni component. Moreover, the STEM and EDX mapping images of the used J14 particles exhibit an overall uniform distribution of metal elements, apart from a handful of Co and Cu element particulate aggregates (Fig. 4a). The STEM and EDX mapping images of the used J14-Li<sub>1</sub>Zn<sub>3</sub> and J14-Li show a similar picture (Fig. 4c and e). The localized magnification reveals significant aggregation of Cu and Co elements without obvious overlap (not an alloy feature),<sup>40</sup> while Ni, Mg, and Zn are homogeneously distribu-

ted (Fig. 4b, d and e). Among them, Cu and Co exhibit differences in the sizes of aggregates, with smaller size versus J14 in J14-Li<sub>1</sub>Zn<sub>3</sub> and larger size in J14-Li. In conjunction with the XRD results, these results suggest that the catalysts maintain a high entropy structure after catalysis, and Cu and Co undergo exsolution without forming an alloy. Li doping could promote the metal exsolution, with moderate doping enhancing dispersivity and excessive doping triggering agglomeration.

To probe the surface states of the catalysts, we carried out X-ray photoelectron spectroscopy (XPS) analysis on the used catalysts. Cu 2p and LMM XPS analyses revealed the coexistence of Cu<sup>2+</sup> and Cu<sup>+0</sup> species across J14, J14-Li<sub>1</sub>Zn<sub>3</sub>, and J14-Li catalysts (Fig. 5a and Fig. S10).<sup>41</sup> The Cu<sup>+0</sup> concentration increased in the order of J14 (71.6%) < J14-Li<sub>1</sub>Zn<sub>3</sub> (83.6%) < J14-Li (87.7%), correlating with increasing Li incorporation. Similarly, the Co 2p spectra reveal the presence of Co<sup>2+</sup> and Co<sup>0</sup> on the J14, J14-Li<sub>1</sub>Zn<sub>3</sub>, and J14-Li catalysts, with Co<sup>0</sup> concentrations of 6.2% for J14, 16% for J14-Li<sub>1</sub>Zn<sub>3</sub>, and 22.2% for J14-Li (Fig. 5b).<sup>42</sup> Notably, the metallic state of Ni was also identified in the Ni 2p spectra, with concentrations of 6.5%, 17.7%, and 18.5% for J14, J14-Li<sub>1</sub>Zn<sub>3</sub>, and J14-Li, respectively (Fig. 5c).<sup>43</sup> Nevertheless, no Ni aggregation was distinctly identified in the former EDX mapping findings. It suggests that Ni undergoes exsolution as well, while metallic Ni species should be present in a highly dispersed state. Meanwhile, Ni<sup>2+</sup>-OH species were identified on J14-Li.<sup>44</sup> In addition, XPS



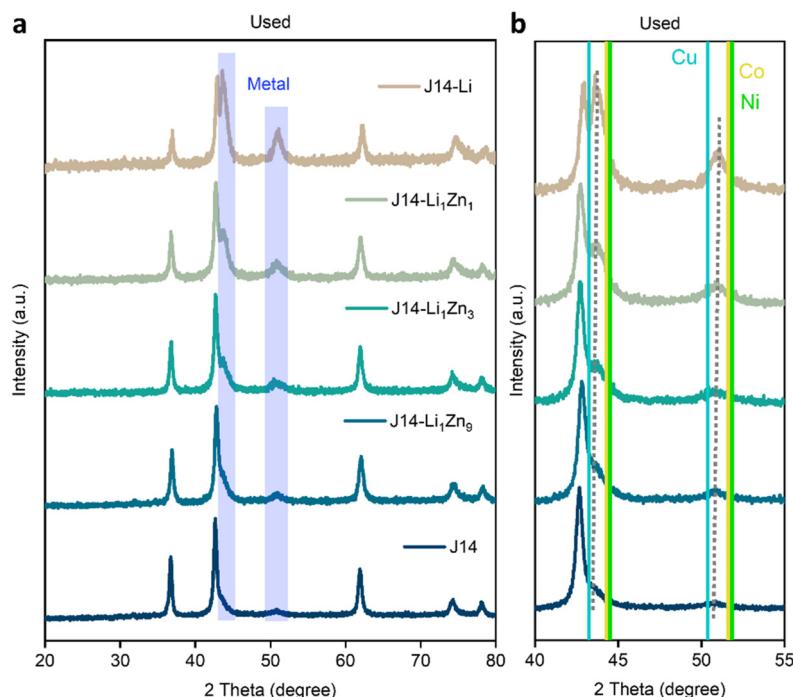


Fig. 3 (a) Overall and (b)  $40^\circ$ – $55^\circ$  magnified XRD patterns of used J14-Li, J14-Li<sub>1</sub>Zn<sub>1</sub>, J14-Li<sub>1</sub>Zn<sub>3</sub>, J14-Li<sub>1</sub>Zn<sub>9</sub>, and J14.

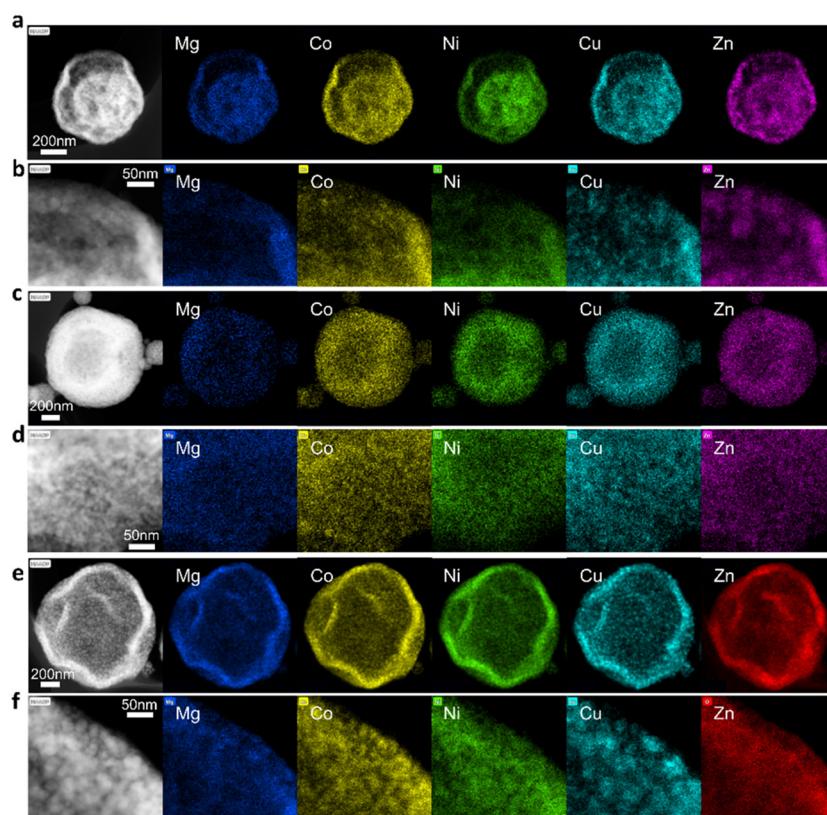


Fig. 4 Particle and localized magnified HADDF-STEM and EDX mapping images of used J14 (a and b), J14-Li<sub>1</sub>Zn<sub>3</sub> (c and d), and J14-Li (e and f).

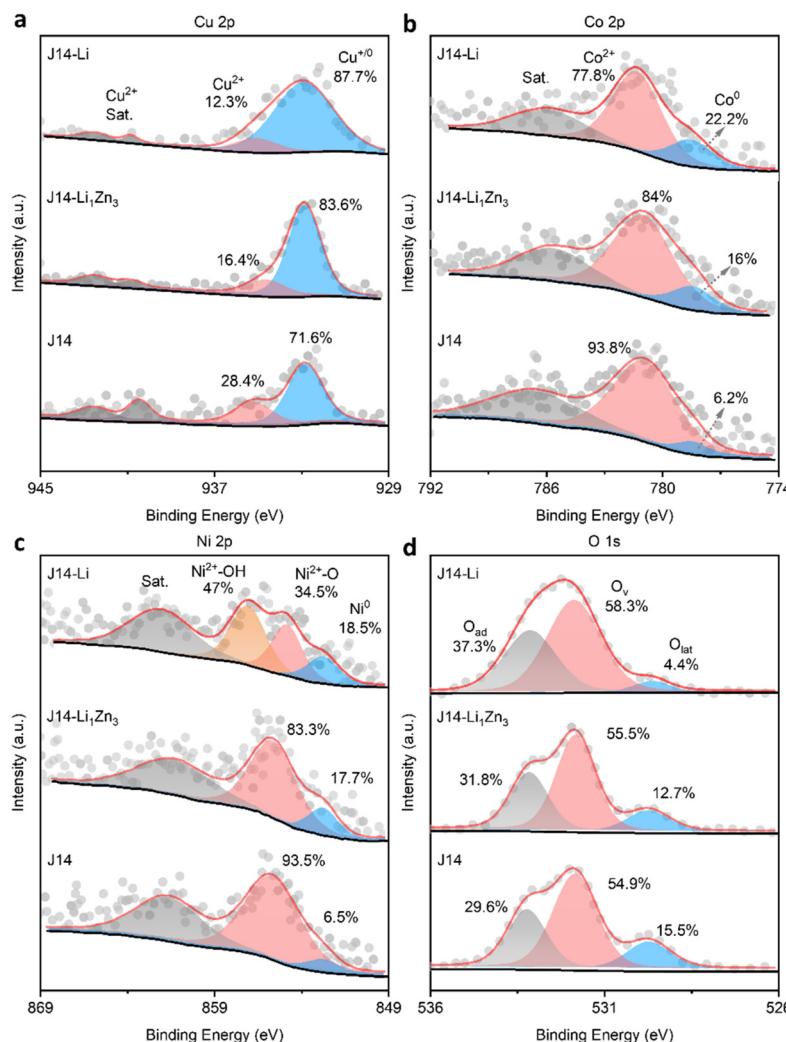


Fig. 5 XPS spectra of Cu 2p (a), Co 2p (b), Ni 2p (c), and O 1s (d) of used J14-Li, J14-Li<sub>1</sub>Zn<sub>3</sub>, and J14.

analysis of Mg, Zn, and Li revealed their oxidized states (Fig. S11–S13).<sup>45–47</sup> These results reveal that Cu dominates the metal sites, and Li incorporation promotes the exsolution of Cu, Co, and Ni metals, which is consistent with XRD results. As shown in Fig. 5d, XPS deconvolution of the O 1s spectra across all samples showed three distinct components at 529.7 eV (lattice oxygen, O<sub>lat</sub>), 531.8 eV (oxygen vacancies, O<sub>v</sub>), and 533.2 eV (adsorbed oxygen species, O<sub>ad</sub>).<sup>48</sup> The O<sub>ad</sub> primarily comprises hydroxyl groups and carbonate-related species (Fig. 5c, S11, and S13). Quantitative analysis shows that with increasing Li doping, the O<sub>lat</sub> concentration decreases progressively from 15.5% (J14) to 4.4% (J14-Li), accompanied by concurrent increases in O<sub>v</sub> (54.9% → 58.3%) and O<sub>ad</sub> (29.6% → 37.3%). This compositional evolution confirms that Li modification concurrently promotes O<sub>v</sub> generation and O<sub>ad</sub> stabilization.

To study the reduction behavior of the catalysts, fresh J14, J14-Li<sub>1</sub>Zn<sub>3</sub>, and J14-Li catalysts were subjected to H<sub>2</sub>-TPR analysis (Fig. S14). For J14, reduction peaks at 187 °C and 204 °C are attributed to stepwise Cu<sup>2+</sup> → Cu<sup>+</sup> → Cu<sup>0</sup> reduction, while

the feature at 253 °C corresponds to Co<sup>2+</sup>/Ni<sup>2+</sup> reduction.<sup>49–51</sup> The broad peak at 631 °C is attributed to lattice oxygen reduction accompanied by structural collapse due to over-reduction.<sup>52</sup> In the Li-doped samples, the lattice oxygen reduction peak progressively shifted to lower temperatures (405 °C, 525 °C, and 584 °C for J14-Li<sub>1</sub>Zn<sub>3</sub>; 444 °C for J14-Li). Quantitative analysis exhibits that the consumption of H<sub>2</sub> during reduction follows the order of J14-Li (5222.5 μmol g<sub>cat</sub><sup>-1</sup>) > J14-Li<sub>1</sub>Zn<sub>3</sub> (4520.5 μmol g<sub>cat</sub><sup>-1</sup>) > J14 (3610.3 μmol g<sub>cat</sub><sup>-1</sup>) (Table S4). These findings indicate that Li doping enhances catalyst reducibility, thereby promoting metal exsolution and oxygen vacancy generation. Given that Co and Ni are established active sites for CH<sub>4</sub>, the additional exsolved Co and Ni sites are considered a primary factor contributing to increased CH<sub>4</sub> byproduct formation.<sup>53,54</sup>

#### Structure–activity relationship study

To gain insights into the adsorption and activation of catalysts acting on reactants, we performed CO<sub>2</sub> temperature-pro-



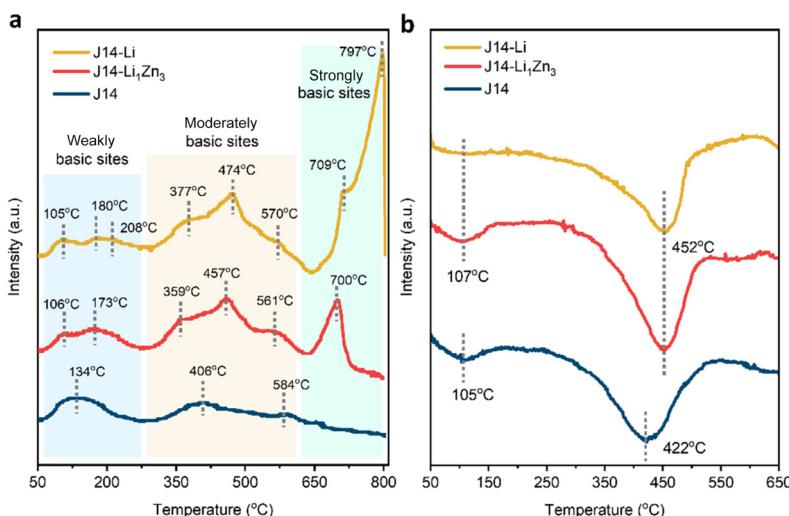
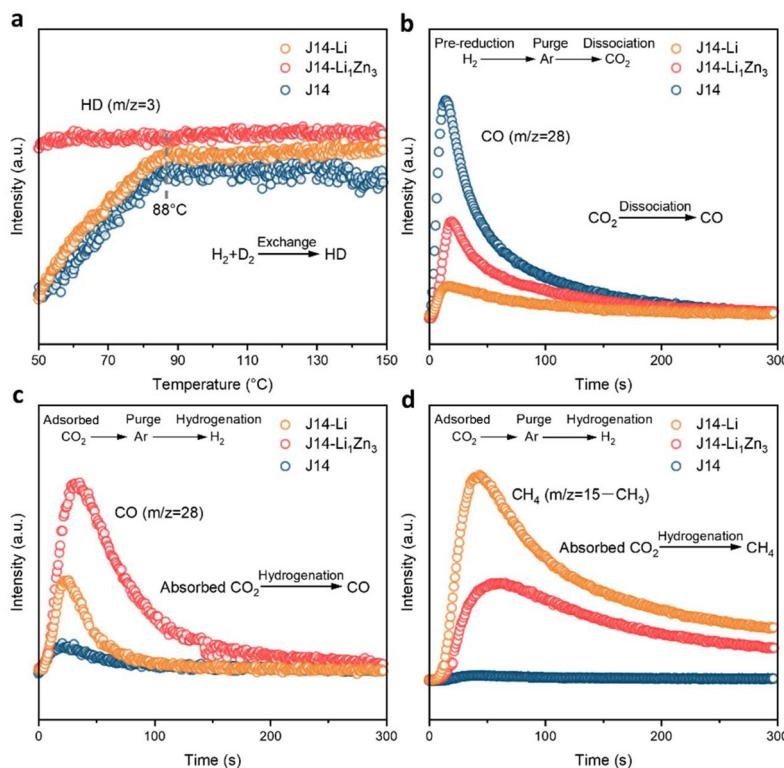


Fig. 6 Chemisorption experiment of used catalysts. (a)  $\text{CO}_2$ -TPD and (b)  $\text{H}_2$ -TPD plots of used J14-Li, J14-Li<sub>1</sub>Zn<sub>3</sub>, and J14.

grammed desorption ( $\text{CO}_2$ -TPD),  $\text{H}_2$ -TPD, and H-D exchange mass spectrometry (MS) experiments. In the  $\text{CO}_2$ -TPD analysis of J14, two types of basic sites are identified (Fig. 6a): one is weakly basic sites, with a peak temperature ( $T_p$ ) of 134 °C, and the other is moderately basic sites, with  $T_p$  in the 300–600 °C range.<sup>55</sup> With the introduction of Li, the overall catalyst basicity is enhanced, where the variety of weakly and moderately basic sites increases, accompanied by the generation of new strongly basic sites. Quantitative analysis reveals that the number of weakly basic sites follows the order of J14-Li<sub>1</sub>Zn<sub>3</sub> (6.2  $\mu\text{mol g}_{\text{cat}}^{-1}$ ) > J14 (5.5  $\mu\text{mol g}_{\text{cat}}^{-1}$ ) > J14-Li (3.6  $\mu\text{mol g}_{\text{cat}}^{-1}$ ), and that of moderately basic sites follows the order of J14-Li (23.7  $\mu\text{mol g}_{\text{cat}}^{-1}$ ) > J14-Li<sub>1</sub>Zn<sub>3</sub> (22.7  $\mu\text{mol g}_{\text{cat}}^{-1}$ ) > J14 (10.5  $\mu\text{mol g}_{\text{cat}}^{-1}$ ) (Table S5). Meanwhile, the strongly basic sites increase sharply with Li doping (7.1  $\mu\text{mol g}_{\text{cat}}^{-1}$  in J14-Li<sub>1</sub>Zn<sub>3</sub>, 70.6  $\mu\text{mol g}_{\text{cat}}^{-1}$  in J14-Li). Literature evidence suggests that weakly and moderately basic sites serve as primary active centers for  $\text{CO}_2$  hydrogenation, while excessive  $\text{CO}_2$  adsorption on strongly basic sites is counterproductive.<sup>56</sup> In this case, the promotion of effective surface basicity by Li doping approaches saturation in the J14-Li<sub>1</sub>Zn<sub>3</sub> catalyst.  $\text{H}_2$ -TPD analysis reveals that there are two desorption peaks at 105 °C and 422 °C for J14, assigned to physisorbed  $\text{H}_2$  and strongly chemisorbed/metal-bound hydrogen species, respectively, with quantitative analysis showing values of 5.5 and 10.5  $\mu\text{mol g}_{\text{cat}}^{-1}$  (Fig. 6b and Table S6). For J14-Li<sub>1</sub>Zn<sub>3</sub>, both peaks shifted to higher temperatures (107 °C and 452 °C), with increased desorption quantities (4.8 and 52.8  $\mu\text{mol g}_{\text{cat}}^{-1}$ ), indicating enhanced  $\text{H}_2$  adsorption. In contrast, J14-Li exhibits decreased desorption quantities of the two hydrogen species (2.5 and 41.7  $\mu\text{mol g}_{\text{cat}}^{-1}$ ) with a similar desorption temperature, indicating a decline in  $\text{H}_2$  adsorption sites. As metal sites are generally regarded to adsorb hydrogen species, this variation could be attributed to an increase in accessible metal sites in J14-Li<sub>1</sub>Zn<sub>3</sub> and a decrease in J14-Li. This is in agreement with the modulation of metal sites by Li-doping as shown above.

Besides, the HD exchange MS analysis results are shown in Fig. 7a. For J14, the HD signal ( $m/z = 3$ ) intensity progressively increased from 50 °C and reached equilibrium near 88 °C. The Li-modified J14-Li catalyst demonstrated comparable temperature-dependent behavior but with slightly higher HD signal intensities. Notably, J14-Li<sub>1</sub>Zn<sub>3</sub> achieved H/D exchange equilibrium already at 50 °C. These findings conclusively establish a hydrogen dissociation efficiency gradient as follows: J14-Li<sub>1</sub>Zn<sub>3</sub> > J14-Li > J14.<sup>56</sup>

Furthermore, elucidating the reaction mechanism is critical for understanding catalytic behavior. The RWGS reaction primarily proceeds through two distinct pathways: redox and associative.<sup>57</sup> In the redox pathway,  $\text{CO}_2$  undergoes direct catalytic reduction to CO without requiring hydrogen participation. Conversely, the associative pathway involves sequential surface adsorption of  $\text{CO}_2$  followed by hydrogenation to CO. We conducted  $\text{CO}_2$  dissociation experiments (Fig. 7b) and  $\text{CO}_2$  adsorption-reduction experiments (Fig. 7c and d), with the product signals detected using MS, to identify the redox and associative pathways proceeding.<sup>22</sup> Upon the injection of  $\text{CO}_2$  alone at 350 °C (Fig. 7b), CO signals emerged for all samples, with intensities following the order of J14 > J14-Li<sub>1</sub>Zn<sub>3</sub> > J14-Li. This indicates the existence of redox pathways in the catalysts, which are progressively suppressed by Li doping. After  $\text{CO}_2$  adsorption saturation and subsequent  $\text{H}_2$  injection at 350 °C, CO (Fig. 7c) and CH<sub>4</sub> (Fig. 7d) signals appeared, indicating that adsorbed  $\text{CO}_2$  undergoes both desired hydrogenation to CO and partial overhydrogenation to CH<sub>4</sub>. Notably, CO signal intensities followed the order of J14-Li<sub>1</sub>Zn<sub>3</sub> > J14-Li > J14 (Fig. 7c), while CH<sub>4</sub> intensities exhibited the reverse trend: J14-Li > J14-Li<sub>1</sub>Zn<sub>3</sub> > J14 (Fig. 7d). The results suggest that Li doping enhances the associative pathway while concomitantly promoting overhydrogenation, with the severity of this side reaction exhibiting a positive correlation with Li content. This is consistent with the optimal promotion of RWGS activity by moderate Li doping (J14-Li<sub>1</sub>Zn<sub>3</sub>), whereas overdoping yields



**Fig. 7** Chemical reaction mass spectrometry experiments. (a) HD exchange, (b)  $\text{CO}_2$  dissociation, and (c and d)  $\text{CO}_2$  adsorption–reduction experiments on used J14-Li, J14-Li<sub>1</sub>Zn<sub>3</sub>, and J14.

severe  $\text{CH}_4$  byproducts (J14-Li). Afterward, *in situ* diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) was performed under sequential inlet of  $\text{CO}_2$ ,  $\text{N}_2$  and  $\text{H}_2$ , to identify the hydrogenation intermediate species in the associative pathway (Fig. S15–S17). Upon  $\text{CO}_2$  introduction, carbonate species formed on J14, J14-Li<sub>1</sub>Zn<sub>3</sub>, and J14-Li surfaces. Switching to  $\text{N}_2$  purging induced rapid carbonate desorption from J14, while J14-Li<sub>1</sub>Zn<sub>3</sub> exhibited intermediate desorption kinetics and J14-Li retained the most persistent carbonate species. This trend demonstrates that Li incorporation enhances  $\text{CO}_2$  adsorption stability, consistent with the  $\text{CO}_2$ -TPD profiles (Fig. 6a). Subsequent  $\text{H}_2$  exposure consumed surface carbonates on J14, generating bicarbonate and formate species. In contrast, carbonate hydrogenation on J14-Li<sub>1</sub>Zn<sub>3</sub> and J14-Li predominantly yielded bicarbonate intermediates. These observations suggest that Li doping mainly promotes  $\text{CO}_2$  hydrogenation following the carbonate associative pathway.

## Conclusions

In conclusion, we demonstrated that substituting Zn with low-valent alkali metal Li<sup>+</sup> in the J14 HEO framework enables dual regulation of metallic sites and surface basicity. Optimal Li loading achieves simultaneous enhancement of RWGS activity and stability, whereas excessive doping triggers gross methanation side reactions. Characterization and structure–activity relationship analyses reveal that moderate Li incorporation

improves exsolution and dispersion of Cu, Co, and Ni metals, while elevating the density of weakly and moderately basic sites. This dual effect synergistically facilitates  $\text{H}_2$  dissociation and  $\text{CO}_2$  activation pathways. Conversely, excessive Li doping induces metallic site aggregation, enriching the methanation-active species Co and Ni, and preferentially generates ineffective strongly basic sites. Additionally, Li doping suppresses the redox pathway while enhancing the associative pathway (carbonate), with  $\text{CH}_4$  byproducts originating from over-hydrogenation during the latter. This low-valent alkali metal doping strategy presents a promising approach for enhancing catalytic performance in high-entropy oxide systems.

## Author contributions

K. Wang conducted the experiment and, along with R. Zhang and X. Wang, carried out the investigation. K. Wang, X. Wang and J. Xu developed the methodology and wrote the original draft, as well as being involved in the review and editing of the writing. X. Wang, S. Song, J. Xu and H. Zhang conceived and co-supervised the project. All authors participated in the discussion and data analysis.

## Conflicts of interest

There are no conflicts to declare.



## Data availability

The data supporting this article have been included as part of the SI. Methods, experimental details and supplementary figures. See DOI: <https://doi.org/10.1039/d5qi01099c>.

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