



Cite this: *Green Chem.*, 2020, **22**, 8169

Received 28th September 2020,

Accepted 2nd November 2020

DOI: 10.1039/d0gc03280h

rs.c.li/greenchem

## From 'Gift' to gift: producing organic solvents from CO<sub>2</sub>

Zhengkai Chen, <sup>a</sup> Shiyong Du,<sup>a</sup> Jiajun Zhang<sup>a</sup> and Xiao-Feng Wu <sup>\*a,b,c</sup>

'Gift' means 'poison' in German, which fits the situation of CO<sub>2</sub> in our atmosphere from some points of view. Hence, the utilization and transformation of CO<sub>2</sub> into highly value-added chemicals are like going from 'Gift' to gift and have attracted considerable attention from the chemical community. In this review, the latest advances in the field of production of commonly used organic solvents from CO<sub>2</sub> are summarized and discussed.

### 1 Introduction

As one of the main components of greenhouse gases, the steady increase of CO<sub>2</sub> concentration has become the chief culprit of global climate change, which has caused serious social concerns. Contemporary chemists are obliged to face this severe challenge and seek suitable and sustainable methods to solve this problem. On the other hand, as an ideal and versatile C1 building block, much attention on the valorization of CO<sub>2</sub> has been attracted among chemists due to its abundance, easy availability, nontoxicity and renewability.<sup>1–8</sup>

Recent years have witnessed the rapid development of chemical transformations of CO<sub>2</sub> into a variety of high value-added chemicals.<sup>9–18</sup> Among these transformations, the production of various organic solvents from CO<sub>2</sub> is of prime significance, as organic solvents are widely used in academic research and are usually employed as raw materials in the chemical industry. In addition, the utilization of supercritical CO<sub>2</sub> (scCO<sub>2</sub>) as a solvent in various chemical transformations has been flourishing in the past decades; these have found wide applications in a range of research fields due to the nontoxic and nonflammable properties of CO<sub>2</sub>.<sup>19–23</sup>

Considering the huge demand for organic solvents, the transformation of CO<sub>2</sub> into organic solvents has emerged as an attractive and promising research area, especially for industrial processes. However, CO<sub>2</sub> is a highly oxidized form of carbon and thermodynamically stable and/or kinetically inert; hence its activation and utilization typically require the involvement of reactive substances with high energy or severe reaction

<sup>a</sup>Department of Chemistry, Zhejiang Sci-Tech University, Hangzhou 310018, People's Republic of China. E-mail: xiao-feng.wu@catalysis.de

<sup>b</sup>Dalian National Laboratory for Clean Energy, Dalian Institute of Chemical Physics, Chinese Academy of Science, 116023 Dalian, Liaoning, China

<sup>c</sup>Leibniz-Institut für Katalyse e. V. an der Universität Rostock, Albert-Einstein-Straße 29a, 18059 Rostock, Germany



**Zhengkai Chen**

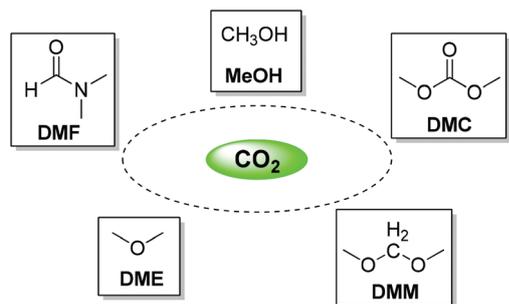
Zhengkai Chen was born in 1988 in Henan, China. He obtained his B.S. degree from Zhengzhou University in 2010. He received a Ph.D. degree from Zhejiang University under the supervision of Prof. Yuhong Zhang in 2015. Then he joined the Department of Chemistry, Zhejiang Sci-Tech University, and was promoted to associate professor in 2019. His current research interests focus on transition-metal-catalyzed carbonylative transformations

and new methods for the synthesis of functionalized nitrogen-containing heterocycles.



**Shiyong Du**

Shiyong Du was born in 1994 in Jilin, China. He obtained his B.S. degree from Qingdao University of Science and Technology in 2016. He is currently studying towards an M.S. degree at Zhejiang Sci-Tech University under the supervision of Dr Zhengkai Chen and Prof. Xiao-Feng Wu. His current research interests focus on the transition-metal-catalyzed synthesis of functionalized nitrogen-containing heterocycles.

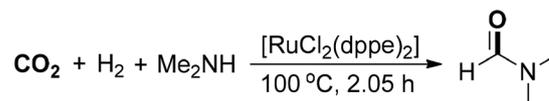


Scheme 1 Producing organic solvents from CO<sub>2</sub>.

conditions,<sup>24,25</sup> limiting the wide utility of CO<sub>2</sub> transformations at some extent. With respect to solvent synthesis from CO<sub>2</sub>, relevant research progress mainly focuses on methanol, *N,N*-dimethylformamide (DMF), dimethyl carbonate (DMC), dimethyl ether (DME), and so on. Virtually, there are a large number of publications about methanol synthesis from CO<sub>2</sub> via diverse catalytic systems and there have been several excellent reviews on this subject during the past decades.<sup>4,7,26–28</sup> Therefore, this review will emphatically introduce the preparation of DMF and DMC from CO<sub>2</sub> and select some of the mainstream studies about methanol synthesis, as well as the synthesis of some other useful solvents (Scheme 1).

## 2 Synthesis of DMF from CO<sub>2</sub>

*N,N*-Dimethylformamide (DMF) is a frequently used polar solvent and extremely versatile chemical reagent in organic



Scheme 2 Ru-catalyzed DMF synthesis from CO<sub>2</sub>.

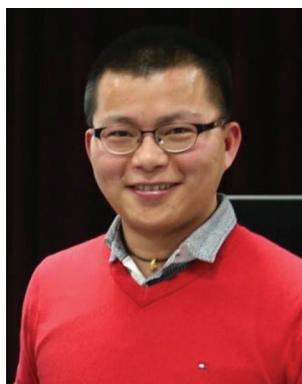
synthesis.<sup>29,30</sup> The conventional method for the construction of DMF is the reaction of dimethylamine with carbon monoxide in methanol, which was first reported by Haynes and co-workers in 1970.<sup>31</sup> Afterwards, Kudo and co-workers developed a PdCl<sub>2</sub>-catalyzed protocol for the synthesis of DMF with 40 bar of CO<sub>2</sub> and 80 bar of H<sub>2</sub> at 170 °C.<sup>32</sup> Vaska's group optimized the reaction by testing diverse metal complexes and DMF could be produced in the presence of an active platinum-based catalyst ([Pt<sub>2</sub>(μ-dppm)<sub>3</sub>].<sup>33,34</sup> Later, Noyori and co-workers achieved Ru-catalyzed production of DMF in supercritical CO<sub>2</sub> (130 bar) with a higher turnover number (TON) of up to 370 000.<sup>35,36</sup> A well-defined homogeneous RuCl<sub>2</sub>[P(CH<sub>3</sub>)<sub>3</sub>]<sub>4</sub> catalyst was the key factor for the reaction and scCO<sub>2</sub> was regarded as both reaction medium and reactant. In the reaction, ammonium formate salt was generated.

An improved protocol for the synthesis of DMF was demonstrated by Baiker and co-workers (Scheme 2).<sup>37</sup> A bidentate Ru/phosphine complex [RuCl<sub>2</sub>(dppe)<sub>2</sub>] was applied as a highly efficient catalyst to realize a TON of up to 740 000 and the reaction was conducted at 100 °C under 130 bar of CO<sub>2</sub> and 85 bar of H<sub>2</sub>. The reaction could be scaled up to produce 530 kg of DMF within 2 hours by using 1 gram of ruthenium catalyst. Notably, the solvent methyl formate was formed under a similar catalytic system in the presence of methanol and tri-



Jiajun Zhang

Jiajun Zhang was born in 1996 in Hebei, China. He obtained his B.S. degree from Dezhou University in 2018. He is currently studying towards an M.S. degree at Zhejiang Sci-Tech University under the supervision of Dr Zhengkai Chen and Prof. Xiao-Feng Wu. His current research interests focus on transition-metal-catalyzed carbonylative transformations and metal-free-mediated synthesis of nitrogen-containing heterocycles.



Xiao-Feng Wu

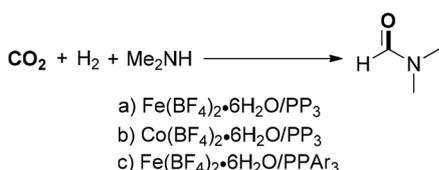
Xiao-Feng Wu was born in China. He studied chemistry at Zhejiang Sci-Tech University (China), where he got his bachelor's degree in science (2007). In the same year, he went to Rennes 1 University (France) and earned his master's degree in 2009. Then he joined Matthias Beller's group at the Leibniz Institute for Catalysis (Germany), where he completed his PhD defense in January 2012. Subsequently he started his independent research

at LIKAT and ZSTU where he was promoted to professor in 2013. In March 2017, Xiao-Feng defended his Habilitation successfully from Rennes 1 University (France). In 2020, he joined the Dalian Institute of Chemical Physics (DICP) and is leading a research group on practical synthesis. Xiao-Feng has authored >350 publications in international journals; meanwhile, he is also the editor or author of >10 books. In 2019, Xiao-Feng was invited to publish his Author Profile in *Angew. Chem., Int. Ed. (Angew. Chem., Int. Ed., 2019, 58, 8624)*.

methylamine. Then, a sol-gel-derived heterogeneous catalyst containing ruthenium complexes was synthesized and utilized for DMF synthesis with high turnover frequencies (up to  $18\,400\text{ h}^{-1}$ ), which was completed by the group of Baiker.<sup>38–40</sup> The serial positive results for DMF synthesis under ruthenium catalysis provide many insights for further intensive investigation upon industrialized application, such as developing soluble catalytic complexes in the supercritical system and suitable ligands.

Ito and co-workers designed a molybdenum complex,  $\text{MoH}_3[\text{Si}(\text{Ph})[\text{Ph}_2\text{PCH}_2\text{CH}_2\text{P}(\text{Ph})\text{C}_6\text{H}_4\text{-}o]_2]$ , and first applied it to catalytic DMF synthesis from  $\text{CO}_2$ .<sup>41</sup> The insertion of  $\text{CO}_2$  into the Mo–H bond produced another formal molybdenum complex, which was identified as an active catalyst and the key intermediate in DMF synthesis. A cheap heterogeneous Cu–ZnO catalyst mediated synthesis of DMF from  $\text{CO}_2$ ,  $\text{H}_2$ , and dimethylamine with high efficiency was disclosed by Han and co-workers.<sup>42</sup> Dimethylammonium dimethylcarbamate (DIMCARB) was used as a safe and convenient source of dimethylamine. The low-toxic Cu and ZnO catalyst showed good synergistic effects and great potential for application in the solvent-free conditions for producing DMF. After four years, another heterogeneous *trans*-bis(glycinato)copper(II) complex was developed to catalyze DMF synthesis in a highly efficient manner, which was disclosed by Jain's group.<sup>43</sup> In 2018, Sadeghzadeh and co-workers reported a new class of copper(II) complex based on  $\text{FeNi}_3/\text{KCC-1}$  for the *N*-formylation of amines *via*  $\text{CO}_2$  reductive hydrogenation and DMF could be delivered in 91% yield.<sup>44</sup>

Beller, Laurency and co-workers developed a series of non-precious metals to catalyze DMF synthesis from  $\text{CO}_2$ . An active iron catalyst system was *in situ* generated from  $\text{Fe}(\text{BF}_4)_2 \cdot 6\text{H}_2\text{O}$  and the tetradentate ligand  $\text{P}(\text{CH}_2\text{CH}_2\text{PPh}_2)_3$  for the hydrogenation of carbon dioxide (Scheme 3a).<sup>45</sup> Under the established catalytic system, DMF was produced in 75% yield with a TON of 727 with 30 bar of  $\text{CO}_2$  and 60 bar of  $\text{H}_2$  at  $100\text{ }^\circ\text{C}$ . Soon after, a novel cobalt dihydrogen complex ( $\text{Co}(\text{BF}_4)_2 \cdot 6\text{H}_2\text{O}/\text{PP}_3$ ) was applied to DMF synthesis under similar conditions, showing an improved catalytic activity with a TON of 1308 (Scheme 3b).<sup>46</sup> Another efficient iron-based catalyst with a tetradentate phosphorus ligand [tris(2-(diphenylphosphino)phenyl)phosphine] could enable the production of DMF in good yield with higher TONs (5104) (Scheme 3c).<sup>47</sup> Similarly, diethylformamide could be obtained in moderate yield with a TON of 2114, which was substantially higher than that of a previously reported iron-catalyzed system. These well-defined iron- or cobalt-based catalyst systems achieved significantly

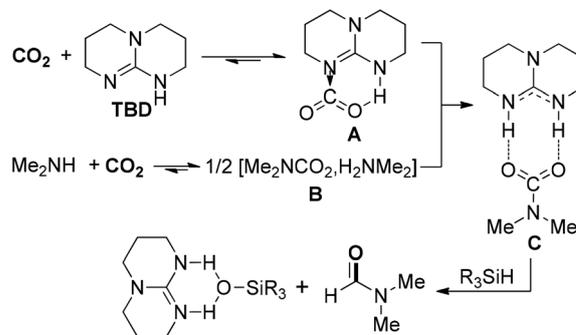


Scheme 3 Fe- or Co-catalyzed DMF synthesis from  $\text{CO}_2$ .

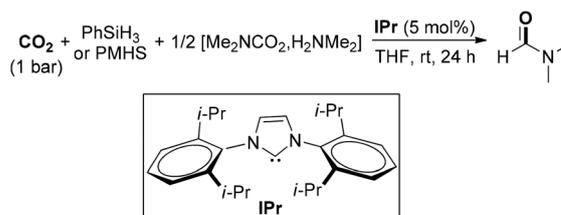
higher yields and TONs for  $\text{CO}_2$  hydrogenation than those of other non-precious-metal-based catalysts and even superior to many known precious-metal catalytic systems.

Except for commonly used dihydrogen ( $\text{H}_2$ ), other reductants with high activity were also explored for the hydrogenation of  $\text{CO}_2$ , such as hydrosilanes ( $\text{R}_3\text{Si-H}$ ) and hydroboranes ( $\text{R}_2\text{B-H}$ ), due to active Si–H and B–H bonds. In 2011, Cantat and co-workers reported a diagonal transformation for the synthesis of formamides from  $\text{CO}_2$ , in which organosilanes were chosen as cheap and nontoxic reducing agents (Scheme 4).<sup>48</sup> In the organocatalytic process, 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD) was an effective catalyst to promote the insertion of  $\text{CO}_2$  into N–H bonds to form the  $\text{CO}_2$  adduct **A**. The carbamate  $[\text{Me}_2\text{NCO}_2][\text{H}_2\text{NMe}_2]$  **B** reacted with **A** to give salt **C**, which was reduced by phenylsilane to lead to the DMF product and silanol by-product. The protocol exhibited several advantages over the previously established amine/ $\text{CO}_2$ / $\text{H}_2$  formylation system, including no use of metal catalyst, a lower pressure, solvent-free conditions and wide scope of amines. Considering the use of cheap and nontoxic silanes as reductants, the organocatalytic protocols for the formylation of amines with  $\text{CO}_2$  perhaps have broader prospects on the way to industrialization.

Cantat and co-workers further explored the organocatalytic formylation of N–H bonds by using N-heterocyclic carbenes, which featured mild reaction conditions and the utilization of two abundant and nontoxic chemical wastes of  $\text{CO}_2$  and polymethylhydrosiloxane (PMHS) (Scheme 5).<sup>49</sup> The combination of NHC and silane enabled the formation of DMF in high yield at room temperature under 1 bar of  $\text{CO}_2$  starting from carba-



Scheme 4 TBD-catalyzed synthesis of DMF from  $\text{CO}_2$ .



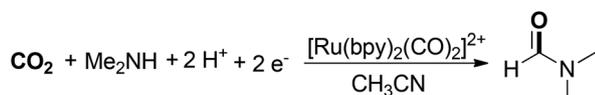
Scheme 5 N-Heterocyclic carbene (NHC)-catalyzed synthesis of DMF from  $\text{CO}_2$ .

mate  $[\text{Me}_2\text{NCO}_2][\text{H}_2\text{NMe}_2]$ . The highly active organocatalytic system was also amendable for the formylation of various N–H bonds, including amines, anilines, imines, hydrazines, hydrazones and N-heterocycles. Under this efficient organocatalytic system, a large-scale  $\text{CO}_2$  recycling process is expected to be achieved. Another reaction for the formylation of amines using  $\text{CO}_2$  and PMHS was reported by Bhanage and Nale, who applied  $\text{K}_2\text{CO}_3$  as the catalyst.<sup>50</sup>

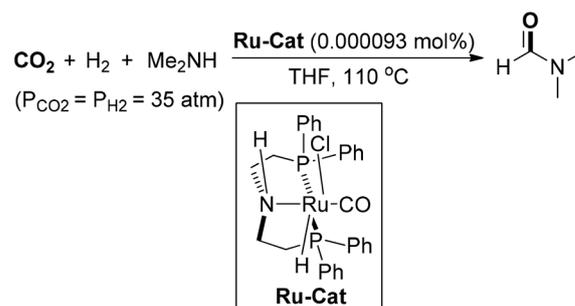
In 2014, Shi and co-workers prepared a heterogeneous Pd/ $\text{Al}_2\text{O}_3$ -NR-RD catalyst and utilized it for the catalytic formylation of amines with  $\text{CO}_2$ - $\text{H}_2$  under mild conditions.<sup>51</sup> High catalytic activity was observed for the production of DMF in 84% yield. In the same year, another heterogeneous catalytic reaction for exclusive DMF synthesis was described by Cao and co-workers.<sup>52</sup> A bifunctional catalyst based on partially reduced iridium oxide supported on  $\text{TiO}_2$  was created and found to show excellent activity for DMF synthesis through reductive activation of  $\text{CO}_2$  under a  $\text{H}_2$  atmosphere. The method directly employed available aqueous  $\text{NHMe}_2$  as the amine source instead of previously reported expensive dimethylammonium dimethylcarbamate.

Tanaka and co-workers developed a photocatalytic  $\text{CO}_2$  reduction reaction for the selective synthesis of DMF (Scheme 6).<sup>53</sup> In the transformation, a  $[\text{Ru}(\text{bpy})_2(\text{CO})_2]^{2+}/[\text{Ru}(\text{bpy})_3]^{2+}/\text{Me}_2\text{NH}/\text{Me}_2\text{NH}_2^+$  system was established to enable photocatalytic  $\text{CO}_2$  reduction. The nucleophilic attack of  $\text{Me}_2\text{NH}$  on  $[\text{Ru}(\text{bpy})_2(\text{CO})_2]^{2+}$  produced  $[\text{Ru}(\text{bpy})_2(\text{CO})(\text{CONMe}_2)]^+$ , which acted as the precursor of DMF.<sup>54</sup>  $\text{Me}_2\text{NH}$  and  $\text{Me}_2\text{NH}_2^+$  were used as electron donor and proton source, respectively. It was also found that the presence of the  $\text{Li}^+$  ion could greatly inhibit DMF production because  $\text{Li}^+$  blocked the formation of the RuCO complex through its strong stabilization of the Ru– $\text{CO}_2$  scaffold.

In 2015, Ding and co-workers demonstrated a highly efficient catalytic system for N-formylation of amines with  $\text{CO}_2$  and  $\text{H}_2$ , which utilized ruthenium-pincer-type complexes as catalysts to produce diverse formamides with high efficiency and selectivity (Scheme 7).<sup>55</sup> With regard to DMF synthesis, the N-formylation of dimethylamine was achieved with the ruthenium catalyst at a loading of 0.000093 mol%, producing DMF in 56% yield with a TON value of up to 599 000. Noteworthy was that the ruthenium catalyst could be recycled for 12 runs for the preparation of DMF without significant loss of activity, which showed huge potential of practical utilization of this protocol. Gratifyingly, the industrial application of this cost-effective reaction of  $\text{CO}_2$  hydrogenation for DMF production was successfully realized in 2019. It is the first kiloton pilot plant of DMF production in the world, which provides a useful and practical pathway for  $\text{CO}_2$  utilization.



Scheme 6 Photocatalytic  $\text{CO}_2$  reduction for the synthesis of DMF.

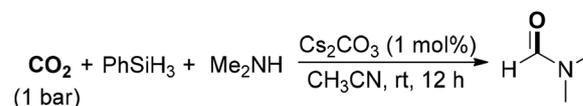


Scheme 7 Ruthenium-catalyzed DMF synthesis from  $\text{CO}_2$ .

Fu, Lin and co-workers reported readily available alkali-metal carbonates especially a cesium carbonate catalyzed reaction for the formylation of amines with  $\text{CO}_2$  and hydrosilanes (Scheme 8).<sup>56</sup> Under mild conditions (1 bar of  $\text{CO}_2$  at room temperature), DMF could be delivered in 95% yield in the presence of  $\text{PhSiH}_3$  as a reductant. In addition, methylation of amines could also be attained and the selectivity was readily controlled by tuning the reaction temperature and silane. An obvious “cesium effect” upon the catalytic activity of alkali-metal carbonates was observed in the reaction, which might originate from the increased solubility of the carbonate salt.

Jain and co-workers synthesized a graphene oxide (GO)-immobilized heteroleptic iridium complex and used it as the first heterogenized homogeneous catalyst for DMF preparation from  $\text{CO}_2$ ,  $\text{H}_2$  and dimethylamine under solvent-free conditions.<sup>57</sup> The catalyst could be easily recovered and recycled six times without the loss of catalytic efficiency.

An amine-modified *meso*- $\text{Al}_2\text{O}_3$ @MCM-41, developed by Bhanage and co-workers, was applied as a catalyst for the formylation of amines with  $\text{CO}_2$ .<sup>58</sup> Under the developed heterogeneous catalytic system, DMF could be obtained in excellent 98% yield with dimethylamine borane (DMAB) as a green reducing source. Then, DMAB was applied to another heterogeneous catalytic N-formylation of amines for the synthesis of N-formamides and benzimidazole,<sup>59</sup> which employed ruthenium nanoparticles (Ru-NPs) supported on polymeric ionic liquids (PILs) as effective catalysts to give DMF in 89% yield with a TON of 296. Subsequently, the same authors discovered an N-heterocyclic olefin (NHO) organocatalyst promoted chemical fixation of  $\text{CO}_2$  through the N-formylation of amines by using polymethylhydrosiloxane (PMHS) or 9-borabicyclo [3.3.1]nonane (9-BBN) as the reducing agent.<sup>60</sup> In the reaction, DMF could be produced in good yield under mild conditions. The *in situ* formed zwitterionic NHO-carboxylate ( $\text{NHO}-\text{CO}_2$ ) adducts were the key factor for the activation of  $\text{CO}_2$ . By the

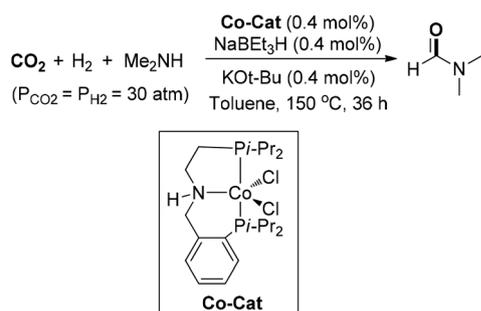


Scheme 8 Cesium carbonate catalyzed DMF synthesis from  $\text{CO}_2$ .

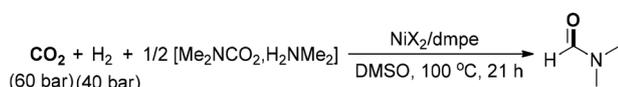
use of  $B(C_6F_5)_3$  as an efficient organocatalyst and dimethylamine borane ( $Me_2NHBH_3$ ) as a green hydrogen transfer source, N-formylation of amines *via* hydrogenation of  $CO_2$  led to DMF in 89% yield with a TON of 1112.<sup>61</sup> The interaction of bulky boron catalyst with amines could effectively activate  $CO_2$  and  $Me_2NHBH_3$  molecules. The abovementioned transformations all enable the production of DMF in high yields but with moderate TONs, which is seemingly far from industrial application.

An Earth-abundant cobalt-catalyzed N-formylation of various amines under  $CO_2$  and  $H_2$  pressure (30 bar each) was disclosed by Milstein and co-workers (Scheme 9).<sup>62</sup> A Co-PNP pincer complex was synthesized and could be transformed into active species in the presence of catalytic  $NaHBET_3$  and *t*-BuOK. For large-scale DMF synthesis, the lower catalyst loading (0.4 mol%) rendered the formation of DMF in 54% yield with a TON of 130 with the addition of 4 Å molecular sieves. Later, Tu and co-workers explored a series of NHC-Ir coordination assemblies as solid molecular catalysts for N-formylation of diverse amines.<sup>63</sup> Moderate yield of DMF was attained, even at 0.1 mol% catalyst loading, and the solid catalyst could be reused more than 10 runs.

Jessop and co-workers also developed an abundant-metal-catalyzed formylation of amines by catalytic hydrogenation of  $CO_2$  to prepare formamides (Scheme 10).<sup>64</sup> Dimethylammonium dimethylcarbamate was adopted under the catalysis of Ni(II)-phosphine complexes for the synthesis of DMF with a high TON value. Several metal complexes showed catalytic activity and Ni(II) salts were the superior choices. Another homogeneous catalyzed hydrogenation of carbon dioxide to DMF was achieved by using an *in situ* generated ruthenium catalyst from  $RuCl_3 \cdot H_2O$  and the phosphine ligand 2,2'-bis(diphenylphosphinomethyl)-1,1'-biphenyl (BISBI).<sup>65</sup> An aqueous biphasic solvent system was utilized, where the catalyst could be recycled by immobilization in a nonpolar alcoholic solvent and the product could be extracted *in situ* into



**Scheme 9** Ruthenium-catalyzed DMF synthesis from  $CO_2$ .

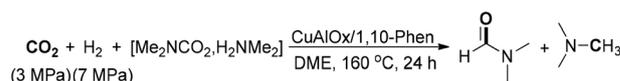


**Scheme 10** Ni(II)-catalyzed DMF synthesis from  $CO_2$ .

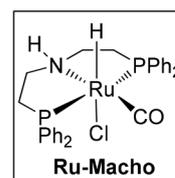
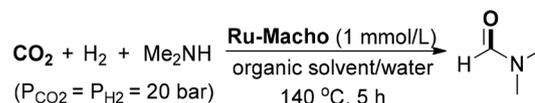
the aqueous phase. Then, the developed reaction system of DMF production was successfully transferred from lab-scale to a continuously operated miniplant with a low concentration of carbon monoxide as the only byproduct.<sup>66</sup> The positive results highlighted long-term (over 95 h) stability and selectivity of the catalytic system. The continuous addition of the ternary amine could result in the increase of the yield by tuning the basicity of the reaction system. The obtained product could be easily isolated through distillation without decomposition, exhibiting good prospects for scaled-up production.

Recently, Shi and co-workers developed a method for the integration of nano- and molecular catalysis through the synthesis of N-doped carbon layers on  $AlO_x$ -supported nano-Cu, which could be employed for the preparation of DMF in a controllable manner from dimethylamine and  $CO_2/H_2$  (Scheme 11).<sup>67</sup> The catalytic material was *in situ* formed by the reaction of  $CuAlO_x$  and 1,10-phen under a  $H_2$  atmosphere. The active catalyst could be easily recycled in three runs for the production of DMF with high yield and selectivity. In addition, the  $CuAlO_x$  catalyst also exhibited good performance for the catalytic hydrogenation of DMF to  $N(CH_3)_3$ . Later, the same authors demonstrated a heterogeneous Pd supported on natural palygorskite catalyst for amine formylation with  $CO_2$  and  $H_2$ .<sup>68</sup> In the transformation, DMF could be produced in 86% yield by using dimethylamine aqueous solution as the starting reagent. Another heterogeneous Pd-catalyzed  $CO_2$  fixation of amine to prepare DMF was described by Islam and co-workers, which utilized Merrifield resin supported palladium nanomaterial (Pd-PS-amp catalyst) as a catalyst and poly(methylhydrosiloxane) (PMHS) as a hydride transferring agent.<sup>69</sup>

Vorholt and co-workers demonstrated a ruthenium-catalyzed synthesis of DMF from  $CO_2$  in a biphasic solvent system (Scheme 12).<sup>70</sup> The PNP-pincer complex Ru-Macho was used as an active catalyst, which was identical to the catalyst in Ding and co-workers work.<sup>55</sup> Several key factors of the reaction were



**Scheme 11**  $CuAlO_x$ -catalyzed DMF synthesis from  $CO_2$ .



**Scheme 12** Ru-Macho-catalyzed DMF synthesis from  $CO_2$ .

investigated, including organic solvent, reaction pathways, the formate route and the concentration of CO<sub>2</sub>/amine. Adding carbon dioxide *via* reactive absorption to aqueous dimethylaminoethanol could enable DMF production in up to 81% yield, presumably due to the higher activities resulting from high basicity. Recently, this homogeneous biphasic protocol has been implemented on a miniplant scale by the same authors.<sup>71</sup> The catalyst Ru-Macho complex could be recycled through immobilization in an alcohol phase and maintained high stability over 230 h, providing DMF in an average yield of 48%. A two-step process was designed to be applied for the synthesis of other formamides.

Very recently, an efficient heterogeneous catalytic system for DMF synthesis by hydrogenation of CO<sub>2</sub> was established by Yoon and co-workers,<sup>72</sup> which employed ruthenium-grafted bisphosphine-based porous organic polymer (Ru@PP-POP) as a recyclable catalyst. In a batch process, a TON of up to 160 000 was obtained and excellent productivity and durability were observed in a continuous-flow process, thus offering great potential for industrial application of CO<sub>2</sub> hydrogenation for DMF production.

A bifunctional heterogeneous Ru catalyst was developed by Ding, Yan and co-workers for the N-formylation of amine and CO<sub>2</sub>.<sup>73</sup> The Ru-PPh<sub>3</sub>-SO<sub>3</sub>Na@POP catalyst, generated from the copolymerization of 3v-PPh<sub>3</sub> and sodium *p*-styrenesulfonate, could immobilize metals and alkali on porous organic polymers, enabling the formation of DMF from dimethylamine in 62% yield with 3 MPa of CO<sub>2</sub> and H<sub>2</sub>.

### 3 Synthesis of MeOH from CO<sub>2</sub>

As the simplest aliphatic alcohol and a kind of important industrial raw material, the annual production of methanol exceeds 100 million tons and still increases year by year.<sup>74</sup> Methanol is currently produced from coal, biomass, especially natural gas and syngas,<sup>75–77</sup> which is usually utilized as the precursor of many important industrial products, alternative fuels and hydrogen storage materials (12.5 wt% H<sub>2</sub>).<sup>78,79</sup>

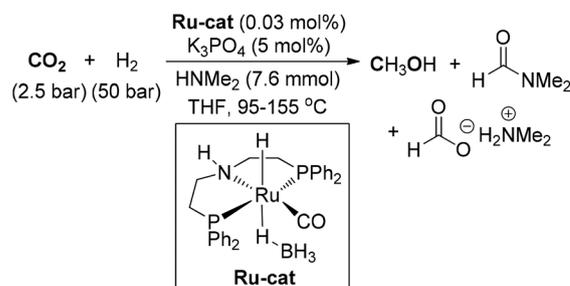
The industrial-scale synthesis of methanol lies in the catalytic reactions of syngas in the presence of Cu/ZnO/Al<sub>2</sub>O<sub>3</sub>-type heterogeneous catalysts under high pressure and elevated temperature.<sup>80,81</sup> The production of MeOH solely from the hydrogenation of CO<sub>2</sub> with heterogeneous catalysts has been intensively investigated and several excellent relevant reviews have been published.<sup>4,82–87</sup> Very recently, Zhang and co-workers have summarized the significant advances in heterogeneous catalysis of CO<sub>2</sub> hydrogenation to methanol in detail.<sup>88</sup> In addition, the catalytic reduction of CO<sub>2</sub> to methanol could be realized in the presence of stoichiometric amounts of reducing agents, such as boranes or silanes.<sup>89–95</sup> In this section, we will selectively introduce some seminal work regarding MeOH synthesis from the hydrogenation of CO<sub>2</sub> with homogeneous catalysts.

In 2011, Milstein and co-workers reported the first homogeneous catalytic synthesis of MeOH from the hydrogenation

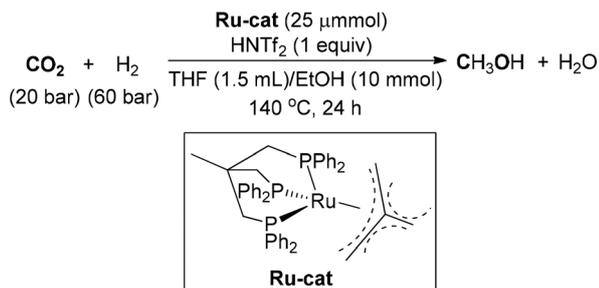
of carbonic acid derivatives and formates using pincer-type Ru<sup>II</sup> catalysts, which constituted indirect routes from CO<sub>2</sub> to methanol.<sup>96,97</sup> Although the hydrogenation of dimethyl carbonate could generate methanol, the dimethyl carbonate was more expensive than methanol, which made it not an economical choice. After one year, Ding and co-workers described the catalytic hydrogenation of cyclic carbonates from CO<sub>2</sub> and epoxides for the preparation of methanol and diols with readily available (PNP) Ru<sup>II</sup> pincer complexes as catalysts.<sup>98</sup> Starting from ethylene carbonate, two important bulk chemicals, methanol and ethylene glycol (EG), were readily produced with high TON values under relatively mild conditions. It should be noted that ethylene carbonate could be industrially obtained by reacting ethylene oxide with CO<sub>2</sub>. Poly(propylene carbonate) could also be hydrogenated to deliver 1,2-propylene diol and methanol. Another indirect methanol production from CO<sub>2</sub> through a formic acid disproportionation strategy with a homogeneous iridium catalyst was reported by Laurency and co-workers.<sup>99</sup>

Sanford and Huff developed a cascade reaction with three different homogeneous catalysts to complete the hydrogenation of CO<sub>2</sub> to methanol *via* formic acid and methyl formate intermediates with a maximum TON of 21.<sup>100</sup> Then, they achieved the homogeneous Ru-pincer complex catalyzed reduction of CO<sub>2</sub> to methanol in the presence of NHMe<sub>2</sub> (Scheme 13).<sup>101</sup> Under basic reaction conditions, MeOH could be produced with a TON of up to 550. The additional amine reacted with CO<sub>2</sub> to generate dimethylammonium dimethylcarbamate, which coupled with formic acid to deliver DMF. In the same year, Ding and co-workers also accomplished a one-pot sequential N-formylation and hydrogenation process for the conversion of CO<sub>2</sub> to MeOH *via* a formamide intermediate by using Ru-pincer complex as catalyst.<sup>55</sup>

In 2012, a homogeneous catalytic hydrogenation of CO<sub>2</sub> to methanol with a single ruthenium phosphine complex was investigated by Leitner, Klankermayer and co-workers (Scheme 14).<sup>102</sup> By adopting (Triphos)Ru-(TMM) (TMM = trimethylenemethane) as catalyst and bis(trifluoromethane)sulfonimide (HNTf<sub>2</sub>) as acidic additive, a TON of up to 221 for MeOH synthesis was attained under 20/60 bar of CO<sub>2</sub>/H<sub>2</sub>. The counterion introduced from the acid exerted a great impact upon the catalyst's performance. The reaction was further explored through a detailed mechanistic study, which demon-



**Scheme 13** Ru-catalyzed hydrogenation of CO<sub>2</sub> to MeOH.

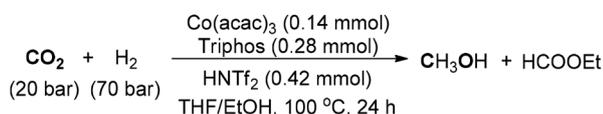
Scheme 14 Ru-catalyzed synthesis of MeOH from CO<sub>2</sub>.

strated that the hydrogenation of CO<sub>2</sub> to methanol could occur under a single cationic Triphos–Ru catalytic system without the need for an alcohol additive.<sup>103</sup> Furthermore, an aqueous biphasic system of 2-MTHF–water was developed for MeOH synthesis and catalyst recycling.

Milstein and co-workers described a CO<sub>2</sub> hydrogenation reaction by using PNN pincer Ru catalysts, in which CO<sub>2</sub> was captured by aminoethanols combined with hydrogenation of the captured oxazolidinone product for the formation of MeOH.<sup>104</sup> The above two procedures could be performed in the same reaction mixture without additional isolation or purification steps. Valinol was also used to capture CO<sub>2</sub> at 1 bar in the presence of catalytic Cs<sub>2</sub>CO<sub>3</sub>. The approach features a low pressure of CO<sub>2</sub> and high energy utilization rate, promoting the development of CO<sub>2</sub> conversion into other value-added chemicals.

The Ru-pincer complex was applied for the synthesis of MeOH from CO<sub>2</sub> with pentaethylenehexamine (PEHA) in an ethereal solvent, which was presented by Olah, Prakash and co-workers.<sup>105</sup> It was the first example of reductive conversion of CO<sub>2</sub> from air to MeOH with a homogeneous catalyst, despite the low CO<sub>2</sub> concentration (400 ppm). Then, the group of Prakash developed a tandem system for CO<sub>2</sub> capture in aqueous amine solution and hydrogenation to methanol in a biphasic 2-MTHF/water system.<sup>106</sup> The catalytic combination of Ru-MACHO-BH complex with high-boiling polyamine PEHA exhibited the best activity for MeOH synthesis. Further investigation towards mechanistic insights into Ru pincer/amine mediated hydrogenation of CO<sub>2</sub> to MeOH was performed by the same authors.<sup>107</sup> The observation revealed that Ru-Macho showed the highest catalytic activity in both amine formylation and formamide hydrogenation. In addition, (di/poly)amines were also effective for MeOH formation.

In 2017, Beller and co-workers disclosed the first homogeneous non-noble-metal catalyst for the synthesis of MeOH from hydrogenation of CO<sub>2</sub> (Scheme 15).<sup>108</sup> The reaction could

Scheme 15 Co-catalyzed synthesis of MeOH from CO<sub>2</sub>.

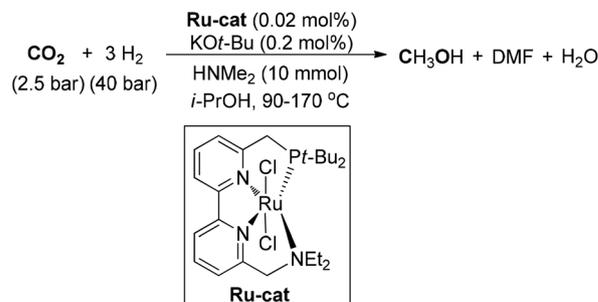
be operated at 100 °C with high reactivity in the presence of *in situ* generated catalyst from [Co(acac)<sub>3</sub>], Triphos, and HNTf<sub>2</sub>. Mechanistic studies revealed that a cationic cobalt/Triphos complex was regarded as an active catalyst, which was produced after slow removal of the acetylacetonate ligands. The study will stimulate the development of other non-noble-metal-catalyzed homogeneous hydrogenation of CO<sub>2</sub> to methanol. Other studies involving Earth-abundant metal-based complexes as catalysts for hydrogenation of CO<sub>2</sub> to methanol were consecutively reported in the same year.<sup>109,110</sup>

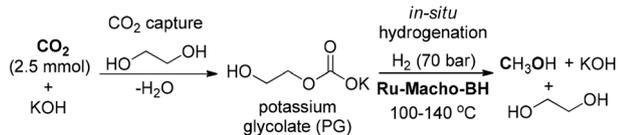
Zhou and co-workers designed a ruthenium complex with a tetradentate bipyridine ligand and applied it for the conversion of CO<sub>2</sub> to achieve MeOH synthesis (Scheme 16).<sup>111</sup> Under 2.5 atm of CO<sub>2</sub> and 40 atm of H<sub>2</sub>, catalytic hydrogenation of CO<sub>2</sub> could enable the production of MeOH with a TON of 2100 in the presence of HNMe<sub>2</sub>. The tetradentate bipyridine ligand proved to be the key factor for the stability of the ruthenium catalyst. In addition, hydrogenation of CO<sub>2</sub> to formamides and hydrogenation of formamides to methanol and amines was accomplished with a high TON value under the catalytic system.

In comparison with the three-catalyst cascade strategy established by Sanford and co-workers,<sup>100</sup> an improved homogeneous catalytic cascade system for CO<sub>2</sub> hydrogenation to MeOH was demonstrated by Goldberg and co-workers.<sup>112</sup> The combination of Ru(H)<sub>2</sub>[P(CH<sub>2</sub>CH<sub>2</sub>PPh<sub>2</sub>)<sub>3</sub>]/Sc(OTf)<sub>3</sub>/Ir(<sup>t</sup>BuPCP) (CO) was identified as an active catalyst for the synthesis of MeOH with a TON of 428 *via* formic acid and formate ester intermediates. Sc(OTf)<sub>3</sub> in the transformation served as both a Lewis and Brønsted acid donor.

Very recently, Leitner, Werlé and co-workers established a cobalt-based catalytic system that could achieve selective transformation of CO<sub>2</sub> individually to the formic acid, the formaldehyde, or the methanol level.<sup>113</sup> The catalyst was prepared based on the 3d transition-metal cobalt with a PNP pincer-type triazine ligand. For methanol synthesis, the catalytic hydrosilylation of CO<sub>2</sub> was conducted in [D<sub>6</sub>]-DMSO at 80 °C under a constant flow of CO<sub>2</sub> at 1 bar for 4 h with phenylsilane, producing the methoxysilane species with 99% selectivity.

Prakash and co-workers reported a Ru-catalyzed system for CO<sub>2</sub> capture and conversion to MeOH by using alkali-metal hydroxide as a CO<sub>2</sub> capturing agent and ethylene glycol as a formate ester promoter (Scheme 17).<sup>114</sup> In the one-pot trans-

Scheme 16 Ru-catalyzed synthesis of MeOH from CO<sub>2</sub>.



**Scheme 17** Ru-catalyzed hydrogenation of CO<sub>2</sub> captured in ethylene glycol for MeOH synthesis.

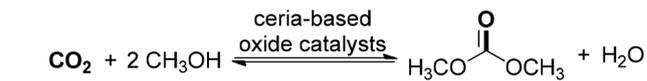
formation, CO<sub>2</sub> could be readily captured by ethylene glycol in the presence of KOH to form potassium glycolate (PG), which underwent *in situ* hydrogenation using Ru-PNP catalyst under 70 bar of H<sub>2</sub> at 100–140 °C to realize MeOH production with high activity. The high CO<sub>2</sub> capture efficiency of this protocol and regeneration of the hydroxide base rendered it superior to the previously established amine-based methods for the conversion of CO<sub>2</sub> from ambient air to methanol in a scalable process. The novel protocol is of great significance for the development of CO<sub>2</sub> capture and conversion in a highly efficient manner.

## 4 Synthesis of DMC from CO<sub>2</sub>

Dimethyl carbonate (DMC) is regarded as an environmentally benign solvent and versatile reagent for organic synthesis owing to its low toxicity, low viscosity and high biodegradability.<sup>115–119</sup> DMC also act as an alternative for several toxic organic compounds and as non-aqueous electrolyte for lithium batteries.<sup>120,121</sup> Conventional approaches for the synthesis of DMC lie in phosgenation and carbonylation of methanol, and transesterification of ethylene carbonate (EC) and methanol, which suffer from considerable issues regarding operational safety and environmental protection. Thus, direct DMC synthesis from abundant CO<sub>2</sub> and methanol has emerged as an attractive and powerful pathway from the viewpoint of sustainable development and green chemistry.

Although the direct synthesis of DMC from carbon dioxide and methanol constitutes a state-of-the-art process, some drawbacks still exist, which include the low yield and slow reaction rate, resulting from highly stable CO<sub>2</sub> and thermodynamic limitations of the reaction. Key solutions to overcome these difficulties focus on the development of novel catalysts and diverse dehydrating agents. In this regard, tremendous effort has been devoted to this aspect and several excellent reviews summarizing relevant achievements have been thereby presented.<sup>122–124</sup> Therefore, in this section we will emphatically describe the latest developments on DMC synthesis from CO<sub>2</sub> in the last five years.

Due to their excellent catalytic activity, selectivity, oxidation–reduction properties and larger specific surface area, ceria-based oxide catalysts have attracted considerable attention for the direct synthesis of DMC from CO<sub>2</sub> (Scheme 18).<sup>125–129</sup> Ceria could provide selective catalytic sites to activate CO<sub>2</sub> for the enhancement of the reaction rate of CO<sub>2</sub> and alcohols to organic carbonates.<sup>130</sup> Considering the



**Scheme 18** Ceria-based oxide catalyzed synthesis of DMC from CO<sub>2</sub>.

unfavourable nature of bare CeO<sub>2</sub>, including small surface areas, poor durability and quick deactivation, doping CeO<sub>2</sub> with transition metals (M) to form M<sub>x</sub>Ce<sub>1-x</sub>O<sub>2</sub> composites is usually employed in the catalytic reaction.

Wang and co-workers investigated the direct synthesis of DMC from CO<sub>2</sub> by using a series of CeO<sub>2</sub> nanocrystals of various structures (spindle, cube, and octahedron).<sup>131</sup> With the addition of 2,2-dimethoxypropane (DMP) as an effective dehydrating agent, spindle-CeO<sub>2</sub> exhibited a more favourable catalytic activity than other CeO<sub>2</sub> catalysts. The hydrolysis of DMP could *in situ* remove water from the reaction system, thereby overcoming the thermodynamic limitation of the reaction and increasing the DMC yield. In 2017, Kumar and co-workers prepared several calcium–cerium mixed-metal oxide catalysts (CeO<sub>2</sub>–CaO) with various Ce/Ca molar ratios and applied them with 3 Å molecular sieves to the direct conversion of CO<sub>2</sub> to DMC.<sup>132</sup> The acidity and basicity of catalysts exerted a fundamental effect upon the DMC yield and the ceria–calcium oxide catalyst could be reused in five runs.

Owing to the surface properties and acid/base sites related to catalytic performance, the ceria/zirconia (Ce<sub>x</sub>Zr<sub>1-x</sub>O<sub>2</sub>) solid solutions have attracted considerable attention in the field of the catalytic synthesis of DMC from CO<sub>2</sub>.<sup>133–135</sup> Recently, Kim and co-workers synthesized a series of Ce<sub>x</sub>Zr<sub>1-x</sub>O<sub>2</sub> solid solutions ( $x = 0.25, 0.5, 0.75$ ) with distinct morphology, acid/base sites and high surface area.<sup>136</sup> The prepared Ce<sub>x</sub>Zr<sub>1-x</sub>O<sub>2</sub> solid solutions with modified physicochemical properties possessed excellent catalytic activity and stability in DMC synthesis from CO<sub>2</sub> under mild conditions.

Diverse Zr-doped CeO<sub>2</sub> nanorods with different ratios of Zr/Ce were prepared and used for the catalytic synthesis of DMC from CO<sub>2</sub> and methanol at 6.8 MPa and 140 °C.<sup>137</sup> Doping of Zr atoms into the ceria lattice resulted in the formation of oxygen vacancy sites, which could promote the adsorption and activation of CO<sub>2</sub> and stabilize the final products by filling one oxygen atom of the CO<sub>2</sub> molecule.<sup>138</sup> It had been reported that CeO<sub>2</sub> nanorods with high density of defect sites and acid–base sites showed higher activity than nanocubes and nano-octahedra.<sup>139</sup> Among the developed Zr-doped CeO<sub>2</sub> nanorods, Zr<sub>0.1</sub>Ce nanorods with the highest amount of oxygen vacancies showed the highest activity for DMC synthesis, implying a linear relationship between the concentration of surface oxygen vacancies and catalytic activity.

TiO<sub>2</sub>-doped CeO<sub>2</sub> catalysts have also attracted considerable interest in the application of DMC synthesis because of the enhancement of the oxygen deficiency and acidity of the surface by doping TiO<sub>2</sub> into CeO<sub>2</sub>.<sup>140</sup> Meng and co-workers synthesized a number of TiO<sub>2</sub>-doped CeO<sub>2</sub> nanorods and applied them to the direct synthesis of DMC from CO<sub>2</sub> and CH<sub>3</sub>OH in

a fixed-bed reactor.<sup>141</sup> Better catalytic activities of ceria nanorods were observed with the introduction of TiO<sub>2</sub> and the highest catalytic performance was achieved on Ti<sub>0.04</sub>Ce<sub>0.96</sub>O<sub>2</sub> nanorod catalyst with a DMC selectivity of 83.1%. Kinetic and mechanistic studies revealed CO<sub>2</sub> adsorption and activation were rate-determining steps.

Ionic liquids have many excellent properties, such as thermal stability, negligible vapor pressure, reusability, high solubility in various solvents, and high CO<sub>2</sub> adsorption capacity under mild conditions.<sup>142</sup> The combination of porous metal oxide with ionic liquids (ILs) could be used as an effective method to overcome the limitations of the direct conversion of CO<sub>2</sub> to DMC. Very recently, Kim and co-workers prepared a series of ionic liquids with electrospun MgO–CeO<sub>2</sub> metal oxide nanofiber sponge-500 (EMCMONS-500).<sup>143</sup> The synergism between the ILs and EMCMONS-500 enabled a high catalytic performance towards DMC synthesis, as demonstrated that around 73.1 mmol g<sup>-1</sup> cat DMC yield and 98.9% selectivity were obtained under 3 MPa CO<sub>2</sub> pressure. The ILs-EMCMONS-500 catalyst exhibited superior catalytic activity for DMC production to that of other ceria or ILs-based catalysts.<sup>132,144–147</sup>

Except for ceria-based oxide catalysts, a variety of other catalysts, namely, zirconia,<sup>148,149</sup> heteropoly compounds,<sup>150,151</sup> ionic liquids,<sup>152,153</sup> potassium methoxide,<sup>154</sup> tin(IV) oxide,<sup>155–157</sup> H<sub>3</sub>PO<sub>4</sub>–V<sub>2</sub>O<sub>5</sub>,<sup>158</sup> and Cu–Ni or Cu–Fe bimetallic species supported on different carriers,<sup>159–162</sup> have been extensively studied for DMC preparation through the conversion of CO<sub>2</sub> with methanol.

In 2017, Wu, Hu and co-workers employed an imidazolium hydrogen carbonate ionic liquid ([C<sub>n</sub>C<sub>m</sub>Im][HCO<sub>3</sub>]) for the direct synthesis of DMC from CO<sub>2</sub> and methanol at room temperature.<sup>163</sup> Bifunctional [C<sub>1</sub>C<sub>4</sub>Im][HCO<sub>3</sub>] was used as an effective and recyclable catalyst and dehydrant, producing DMC with 74% CH<sub>3</sub>OH conversion (Scheme 19). The two roles of the imidazolium hydrogen carbonate ionic liquid system have many advantages and remarkably simplify the whole chemical process, offering the possibility of the further scaled application of this method.

The utilization of zirconium oxide (ZrO<sub>2</sub>) as catalyst for the synthesis of DMC from CO<sub>2</sub> was previously reported by Tomishige and co-workers.<sup>133,134,148,164</sup> Bell and Jung performed a relevant mechanistic investigation in detail using *in situ* infrared (IR) spectroscopy.<sup>165,166</sup> Inumaru and co-workers prepared diverse ZrO<sub>2</sub> nanocrystals by hydrothermal

synthesis at different temperatures and tested the catalytic activity in DMC formation.<sup>167</sup> Due to their high surface area and high reaction rate per unit surface area, a high catalytic activity of ZrO<sub>2</sub> nanocrystals was observed and the surface sites had a positive impact on the rate-determining step of the reaction.

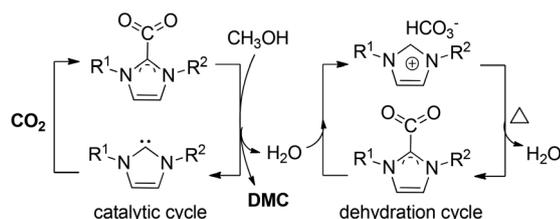
Meng, Xiao and co-workers designed and prepared a series of alkali-adopted Cu–Ni/diatomite catalysts for application in DMC synthesis from CO<sub>2</sub> and methanol.<sup>168</sup> The results revealed that alkali adoption could promote polarization of the Cu–Ni lattice and increase electron transformation from Cu–Ni to CO<sub>2</sub>, thereby greatly promoting the catalytic activity of Cu–Ni bimetallic catalysts. DMC could be obtained with 85.9% selectivity and 9.22% CH<sub>3</sub>OH conversion under the reaction conditions. The incorporation of an alkali into the Cu–Ni bimetallic catalyst could decrease the decomposition and reduction temperatures, which contributed to the formation of a nano-scale dispersion of bimetallic particles. The authors further investigated the highly active K<sub>2</sub>O-promoted Cu–Ni catalyzed direct DMC synthesis with 3 Å molecular sieves (MS) as a dehydrating agent.<sup>169</sup> The developed *in situ* dehydrating system enabled higher methanol conversion and selectivity by shifting the reaction equilibrium to a high DMC yield. Recently, a novel Cu<sub>x</sub>Ni<sub>y</sub>@POP-PPh<sub>3</sub> catalyst was synthesized and used in direct DMC synthesis by Chen, Ye and co-workers.<sup>170</sup> The CuNi alloy nanoparticles were encapsulated in thermally stable triphenylphosphine porous organic polymers, which exhibited high catalytic performance to achieve DMC production with 10.5% CH<sub>3</sub>OH conversion and 80% selectivity.

Wang and co-workers prepared a series of Y<sub>2</sub>O<sub>3</sub>-T catalysts through a one-pot calcination method from Y(NO<sub>3</sub>)<sub>3</sub>·6H<sub>2</sub>O and applied them to study the thermodynamics of the direct synthesis of DMC from CO<sub>2</sub>.<sup>171</sup> The efficiency of DMC formation was closely related to the moderate acidity–basicity amounts of the catalysts. Y<sub>2</sub>O<sub>3</sub>-750 showed the best catalytic performance to give the highest yield of DMC at 90 °C under 8 MPa of CO<sub>2</sub>. It is the first example of utilizing yttrium oxide as a single metal oxide catalyst to catalyze DMC synthesis from CO<sub>2</sub> and methanol.

## 5 Synthesis of DME/DMM from CO<sub>2</sub>

Dimethyl ether (DME) and dimethoxymethane (DMM) are known to be excellent fuel additives and green solvents, which have attracted considerable interest in recent years.<sup>172–174</sup> DME can be synthesized by acid-catalyzed dehydration of methanol or from syngas with bifunctional catalysts.<sup>175</sup> DMM is industrially produced through direct oxidation of methanol and a condensation sequence in the presence of suitable catalysts.<sup>176–178</sup> On the basis of extensive studies on CO<sub>2</sub> hydrogenation transformation, the direct conversion of CO<sub>2</sub> has emerged as an appealing alternative route to the generation of DME/DMM.

DME is prepared through CO<sub>2</sub> hydrogenation in a one-pot reaction comprising a methanol synthesis and methanol de-



Scheme 19 The catalytic and dehydration cycle of [C<sub>n</sub>C<sub>m</sub>Im][HCO<sub>3</sub>].

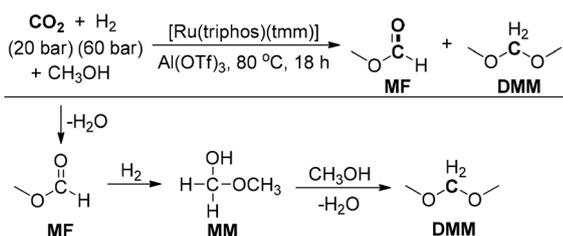
hydration sequence. The latter process can facilitate CO<sub>2</sub> hydrogenation to methanol by shifting the thermodynamic equilibrium,<sup>179</sup> and an effective catalyst for promoting methanol production is also significant. The Cu–Zn bimetallic system has been considered as an excellent catalyst for methanol synthesis from CO<sub>2</sub> hydrogenation.<sup>180</sup> In 2015, Zha and co-workers developed HZSM-5 packed CuO–ZnO–Al<sub>2</sub>O<sub>3</sub> nanoparticles for the catalysis of CO<sub>2</sub> hydrogenation with methanol to produce DME. Under the conditions of 3 MPa of CO<sub>2</sub>/H<sub>2</sub> at 270 °C, 23.4% yield of DME was obtained with 48.5% selectivity.<sup>181</sup> The combination of sulfated zirconia catalysts with a Cu/ZnO/ZrO<sub>2</sub> catalyst for the synthesis of DME was developed by Chareonpanich and co-workers, in which the prepared hybrid catalyst with 20 wt% sulfur loading could lead to a superior DME production yield.<sup>182</sup>

Later, Mota and co-workers prepared several Cu–ZnO catalysts supported on Al<sub>2</sub>O<sub>3</sub>/Nb<sub>2</sub>O<sub>5</sub> and employed them to study the conversion of CO<sub>2</sub> to methanol and dimethyl ether (Scheme 20).<sup>183</sup> The preparation procedure of the catalyst had a crucial influence on DME production, as demonstrated that the impregnated Cu–ZnO/Al<sub>2</sub>O<sub>3</sub> catalyst with better reducibility exhibited the highest activity and selectivity for the formation of DME. The acid function was not the key factor in the process of DME synthesis. Pd/HZSM-5 bifunctional catalysts modified with CeO<sub>2</sub> and CaO promoters were applied for the synthesis of DME through sulfur-containing CO<sub>2</sub> hydrogenation.<sup>184</sup> The addition of CaO reduced the acidity and weakened the CO<sub>2</sub> adsorption of the catalyst, whereas the promoter CeO<sub>2</sub> could increase the acidity and the quantity of adsorbed CO<sub>2</sub>, thereby greatly improving the catalytic activity. Optimal amounts of the promoters were 3 wt% CeO<sub>2</sub> and 1 wt% CaO.

Klankermayer and co-workers reported a ruthenium-catalyzed multistep reaction for the synthesis of dimethoxy-methane (DMM) from CO<sub>2</sub>/H<sub>2</sub> and methanol (Scheme 21).<sup>185</sup> Ru(Triphos)(tmm) was chosen as a catalyst and the Lewis acid



**Scheme 20** Cu–ZnO-catalyzed synthesis of DME from CO<sub>2</sub> hydrogenation.



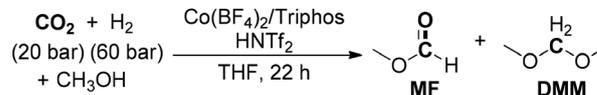
**Scheme 21** Ruthenium-catalyzed synthesis of DMM from CO<sub>2</sub>/H<sub>2</sub>.

Al(OTf)<sub>3</sub> was employed as an effective additive. Mechanistic studies indicated that methyl formate (MF) and methoxy-methanol (MM) were formed as possible intermediates during the reaction. The reaction presumably involved the hydrogenation of CO<sub>2</sub> to form the formic acid and subsequent esterification for producing MF. Then, MF was hydrogenated to MM in the presence of the Ru-Triphos-H<sub>2</sub> catalyst system. Finally, transacetalization of MM with the solvent methanol could give the DMM product. Furthermore, the versatility of this reaction was further investigated by using several other alcohols to successfully produce various dialkoxymethanes with slightly lower TONs. The present catalytic reaction constitutes the first example of the selective conversion of CO<sub>2</sub> and H<sub>2</sub> to formaldehyde.

After one year, the group of Klankermayer achieved the selective transformation of CO<sub>2</sub> to dialkoxymethane ethers using a non-precious transition-metal catalyst system.<sup>186</sup> A tailored Co(BF<sub>4</sub>)<sub>2</sub>/Triphos/HNTf<sub>2</sub> catalytic system was utilized for the production of DMM with a TON of up to 92 at 100 °C (Scheme 22). The developed protocol was also amenable for the formation of dialkoxymethane ethers (DAM) from other selected alcohol substrates. When isopropanol and more acidic hexafluoroisopropanol were used as substrates, methanol was selectively generated as the major product, implying switching of the catalyst system for methanol formation by variation of the alcohol additive or solvent. Moreover, the alteration of substituents on the phenyl groups of the Triphos ligand also affected the catalytic activity, as verified that sterically more demanding and electron-rich Triphos<sup>Xyl</sup> and Triphos<sup>ToI</sup> could enable the production of DMM with higher TONs of 120 and 157, respectively.

The conversion of methanol and CO<sub>2</sub> to produce DMM at 3 MPa and 150 °C in the basic functionalized ionic liquid BmimOH was developed by Cai and co-workers.<sup>187</sup> It was the first example of employing an ionic liquid as catalyst for the synthesis of DMM from CO<sub>2</sub> and methanol.

On the basis of Klankermayer's work on the ruthenium-Triphos-aluminum triflate catalytic system, Trapp and co-workers modified the structure of Triphos ligands and ruthenium catalysts to tune the steric and electronic properties, as well as the coordinating units, thereby increasing the catalytic activity for the production of DMM with higher TONs.<sup>188</sup> Under 90 bar of H<sub>2</sub> and 20 bar CO<sub>2</sub> in the presence of methanol, DMM and MF were produced using a ruthenium catalyst with an N-Triphos<sup>Ph</sup> ligand with maximum turnover numbers of 786 and 1290, in which MF was transformed into DMM with high selectivity. Formaldehyde and methanol could be readily obtained by distillation from the hydrolysis of DMM. Later, the same authors further investigated steric and elec-



**Scheme 22** Cobalt-catalyzed synthesis of DMM from CO<sub>2</sub>/H<sub>2</sub>.

tronic modifications of the Triphos ligand structure and varied the substitution of the apical atom in the backbone with silicon and phosphorus to explore the catalytic activity.<sup>189</sup> Under the optimized conditions, DMM and MF could be formed with maximum turnover numbers of 685 and 1370, which were comparable with the reactivity of their previous work.<sup>188</sup> For ruthenium-catalyzed DMM synthesis, the employment of <sup>Ph</sup>Si-Triphos<sup>Ph</sup> and <sup>Me</sup>Si-Triphos<sup>Ph</sup> as ligands was also a good choice to attain high reactivity.

## 6 Conclusions

Considering the increased global emission of CO<sub>2</sub> and from the viewpoint of sustainability, the development of efficient transformations of CO<sub>2</sub> into useful organic solvents constitutes an attractive and long-term goal for the chemical community. A wide range of strategies of CO<sub>2</sub> conversion have been exploited to produce diverse solvents in the past few decades. Apart from transformations involving precious transition-metal catalysts, reactions using inexpensive Earth-abundant metals have also developed rapidly. However, the wide industrialization of the developed protocol for the transformation of CO<sub>2</sub> to organic solvents is far from realized. Obvious limitations of the developed methodologies still remain, such as the necessity for precious-metal catalysts, harsh reaction conditions, low conversion rate and relatively poor chemo- and regioselectivity. Tremendous efforts should be devoted to solving these troublesome problems in the future. It will be of great significance for developing the efficient industrial-scale production of organic solvents from CO<sub>2</sub> due to the huge demand for solvents in academic research and the chemical industry. It is a very promising and fascinating, but also challenging, field for chemists working on organic synthesis or industrial catalysis.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

We acknowledge financial support from the National Natural Science Foundation of China (21772177), the Natural Science Foundation of Zhejiang Province (LY19B020016) and the Fundamental Research Funds of Zhejiang Sci-Tech University (2019Q065).

## Notes and references

- 1 T. Sakakura, J.-C. Choi and H. Yasuda, *Chem. Rev.*, 2007, **107**, 2365–2387.
- 2 M. Mikkelsen, M. Jørgensen and F. C. Krebs, *Energy Environ. Sci.*, 2010, **3**, 43–81.
- 3 K. Huang, C. L. Sun and Z. J. Shi, *Chem. Soc. Rev.*, 2011, **40**, 2435–2452.
- 4 W. Wang, S. Wang, X. Ma and J. Gong, *Chem. Soc. Rev.*, 2011, **40**, 3703–3727.
- 5 C. Maeda, Y. Miyazaki and T. Ema, *Catal. Sci. Technol.*, 2014, **4**, 1482–1497.
- 6 G. Fiorani, W. Guo and A. W. Kleij, *Green Chem.*, 2015, **17**, 1375–1389.
- 7 K. Dong, R. Razzaq, Y. Hu and K. Ding, *Top. Curr. Chem.*, 2017, **375**, 23.
- 8 A. M. Appel, J. E. Bercaw, A. B. Bocarsly, H. Dobbek, D. L. DuBois, M. Dupuis, J. G. Ferry, E. Fujita, R. Hille, P. J. A. Kenis, C. A. Kerfeld, R. H. Morris, C. H. F. Peden, A. R. Portis, S. W. Ragsdale, T. B. Rauchfuss, J. N. H. Reek, L. C. Seefeldt, R. K. Thauer and G. L. Waldrop, *Chem. Rev.*, 2013, **113**, 6621–6658.
- 9 W. Zhang and X. Lv, *Chin. J. Catal.*, 2012, **33**, 745–756.
- 10 M. Aresta, A. Dibenedetto and A. Angelini, *Chem. Rev.*, 2014, **114**, 1709–1742.
- 11 Q. Liu, L. Wu, R. Jackstell and M. Beller, *Nat. Commun.*, 2015, **6**, 5933.
- 12 A. Tortajada, F. Julia-Hernandez, M. Borjesson, T. Moragas and R. Martin, *Angew. Chem., Int. Ed.*, 2018, **57**, 15948–15982.
- 13 S.-S. Yan, Q. Fu, L.-L. Liao, G.-Q. Sun, J.-H. Ye, L. Gong, Y.-Z. Bo-Xue and D.-G. Yu, *Coord. Chem. Rev.*, 2018, **374**, 439–463.
- 14 S. Wang and C. Xi, *Chem. Soc. Rev.*, 2019, **48**, 382–404.
- 15 C. S. Yeung, *Angew. Chem., Int. Ed.*, 2019, **58**, 5492–5502.
- 16 A. Tlili, E. Blondiaux, X. Frogneux and T. Cantat, *Green Chem.*, 2015, **17**, 157–168.
- 17 X. B. Lu and D. J. Darensbourg, *Chem. Soc. Rev.*, 2012, **41**, 1462–1484.
- 18 J. Klankermayer, S. Wesselbaum, K. Beydoun and W. Leitner, *Angew. Chem., Int. Ed.*, 2016, **55**, 7296–7343.
- 19 A. Baiker, *Chem. Rev.*, 1999, **99**, 453–474.
- 20 P. G. Jessop, T. Ikariya and R. Noyori, *Chem. Rev.*, 1999, **99**, 475–494.
- 21 E. J. Beckman, *J. Supercrit. Fluids*, 2004, **28**, 121–191.
- 22 H.-F. Jiang, *Curr. Org. Chem.*, 2005, **9**, 289–297.
- 23 A. M. López-Periágo, N. Portoles-Gil, P. López-Domínguez, J. Fraile, J. Saurina, N. Aliaga-Alcalde, G. Tobias, J. A. Ayllón and C. Domingo, *Cryst. Growth Des.*, 2017, **17**, 2864–2872.
- 24 W. C. Chueh, C. Falter, M. Abbott, D. Scipio, P. Furler, S. M. Haile and A. Steinfeld, *Science*, 2010, **330**, 1797.
- 25 J. Ma, N. Sun, X. Zhang, N. Zhao, F. Xiao, W. Wei and Y. Sun, *Catal. Today*, 2009, **148**, 221–231.
- 26 Y.-N. Li, R. Ma, L.-N. He and Z.-F. Diao, *Catal. Sci. Technol.*, 2014, **4**, 1498–1512.
- 27 E. Alberico and M. Nielsen, *Chem. Commun.*, 2015, **51**, 6714–6725.
- 28 W.-H. Wang, Y. Himeda, J. T. Muckerman, G. F. Manbeck and E. Fujita, *Chem. Rev.*, 2015, **115**, 12936–12973.
- 29 J. Muzart, *Tetrahedron*, 2009, **65**, 8313–8323.
- 30 S. Ding and N. Jiao, *Angew. Chem., Int. Ed.*, 2012, **51**, 9226–9237.

- 31 P. Haynes, L. H. Slauch and J. F. Kohnle, *Tetrahedron Lett.*, 1970, **11**, 365–368.
- 32 K. Kudo, H. Phala, N. Sugita and Y. Takezaki, *Chem. Lett.*, 1977, **6**, 1495–1496.
- 33 S. Schreiner, J. Y. Yu and L. Vaska, *Inorg. Chim. Acta*, 1988, **147**, 139–141.
- 34 S. Schreiner, J. Y. Yu and L. Vaska, *J. Chem. Soc., Chem. Commun.*, 1988, 602–603.
- 35 P. G. Jessop, Y. Hsiao, T. Ikariya and R. Noyori, *J. Am. Chem. Soc.*, 1994, **116**, 8851–8852.
- 36 P. G. Jessop, Y. Hsiao, T. Ikariya and R. Noyori, *J. Am. Chem. Soc.*, 1996, **118**, 344–355.
- 37 O. Kröcher, R. A. Köppel and A. Baiker, *Chem. Commun.*, 1997, 453–454.
- 38 O. Kröcher, R. A. Köppel and A. Baiker, *J. Mol. Catal. A: Chem.*, 1999, **140**, 185–193.
- 39 O. Kröcher, R. A. Köppel, M. Fröba and A. Baiker, *J. Catal.*, 1998, **178**, 284–298.
- 40 L. Schmid, M. Rohr and A. Baiker, *Chem. Commun.*, 1999, 2303–2304.
- 41 M. Minato, D.-Y. Zhou, K.-i. Sumiura, R. Hirabayashi, Y. Yamaguchi and T. Ito, *Chem. Commun.*, 2001, 2654–2655.
- 42 J. Liu, C. Guo, Z. Zhang, T. Jiang, H. Liu, J. Song, H. Fan and B. Han, *Chem. Commun.*, 2010, **46**, 5770–5772.
- 43 S. Kumar and S. L. Jain, *RSC Adv.*, 2014, **4**, 64277–64279.
- 44 R. Zhiani, S. M. Saadati, M. Zahedifar and S. M. Sadeghzadeh, *Catal. Lett.*, 2018, **148**, 2487–2500.
- 45 C. Federsel, A. Boddien, R. Jackstell, R. Jennerjahn, P. J. Dyson, R. Scopelliti, G. Laurenczy and M. Beller, *Angew. Chem., Int. Ed.*, 2010, **49**, 9777–9780.
- 46 C. Federsel, C. Ziebart, R. Jackstell, W. Baumann and M. Beller, *Chem. – Eur. J.*, 2012, **18**, 72–75.
- 47 C. Ziebart, C. Federsel, P. Anbarasan, R. Jackstell, W. Baumann, A. Spannenberg and M. Beller, *J. Am. Chem. Soc.*, 2012, **134**, 20701–20704.
- 48 C. Das Neves Gomes, O. Jacquet, C. Villiers, P. Thuery, M. Ephritikhine and T. Cantat, *Angew. Chem., Int. Ed.*, 2012, **51**, 187–190.
- 49 O. Jacquet, C. Das Neves Gomes, M. Ephritikhine and T. Cantat, *J. Am. Chem. Soc.*, 2012, **134**, 2934–2937.
- 50 B. Bhanage and D. Nale, *Synlett*, 2016, **27**, 1413–1417.
- 51 X. Cui, Y. Zhang, Y. Deng and F. Shi, *Chem. Commun.*, 2014, **50**, 189–191.
- 52 Q. Y. Bi, J. D. Lin, Y. M. Liu, S. H. Xie, H. Y. He and Y. Cao, *Chem. Commun.*, 2014, **50**, 9138–9140.
- 53 K. Kobayashi, T. Kikuchi, S. Kitagawa and K. Tanaka, *Angew. Chem., Int. Ed.*, 2014, **53**, 11813–11817.
- 54 H. Ishida, H. Tanaka, K. Tanaka and T. Tanaka, *Chem. Lett.*, 1987, **16**, 597–600.
- 55 L. Zhang, Z. Han, X. Zhao, Z. Wang and K. Ding, *Angew. Chem., Int. Ed.*, 2015, **54**, 6186–6189.
- 56 C. Fang, C. Lu, M. Liu, Y. Zhu, Y. Fu and B.-L. Lin, *ACS Catal.*, 2016, **6**, 7876–7881.
- 57 S. Kumar, P. Kumar, A. Deb, D. Maiti and S. L. Jain, *Carbon*, 2016, **100**, 632–640.
- 58 D. B. Nale, D. Rath, K. M. Parida, A. Gajengi and B. M. Bhanage, *Catal. Sci. Technol.*, 2016, **6**, 4872–4881.
- 59 V. B. Saptal, T. Sasaki and B. M. Bhanage, *ChemCatChem*, 2018, **10**, 2593–2600.
- 60 V. B. Saptal and B. M. Bhanage, *ChemSusChem*, 2016, **9**, 1980–1985.
- 61 V. B. Saptal, G. Juneja and B. M. Bhanage, *New J. Chem.*, 2018, **42**, 15847–15851.
- 62 P. Daw, S. Chakraborty, G. Leitus, Y. Diskin-Posner, Y. Ben-David and D. Milstein, *ACS Catal.*, 2017, **7**, 2500–2504.
- 63 Y. Zhang, J. Wang, H. Zhu and T. Tu, *Chem. – Asian J.*, 2018, **13**, 3018–3021.
- 64 M. A. Affan and P. G. Jessop, *Inorg. Chem.*, 2017, **56**, 7301–7305.
- 65 R. Kuhlmann, S. Schmitz, K. Haßmann, A. Prüllage and A. Behr, *Appl. Catal., A*, 2017, **539**, 90–96.
- 66 R. Kuhlmann, A. Prüllage, K. Künnemann, A. Behr and A. J. Vorholt, *J. CO<sub>2</sub> Util.*, 2017, **22**, 184–190.
- 67 Y. Wu, T. Wang, H. Wang, X. Wang, X. Dai and F. Shi, *Nat. Commun.*, 2019, **10**, 2599.
- 68 X. Dai, B. Wang, A. Wang and F. Shi, *Chin. J. Catal.*, 2019, **40**, 1141–1146.
- 69 S. Ghosh, A. Ghosh, S. Biswas, M. Sengupta, D. Roy and S. M. Islam, *ChemistrySelect*, 2019, **4**, 3961–3972.
- 70 R. Kuhlmann, M. Nowotny, K. U. Künnemann, A. Behr and A. J. Vorholt, *J. Catal.*, 2018, **361**, 45–50.
- 71 R. Kuhlmann, K. U. Künnemann, L. Hinderink, A. Behr and A. J. Vorholt, *ACS Sustainable Chem. Eng.*, 2019, **7**, 4924–4931.
- 72 G. H. Gunasekar, S. Padmanaban, K. Park, K. D. Jung and S. Yoon, *ChemSusChem*, 2020, **13**, 1735–1739.
- 73 G. Wang, M. Jiang, G. Ji, Z. Sun, C. Li, L. Yan and Y. Ding, *ACS Sustainable Chem. Eng.*, 2020, **8**, 5576–5583.
- 74 G. A. Olah, *Angew. Chem., Int. Ed.*, 2005, **44**, 2636–2639.
- 75 J.-P. Lange, *Catal. Today*, 2001, **64**, 3–8.
- 76 C. N. Hamelinck and A. P. C. Faaij, *J. Power Sources*, 2002, **111**, 1–22.
- 77 T. Chmielniak and M. Sciazko, *Appl. Energy*, 2003, **74**, 393–403.
- 78 G. A. Olah, *Angew. Chem., Int. Ed.*, 2013, **52**, 104–107.
- 79 M. Nielsen, E. Alberico, W. Baumann, H. J. Drexler, H. Junge, S. Gladiali and M. Beller, *Nature*, 2013, **495**, 85–89.
- 80 K. C. Waugh, *Catal. Today*, 1992, **15**, 51–75.
- 81 M. Behrens, F. Studt, I. Kasatkin, S. Köhl, M. Hävecker, F. Abild-Pedersen, S. Zander, F. Girgsdies, P. Kurr, B.-L. Kniep, M. Tovar, R. W. Fischer, J. K. Nørskov and R. Schlögl, *Science*, 2012, **336**, 893.
- 82 F. Liao, Y. Huang, J. Ge, W. Zheng, K. Tedsree, P. Collier, X. Hong and S. C. Tsang, *Angew. Chem., Int. Ed.*, 2011, **50**, 2162–2165.
- 83 J. Graciani, K. Mudiyansele, F. Xu, A. E. Baber, J. Evans, S. D. Senanayake, D. J. Stacchiola, P. Liu, J. Hrbek, J. F. Sanz and J. A. Rodriguez, *Science*, 2014, **345**, 546.
- 84 L. C. Grabow and M. Mavrikakis, *ACS Catal.*, 2011, **1**, 365–384.

- 85 C. Liu, B. Yang, E. Tyo, S. Seifert, J. DeBartolo, B. von Issendorff, P. Zapol, S. Vajda and L. A. Curtiss, *J. Am. Chem. Soc.*, 2015, **137**, 8676–8679.
- 86 S. Kattel, P. J. Ramirez, J. G. Chen, J. A. Rodriguez and P. Liu, *Science*, 2017, **355**, 1296.
- 87 S. Dang, H. Yang, P. Gao, H. Wang, X. Li, W. Wei and Y. Sun, *Catal. Today*, 2019, **330**, 61–75.
- 88 J. Zhong, X. Yang, Z. Wu, B. Liang, Y. Huang and T. Zhang, *Chem. Soc. Rev.*, 2020, **49**, 1385–1413.
- 89 S. Chakraborty, J. Zhang, J. A. Krause and H. Guan, *J. Am. Chem. Soc.*, 2010, **132**, 8872–8873.
- 90 F. Huang, C. Zhang, J. Jiang, Z.-X. Wang and H. Guan, *Inorg. Chem.*, 2011, **50**, 3816–3825.
- 91 S. N. Riduan, Y. Zhang and J. Y. Ying, *Angew. Chem., Int. Ed.*, 2009, **48**, 3322–3325.
- 92 F. Huang, G. Lu, L. Zhao, H. Li and Z.-X. Wang, *J. Am. Chem. Soc.*, 2010, **132**, 12388–12396.
- 93 Z. Lu and T. J. Williams, *ACS Catal.*, 2016, **6**, 6670–6673.
- 94 C. Erken, A. Kaithal, S. Sen, T. Weyhermuller, M. Holscher, C. Werle and W. Leitner, *Nat. Commun.*, 2018, **9**, 4521.
- 95 H. Li, T. P. Goncalves, Q. Zhao, D. Gong, Z. Lai, Z. Wang, J. Zheng and K. W. Huang, *Chem. Commun.*, 2018, **54**, 11395–11398.
- 96 E. Balaraman, C. Gunanathan, J. Zhang, L. J. Shimon and D. Milstein, *Nat. Chem.*, 2011, **3**, 609–614.
- 97 E. Balaraman, Y. Ben-David and D. Milstein, *Angew. Chem., Int. Ed.*, 2011, **50**, 11702–11705.
- 98 Z. Han, L. Rong, J. Wu, L. Zhang, Z. Wang and K. Ding, *Angew. Chem., Int. Ed.*, 2012, **51**, 13041–13045.
- 99 K. Sordakis, A. Tsurusaki, M. Iguchi, H. Kawanami, Y. Himeda and G. Laurenczy, *Chem. – Eur. J.*, 2016, **22**, 15605–15608.
- 100 C. A. Huff and M. S. Sanford, *J. Am. Chem. Soc.*, 2011, **133**, 18122–18125.
- 101 N. M. Rezayee, C. A. Huff and M. S. Sanford, *J. Am. Chem. Soc.*, 2015, **137**, 1028–1031.
- 102 S. Wesselbaum, T. Vom Stein, J. Klankermayer and W. Leitner, *Angew. Chem., Int. Ed.*, 2012, **51**, 7499–7502.
- 103 S. Wesselbaum, V. Moha, M. Meuresch, S. Brosinski, K. M. Thenert, J. Kothe, T. V. Stein, U. Englert, M. Holscher, J. Klankermayer and W. Leitner, *Chem. Sci.*, 2015, **6**, 693–704.
- 104 J. R. Khusnutdinova, J. A. Garg and D. Milstein, *ACS Catal.*, 2015, **5**, 2416–2422.
- 105 J. Kothandaraman, A. Goepfert, M. Czaun, G. A. Olah and G. K. Prakash, *J. Am. Chem. Soc.*, 2016, **138**, 778–781.
- 106 S. Kar, R. Sen, A. Goepfert and G. K. S. Prakash, *J. Am. Chem. Soc.*, 2018, **140**, 1580–1583.
- 107 S. Kar, R. Sen, J. Kothandaraman, A. Goepfert, R. Chowdhury, S. B. Munoz, R. Haiges and G. K. S. Prakash, *J. Am. Chem. Soc.*, 2019, **141**, 3160–3170.
- 108 J. Schneidewind, R. Adam, W. Baumann, R. Jackstell and M. Beller, *Angew. Chem., Int. Ed.*, 2017, **56**, 1890–1893.
- 109 S. Kar, A. Goepfert, J. Kothandaraman and G. K. S. Prakash, *ACS Catal.*, 2017, **7**, 6347–6351.
- 110 A. P. C. Ribeiro, L. M. D. R. S. Martins and A. J. L. Pombeiro, *Green Chem.*, 2017, **19**, 4811–4815.
- 111 F.-H. Zhang, C. Liu, W. Li, G.-L. Tian, J.-H. Xie and Q.-L. Zhou, *Chin. J. Chem.*, 2018, **36**, 1000–1002.
- 112 W.-Y. Chu, Z. Culakova, B. T. Wang and K. I. Goldberg, *ACS Catal.*, 2019, **9**, 9317–9326.
- 113 H. H. Cramer, B. Chatterjee, T. Weyhermuller, C. Werlé and W. Leitner, *Angew. Chem., Int. Ed.*, 2020, **59**, 15674–15681.
- 114 R. Sen, A. Goepfert, S. Kar and G. K. S. Prakash, *J. Am. Chem. Soc.*, 2020, **142**, 4544–4549.
- 115 P. Tundo, M. Musolino and F. Aricò, *Green Chem.*, 2018, **20**, 28–85.
- 116 G. Fiorani, A. Perosa and M. Selva, *Green Chem.*, 2018, **20**, 288–322.
- 117 P. Tundo and M. Selva, *Acc. Chem. Res.*, 2002, **35**, 706–716.
- 118 B. Schöffner, F. Schöffner, S. P. Verevkin and A. Börner, *Chem. Rev.*, 2010, **110**, 4554–4581.
- 119 F. Aricò and P. Tundo, *Russ. Chem. Rev.*, 2010, **79**, 479–489.
- 120 M. A. Pacheco and C. L. Marshall, *Energy Fuels*, 1997, **11**, 2–29.
- 121 S. Hess, M. Wohlfahrt-Mehrens and M. Wachtler, *J. Electrochem. Soc.*, 2015, **162**, A3084–A3097.
- 122 B. A. V. Santos, V. M. T. M. Silva, J. M. Loureiro and A. E. Rodrigues, *ChemBioEng Rev.*, 2014, **1**, 214–229.
- 123 A. A. Chaugule, A. H. Tamboli and H. Kim, *Fuel*, 2017, **200**, 316–332.
- 124 A. H. Tamboli, A. A. Chaugule and H. Kim, *Chem. Eng. J.*, 2017, **323**, 530–544.
- 125 T. Baidya, A. Gayen, M. S. Hegde, N. Ravishankar and L. Dupont, *J. Phys. Chem. B*, 2006, **110**, 5262–5272.
- 126 G. Dutta, A. Gupta, U. V. Waghmare and M. S. Hegde, *J. Chem. Sci.*, 2011, **123**, 509–516.
- 127 T. Vinodkumar, D. N. Durgasri, S. Maloth and B. M. Reddy, *J. Chem. Sci.*, 2015, **127**, 1145–1153.
- 128 S. Wang, L. Zhao, W. Wang, Y. Zhao, G. Zhang, X. Ma and J. Gong, *Nanoscale*, 2013, **5**, 5582–5588.
- 129 Z. Li, W. Li, H. Abroshan, Q. Ge, G. Li and R. Jin, *Nanoscale*, 2018, **10**, 6558–6565.
- 130 X. Tong, T. Luo, X. Meng, H. Wu, J. Li, X. Liu, X. Ji, J. Wang, C. Chen and Z. Zhan, *Small*, 2015, **11**, 5581–5588.
- 131 S. Wang, J. Zhou, S. Zhao, Y. Zhao and X. Ma, *Chem. Eng. Technol.*, 2016, **39**, 723–729.
- 132 P. Kumar, V. C. Srivastava, R. Gläser, P. With and I. M. Mishra, *Powder Technol.*, 2017, **309**, 13–21.
- 133 K. Tomishige, Y. Furusawa, Y. Ikeda, M. Asadullah and K. Fujimoto, *Catal. Lett.*, 2001, **76**, 71–74.
- 134 K. Tomishige and K. Kunimori, *Appl. Catal., A*, 2002, **237**, 103–109.
- 135 X. Deng, M. Li, J. Zhang, X. Hu, J. Zheng, N. Zhang and B. H. Chen, *Chem. Eng. J.*, 2017, **313**, 544–555.
- 136 A. H. Tamboli, A. A. Chaugule, S. W. Gosavi and H. Kim, *Fuel*, 2018, **216**, 245–254.

- 137 B. Liu, C. Li, G. Zhang, X. Yao, S. S. C. Chuang and Z. Li, *ACS Catal.*, 2018, **8**, 10446–10456.
- 138 S. Huygh, A. Bogaerts and E. C. Neyts, *J. Phys. Chem. C*, 2016, **120**, 21659–21669.
- 139 S.-P. Wang, J.-J. Zhou, S.-Y. Zhao, Y.-J. Zhao and X.-B. Ma, *Chin. Chem. Lett.*, 2015, **26**, 1096–1100.
- 140 S. Watanabe, X. Ma and C. Song, *J. Phys. Chem. C*, 2009, **113**, 14249–14257.
- 141 Z. Fu, Y. Zhong, Y. Yu, L. Long, M. Xiao, D. Han, S. Wang and Y. Meng, *ACS Omega*, 2018, **3**, 198–207.
- 142 K. V. Wagh and B. M. Bhanage, *Green Chem.*, 2015, **17**, 4446–4451.
- 143 A. A. Pawar, D. Lee, W.-J. Chung and H. Kim, *Chem. Eng. J.*, 2020, **395**, 124970.
- 144 U. P and S. Darbha, *J. Chem. Sci.*, 2016, **128**, 957–965.
- 145 Y. Pu, K. Xuan, F. Wang, A. Li, N. Zhao and F. Xiao, *RSC Adv.*, 2018, **8**, 27216–27226.
- 146 Z.-F. Zhang, Z.-W. Liu, J. Lu and Z.-T. Liu, *Ind. Eng. Chem. Res.*, 2011, **50**, 1981–1988.
- 147 A. A. Chaugule, H. A. Bandhal, A. H. Tamboli, W.-J. Chung and H. Kim, *Catal. Commun.*, 2016, **75**, 87–91.
- 148 K. Tomishige, T. Sakaihorii, Y. Ikeda and K. Fujimoto, *Catal. Lett.*, 1999, **58**, 225–229.
- 149 B. Peng, H. Dou, H. Shi, E. E. Ember and J. A. Lercher, *Catal. Lett.*, 2018, **148**, 1914–1919.
- 150 K. W. La, M. H. Youn, J. S. Chung, S. H. Baeck and I. K. Song, *Solid State Phenom.*, 2007, **119**, 287–290.
- 151 K. W. La, J. C. Jung, H. Kim, S.-H. Baeck and I. K. Song, *J. Mol. Catal. A: Chem.*, 2007, **269**, 41–45.
- 152 H. Zhao, B. Lu, X. Li, W. Zhang, J. Zhao and Q. Cai, *J. CO<sub>2</sub> Util.*, 2015, **12**, 49–53.
- 153 M. O. Vieira, A. S. Aquino, M. K. Schütz, F. D. Vecchia, R. Ligabue, M. Seferin and S. Einloft, *Energy Procedia*, 2017, **114**, 7141–7149.
- 154 Q. Cai, B. Lu, L. Guo and Y. Shan, *Catal. Commun.*, 2009, **10**, 605–609.
- 155 D. Aymes, D. Ballivet-Tkatchenko, K. Jeyalakshmi, L. Saviot and S. Vasireddy, *Catal. Today*, 2009, **147**, 62–67.
- 156 P. Švec, H. Catey, Z. Růžičková, J. Holub, A. Růžička and L. Plasseraud, *New J. Chem.*, 2018, **42**, 8253–8260.
- 157 S. R. Sanapureddy and L. Plasseraud, *Appl. Organomet. Chem.*, 2017, **31**, e3807.
- 158 X. L. Wu, M. Xiao, Y. Z. Meng and Y. X. Lu, *J. Mol. Catal. A: Chem.*, 2005, **238**, 158–162.
- 159 J. Bian, M. Xiao, S.-J. Wang, Y.-X. Lu and Y.-Z. Meng, *Appl. Surf. Sci.*, 2009, **255**, 7188–7196.
- 160 J. Bian, M. Xiao, S. J. Wang, Y. X. Lu and Y. Z. Meng, *Catal. Commun.*, 2009, **10**, 1529–1533.
- 161 Y. Zhou, S. Wang, M. Xiao, D. Han, Y. Lu and Y. Meng, *RSC Adv.*, 2012, **2**, 6831–6837.
- 162 Y.-J. Zhou, M. Xiao, S.-J. Wang, D.-M. Han, Y.-X. Lu and Y.-Z. Meng, *Chin. Chem. Lett.*, 2013, **24**, 307–310.
- 163 T. Zhao, X. Hu, D. Wu, R. Li, G. Yang and Y. Wu, *ChemSusChem*, 2017, **10**, 2046–2052.
- 164 K. Tomishige, Y. Ikeda, T. Sakaihorii and K. Fujimoto, *J. Catal.*, 2000, **192**, 355–362.
- 165 K. T. Jung and A. T. Bell, *J. Catal.*, 2001, **204**, 339–347.
- 166 K. T. Jung and A. T. Bell, *Top. Catal.*, 2002, **20**, 97–105.
- 167 T. Akune, Y. Morita, S. Shirakawa, K. Katagiri and K. Inumaru, *Langmuir*, 2018, **34**, 23–29.
- 168 D. Han, Y. Chen, S. Wang, M. Xiao, Y. Lu and Y. Meng, *Catalysts*, 2018, **8**, 302.
- 169 D. Han, Y. Chen, S. Wang, M. Xiao, Y. Lu and Y. Meng, *Catalysts*, 2018, **8**, 343.
- 170 Y. Chen, Y. Yang, S. Tian, Z. Ye, Q. Tang, L. Ye and G. Li, *Appl. Catal., A*, 2019, **587**, 117275.
- 171 W. Sun, L. Zheng, Y. Wang, D. Li, Z. Liu, L. Wu, T. Fang and J. Wu, *Ind. Eng. Chem. Res.*, 2020, **59**, 4281–4290.
- 172 G. A. Olah, A. Goepfert and G. K. S. Prakash, *J. Org. Chem.*, 2009, **74**, 487–498.
- 173 A. Goepfert, M. Czaun, J.-P. Jones, G. K. S. Prakash and G. A. Olah, *Chem. Soc. Rev.*, 2014, **43**, 7995–8048.
- 174 J. Burger, E. Ströfer and H. Hasse, *Chem. Eng. Res. Des.*, 2013, **91**, 2648–2662.
- 175 S. P. Naik, T. Ryu, V. Bui, J. D. Miller, N. B. Drinnan and W. Zmierzczak, *Chem. Eng. J.*, 2011, **167**, 362–368.
- 176 Y. Fu and J. Shen, *Chem. Commun.*, 2007, 2172–2174.
- 177 N. T. Prado, F. G. E. Nogueira, A. E. Nogueira, C. A. Nunes, R. Diniz and L. C. A. Oliveira, *Energy Fuels*, 2010, **24**, 4793–4796.
- 178 M. Li, Y. Long, Z. Deng, H. Zhang, X. Yang and G. Wang, *Catal. Commun.*, 2015, **68**, 46–48.
- 179 W.-J. Shen, K.-W. Jun, H.-S. Choi and K.-W. Lee, *Korean J. Chem. Eng.*, 2000, **17**, 210–216.
- 180 M. V. Twigg and M. S. Spencer, *Appl. Catal., A*, 2001, **212**, 161–174.
- 181 R. Liu, H. Tian, A. Yang, F. Zha, J. Ding and Y. Chang, *Appl. Surf. Sci.*, 2015, **345**, 1–9.
- 182 T. Witoon, T. Permsirivanich, N. Kanjanasoonorn, C. Akkaraphataworn, A. Seubsai, K. Faungnawakij, C. Warakulwit, M. Chareonpanich and J. Limtrakul, *Catal. Sci. Technol.*, 2015, **5**, 2347–2357.
- 183 R. J. da Silva, A. F. Pimentel, R. S. Monteiro and C. J. A. Mota, *J. CO<sub>2</sub> Util.*, 2016, **15**, 83–88.
- 184 R. Chu, C. Song, W. Hou, X. Meng, Z. Miao, X. Li, G. Wu, Y. Wan and L. Bai, *J. Taiwan Inst. Chem. Eng.*, 2017, **80**, 1041–1047.
- 185 K. Thenert, K. Beydoun, J. Wiesenthal, W. Leitner and J. Klankermayer, *Angew. Chem., Int. Ed.*, 2016, **55**, 12266–12269.
- 186 B. G. Schieweck and J. Klankermayer, *Angew. Chem., Int. Ed.*, 2017, **56**, 10854–10857.
- 187 Q. Zhang, H. Zhao, B. Lu, J. Zhao and Q. Cai, *J. Mol. Catal. A: Chem.*, 2016, **421**, 117–121.
- 188 M. Siebert, M. Seibicke, A. F. Siegle, S. Krahl and O. Trapp, *J. Am. Chem. Soc.*, 2019, **141**, 334–341.
- 189 M. Seibicke, M. Siebert, A. F. Siegle, S. M. Gutenthaler and O. Trapp, *Organometallics*, 2019, **38**, 1809–1814.