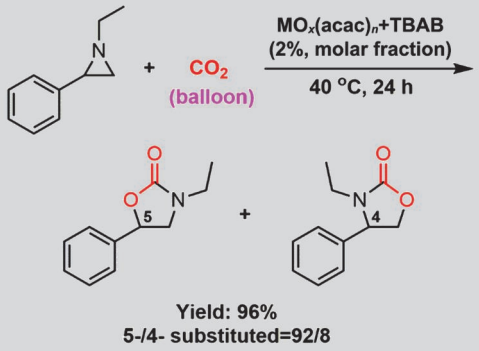
Article

Metal Acetylacetonates as Robust Catalysts for the Synthesis of Oxazolidinone from CO_2 and Aziridine Under Atmospheric Pressure

LI Bohan#, GONG Yujie#, LOU Huimin, WEI Yujuan, GUO Liping✉, WANG Hongmei, ZHANG Zulei and LI Lei✉

Received December 20, 2023
Accepted February 15, 2024
© Jilin University, The Editorial Department of Chemical Research in Chinese Universities and Springer-Verlag GmbH

Metal acetylacetonates, a type of readily synthesized or commercially available metal complex, were demonstrated to be robust catalysts for the synthesis of oxazolidinone from CO_2 and aziridine under condition of atmospheric pressure and mild temperature, exhibiting high chemo- and regio-selectivity. Tetrabutylammonium halides were employed as cocatalysts in the reaction, and it was believed that the reaction activity was influenced by a balance of anions' two abilities, namely their nucleophilicity in ring-opening of aziridines and their leaving capacity in ring-closing of intermediate carbamate salts to form oxazolidinones. Notably, higher nucleophilicity of these anions resulted in increased formation of dimers, which served as by-products of the reaction. The study of mechanism suggested that there should be an alternative pathway involving CO_2 derivative acting as a nucleophile during the ring-opening process, and this pathway could not be ignored when conventional nucleophiles, such as tetrabutylammonium halides are absent.



Keywords Metal acetylacetonate; Carbon dioxide; Aziridine; Oxazolidinone; Atmospheric pressure

1 Introduction

With the combustion of fossil fuels, the amount of carbon dioxide in the atmosphere has increased year by year. It was about 280 ppm (ppm=parts per million)[1] at the beginning of the Industrial Revolution (*ca*. Year 1750) and has risen to 423 ppm in June, 2023.[2] CO_2 is considered one of the primary gases responsible for the greenhouse effect.[3] On the other hand, CO_2 is an abundant, economical, non-toxic, and renewable C1 feedstock for organic synthesis. Therefore, CO_2 has recently garnered significant attention as an environmentally friendly raw material for synthesizing chemical compounds and fuels.[4−8]

Oxazolidinone is an important heterocyclic motif found in commercial pharmaceuticals[9], and it is also a widely used synthetic intermediate in organic synthesis.[10] Since its first synthesis in the 1950s, several routes have been developed for synthesizing oxazolidinone, employing phosgene,[11] carbonate salts,[12] carbamate derivatives or isocyanate,[13] or CO_2 (serves as the carboxyl moiety in oxazolidinone)[14−18] as raw material. Among them, the synthesis of oxazolidinone from CO_2 and aziridine is expected to be a promising approach for CO_2 utilization,[19] since CO_2 is used as C1 resource in this strategy, avoiding the use of phosgene and reactive derivatives of carbonic acid, and the atom economy of this reaction is 100%.

Up to now, some transition metal complexes,[20−24] metal salts,[25] organic salts (including simple organic salts, such as quaternary ammonium/phosphonium salts and functional organic salts),[26−29] various organics,[30−34] and some MOFs,[35−38] have been proven effective in catalyzing oxazolidinone synthesis from CO_2 and aziridine. However, given that CO_2 is a highly oxidized and stable molecule, high pressure and/or high temperature are generally required for its conversion.

As CO_2 utilization is not only a topic related to C1 resource, but also an environmental issue, it is important to consider whether more CO_2 is emitted than converted during its transformation process[39]. A harsh reaction

✉ GUO Liping
guolp@mail.zjxu.edu.cn
✉ LI Lei
lei.li@mail.zjxu.edu.cn
# These authors contributed equally to this work.
Jiaxing Key Laboratory of Molecular Recognition and Sensing, College of Biological, Chemical Sciences and Engineering, Jiaxing University, Jiaxing 314001, P. R. China

https://doi.org/10.1007/s40242-024-3253-z

condition is highly energy-consuming, resulting in high secondary emissions of CO_2. Therefore, reducing secondary CO_2 emissions during the process of CO_2 utilization should be given attention. One approach is to developing syntheses that (a) use simple catalytic systems and (b) take place under mild conditions (low temperature and pressure).[39] Fortunately, a few catalytic systems that work under mild conditions have been developed for this process[24,25]. However, there still remains ample room for further development, such as exploring simple catalytic systems or reducing catalyst usage.

Transition metal complexes, such as prophyrin[20,21] and salen metal complexes[22,23] showed relatively high catalytic activity for the reaction. The reaction was activated by the formation of the coordination bond between the nitrogen atom of aziridine and the metal center of complexes.[21,22] In "CO_2 catalyzed" processes, it is believed that the formation of a coordination bond between the metal center and CO_2 plays a crucial role.[23] Metal β-diketonate complexes, which have similar coordination structures to prophyrin and salen metal complexes have been studied for more than a century and are widely used in fundamental and applied chemistry and technology.[40] In particular, metal acetylacetonate [$MO_x(acac)_n$], the simplest metal β-diketonate complexes, are easily synthesized or commercially available. However, despite their ready availability and good chemical stability, their application to CO_2 chemical fixation remains insufficiently explored. In this work, we present the application of $MO_x(acac)_n$ to the synthesis of oxazolidinone from CO_2 and aziridine under atmospheric pressure.

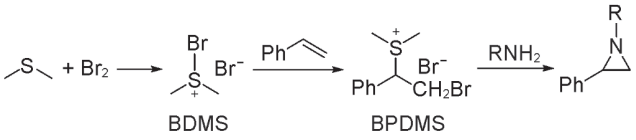
2 Experimental

2.1 General Information

The NMR spectra were recorded with a 400 MHz Varian spectrometer and calibrated with tetramethylsilane (TMS) as an internal reference. GC/MS analysis was performed on an Agilent 7890A gas chromatograph with an Agilent 5975C mass-selective detector. GC analysis was performed on an Agilent 6890 gas chromatograph with an HP-5 column and a flame ionization detector (FID). Reagents and starting materials were all used as received unless otherwise stated.

2.2 Synthesis of Aziridine

Aziridines were synthesized according to the literature[41] (Scheme 1), and a few changes were made, such as the synthesis of (2-bromo-1-phenylethyl)dimethylsulfonium bromide (BPMDS) from dimethyl sulfide and Br_2 was



Scheme 1 Synthesis of aziridine

operated in one-pot and thus the intermediate product bromodimethylsulfonium bromide(BDMS) was not separated out.

The typical procedure is desceribed as below. Br_2 (16.0 g, 0.1 mol) in 20 mL of CH_3CN was added dropwise over 30 min to a 20 mL of CH_3CN solution of dimethyl sulfide (6.2 g, 0.1 mol) in the ice-water bath. During the addition, BDMS was formed as a light orange precipitate (in preliminary experiments, this light orange solid was separated out and characterized by ^1H NMR and ^{13}C NMR, which confirmed that it was BDMS). After the mixture was stirred in the ice-water bath for another 30 min, styrene (11.4 g, 0.11 mol) was added to the mixture in the ice-water bath. The light orange precipitate disappeated for a moment and then the white precipitate of BPMDS started to be formed. After the mixture was stirred in the ice-water bath for 30 min, the product was filtered off, washed with CH_3CN and diethyl ether, respectively, and then dried under vacuum overnight to yield 13.3 g (40%) of a white powder. BDMS: ^1H NMR (400 MHz, D_2O), δ: 2.40 (d, J=1.6 Hz, 6H); ^{13}C NMR (101 MHz, D_2O), δ: 38.45. BPMDS: ^1H NMR (400 MHz, D_2O), δ: 7.52 (dd, J=27.0, 5.5 Hz, 5H), 5.19—5.07 (m, 1H), 4.24—4.10 (m, 2H), 2.87 (s, 3H), 2.59 (s, 3H); ^{13}C NMR (101 MHz, D_2O), δ: 131.11, 129.69, 129.42, 128.73, 60.63, 28.11, 24.19, 22.15.

Then BPMDS (3.26 g, 10 mmol) was dissolved in 20 mL of H_2O at r.t. (*ca.* 27 °C), the solution of amine (40 mmol) in 20 mL of H_2O was added dropwise to the above solution, and then the mixture was stirred overnight. The mixture was poured into 40 mL of saturated brine, extracted with diethyl ether (3×30 mL), and dried with $MgSO_4$. The solvent was removed under reduced pressure, and the colorless liquid was obtained.

1-Enthyl-2-phenylaziridine: colourless liquid, yield 96%. ^1H NMR (400 MHz, $CDCl_3$), δ: 7.35—6.97 (m, 5H), 2.41 (q, J=7.0 Hz, 2H), 2.27 (dd, J=6.1, 3.1 Hz, 1H), 1.87 (d, J=2.7 Hz, 1H), 1.62 (d, J=6.5 Hz, 1H), 1.17 (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$), δ: 140.43, 128.27, 126.80, 126.17, 55.89, 41.17, 37.59, 14.50.

1-Propyl-2-phenylaziridine: colourless liquid, yield 98%. ^1H NMR (400 MHz, $CDCl_3$), δ: 7.35—7.00 (m, 5H), 2.49 (d, J=11.4 Hz, 1H), 2.30 (dd, J=6.8, 4.2 Hz, 2H), 1.91 (d, J=2.7 Hz, 1H), 1.66—1.68 (m, 3H), 0.97 (t, J=7.4 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$), δ: 140.53, 128.28, 126.78, 126.20, 63.62, 41.26, 37.74, 23.07, 12.02.

https://doi.org/10.1007/s40242-024-3253-z

1-Butyl-2-phenylaziridine: colourless liquid, yield 98%. ^{1}H NMR (600 MHz, $CDCl_3$), δ: 7.18 (m, , 5H), 2.42 (d, J=11.5 Hz, 1H), 2.28—2.18 (m, 2H), 1.81 (d, J=3.0 Hz, 1H), 1.57 (d, J=6.5 Hz, 1H), 1.56—1.48 (m, 2H), 1.32 (dd, J=15.0, 7.4 Hz, 2H), 0.84 (t, J=7.4 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$), δ: 140.56, 128.28, 126.77, 126.19, 61.59, 41.28, 37.81, 32.02, 20.64, 14.16.

1-Cyclohexyl-2-phenylaziridine: colourless liquid, yield 83%. ^{1}H NMR (400 MHz, $CDCl_3$), δ: 7.35—7.08 (m, 5H), 2.36 (dd, J=6.3, 3.1 Hz, 1H), 1.85—1.10 (m, 13H); ^{13}C NMR (101 MHz, $CDCl_3$), δ: 140.70, 128.21, 126.68, 126.46, 69.72, 40.15, 35.94, 33.00, 32.33, 26.18, 24.89.

1-Ethyl-2-(*p*-tolyl)aziridine: colourless liquid, yield 97%. ^{1}H NMR (400 MHz, $CDCl_3$), δ: 7.14 (dd, J=16.7, 7.6 Hz, 4H), 2.44 (dd, J=11.3, 7.1 Hz, 2H), 2.39—2.23 (m, 4H), 1.89 (s, 1H), 1.63 (d, J=6.5 Hz, 1H), 1.21 (t, J=6.8 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$), δ: 137.41, 136.34, 128.97, 126.06, 55.91, 41.02, 37.45, 21.10, 14.51.

2.3 General Procedure for the Reaction of CO_2 with Aziridine

A typical procedure for the reaction of CO_2 with aziridine was carried out in a 5 mL glass vial with a magnetic stir bar. For a typical run, aziridine (2 mmol) and catalyst (appropriate amount) were introduced into the vial and the vial was vacuum-sealed and then purged with CO_2 3 times. The vial, which was connected to a balloon filled with CO_2 was then placed in a preheated metal heating module and allowed to stir (400 r/min) for a designated time frame. The product yields and selectivity were determined by GC analysis. Some typical crude products were analyzed by GC/MS and ^{1}H NMR to confirm the composition of the product.

3-Ethyl-5-phenyloxazolidin-2-one: ^{1}H NMR (400 MHz, $CDCl_3$), δ: 7.22—7.08 (m, 5H), 5.37 (t, J=8.0 Hz, 1H), 3.80 (t, J=8.6 Hz, 1H), 3.47—3.18 (m, 3H), 1.09 (t, J=7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$), δ: 157.74, 138.99, 128.97, 128.83, 125.60, 74.39, 51.69, 39.02, 12.62.

3-Ethyl-4-phenyloxazolidin-2-one: ^{1}H NMR (400 MHz, $CDCl_3$), δ: 7.34—7.23(m, 5H), 4.70 (t, J=7.2 Hz, 1H), 4.49 (t, J=8.6 Hz J= 1H), 3.98 (t, J=8.0 Hz 1H), 3.44—3.34 (m, 1H), 2.69—2.28 (m, 1H), 0.95 (t, J=7.1 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$), δ: 158.24, 138.04, 129.40, 129.19, 127.15, 69.95, 59.52, 37.01, 12.25.

3-Propyl-5-phenyloxazolidin-2-one: ^{1}H NMR (400 MHz, $CDCl_3$), δ: 7.39—7.08 (m, 5H), 5.40 (t, J=8.0 Hz, 1H), 3.82 (t, J=8.7 Hz, 1H), 3.34 (t, J=8.1 Hz, 1H), 3.29—3.12 (m, 2H), 1.63—1.49 (m, 2H), 0.88 (t, J=7.6 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$), δ: 157.84, 138.91, 128.74, 128.60, 125.40, 74.19, 51.98, 25.68, 20.42, 10.95.

3-Butyl-5-phenyloxazolidin-2-one: ^{1}H NMR (400 MHz, $CDCl_3$), δ: 7.35—7.20 (m, 5H), 5.42 (t, J=8.0 Hz, 1H), 3.84 (t, J=8.6 Hz, 1H), 3.36 (t, J=7.8 Hz, 1H), 3.32—3.15 (m, 2H), 1.50—1.43 (m, 2H), 1.33—1.23 (m, 2H), 0.89 (t, J=7.2 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$), δ: 157.43, 138.43, 128.74, 128.63, 125.40, 74.26, 52.01, 43.81, 29.25, 19.71, 13.60.

3-Cyclohexyl-5-phenyloxazolidin-2-one: ^{1}H NMR (400 MHz, $CDCl_3$), δ: 7.33—7.30 (m, 5H), 5.40 (t, J=8.4 Hz, 1H), 3.83(t, J=8.4 Hz, 1H), 3.68—3.64(m, 1H), 3.34 (t, J=8.0 Hz, 1H), 0.94—1.80 (m, 10H). ^{13}C NMR (101 MHz, $CDCl_3$), δ: 157.18, 139.15, 128.85, 128.68, 125.47, 74.40, 52.60, 48.34, 30.53, 30.08, 25.30.

3-Ethyl-5-p-tolyloxazolidin-2-one: ^{1}H NMR (400 MHz, $CDCl_3$), δ: 7.23—7.15 (m, 4H), 5.35 (t, J=7.3 Hz, 1H), 3.84 (t, J=8.0 Hz, 1H), 3.36—3.24 (m, 3H), 2.31 (s, 2H), 1.15(t, J=8.0 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$), δ: 157.87, 138.79, 136.05, 129.71, 125.77, 74.49, 51.79, 39.05, 21.28, 12.69.

3 Results and Discussion

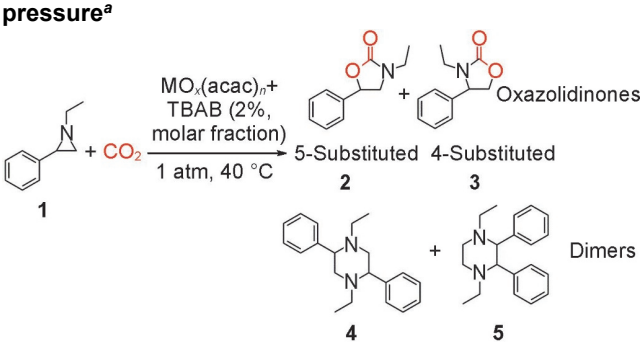
Initial reactions were performed with a series of commercially available $MO_x(acac)_n$ using 1-ethyl-2-phenylaziridine as the substrate and tetrabutylammonium bromide (TBAB) as cocatalyst. The reaction was carried out under the conditions of 1 atm of CO_2 and 40 °C for 24 h, and the catalyst loading was 2% (molar fraction, Table 1).

In general, the oxazolidinones obtained in the reaction consisted of two isomers, 5-substituted and 4-substituted oxazolidinones (Fig. 1). 5-Substituted oxazolidinone **2** accounted for the vast majority, rather than 4-substituted product **3**, the formation of which underwent the ring-opening of aziridine at the less substituted position. When the conversion of the substrate increased to a certain extent, the formation of dimers **4** and **5** of the substrate can be observed (Fig. 1).

When TBAB was used alone, only 11% yield of oxazolidinone was obtained, with 95:5 regioselectivity of 5-substituted to 4-substituted oxazolidinone (Table 1, entry 1). The addition of $Co(acac)_2$ had little effect on the reaction, resulting in an oxazolidinone yield of only 12% (Table 1, entry 2). Regarding the analogous synthesis of cyclic carbonate from CO_2 and epoxide,[42,43] the addition of $Co(acac)_2$ could greatly improve catalytic activity, as the yield of cyclic carbonate increased dramatically from 13% [catalyzed by 0.5% (molar fraction) TBAB alone] to 95% [catalyzed by 0.5% (molar fraction) $Co(acac)_2$+TBAB]. It was partially proved that the conversion of CO_2 with aziridine into oxazolidinone was more difficult than that with epoxide into cyclic carbonate. $Co(acac)_3$ and $Al(acac)_3$ had no apparent effect on promoting the reaction of CO_2 and aziridine either, and the yield of oxazolidinone remained at 13% and 11%, respectively (Table 1, entries 3 and 4). $Fe(acac)_2$, $Fe(acac)_3$, and $Ni(acac)_2$ could boost the reaction slightly, as the yields of oxazolidinone were 17%, 20%, and 24%,

https://doi.org/10.1007/s40242-024-3253-z

Table 1 $MO_x(acac)_n$ as catalyst for the synthesis of oxozolidnone from CO_2 and aziridine under atmospheric pressure[a]



Entry	$MO_x(acac)_n$	Conv.[b] (%)	Oxazolidone[b] Yield (%)	Regiosel.[c]	Dimers yield[b] (%)
1	/	11	11	95:5	0
2	$Co(acac)_2$	12	12	95:5	0
3	$Co(acac)_3$	13	13	95:5	0
4	$Al(acac)_3$	11	11	95:5	0
5	$Fe(acac)_2$	17	17	95:5	0
6	$Fe(acac)_3$	20	19	95:5	1
7	$Ni(acac)_2$	24	23	95:5	1
8	$Zn(acac)_2$	0	0	/	0
9	$Cd(acac)_2$	0	0	/	0
10	$La(acac)_3$	90	82	96:4	7
11	$MoO_2(acac)_2$	88	74	98:2	14
12	$VO(acac)_2$	91	78	98:2	12
13	$V(acac)_3$	95	86	97:3	9
14[d]	$V(acac)_3$	35	27	98:2	7

a. Reaction condition: 1-ethyl-2-phenyl-aziridine (2 mmol), $MO_x(acac)_n$ (0.04 mmol, 2%, molar fraction), TBAB (0.04 mmol, 2%, molar fraction), 1 atm (101325 Pa) of CO_2, 40 °C, 24 h; *b*. determined by GC; *c*. molar ratio of 5-substituted oxazolininone to 4-substituted oxazolidinone; *d*. $V(acac)_3$ for the reaction alone, without TBAB.

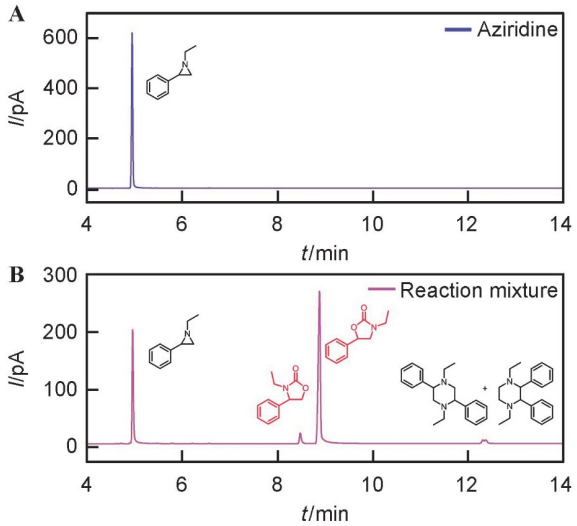


Fig.1 Typical GC spectra of aziridine (A) and the reaction mixture (B)

The substances corresponding to each peak were determined by GC-MS.

respectively, and 1% yield of dimers were formed in the latter two (Table 1, entries 5—7). Curiously, the addition of $Zn(acac)_2$ and $Cd(acac)_2$ did not improve the catalytic activity but inhibited the reaction as no product was generated (Table 1, entries 8 and 9). $La(acac)_3$ and $MoO_2(acac)_2$ showed high catalytic activities, with 90% and 88% of the substrates converted, respectively (Table 1, entries 10 and 11), and the regioselectivity increased, as the ratios of 5-substituted to 4-substituted oxazolidinone were 96:4 and 98:2, respectively. Meanwhile, with the large-scale conversion of substrate, the formation of by-product dimers also became glaringly obvious, the yields of which were 7% and 14%, respectively. The activities of $V(acac)_3$ and $VO(acac)_2$ were also examined, and both exhibited excellent performance (Table 1 entries 12 and 13). $V(acac)_3$ proved to be the optimal catalyst in this reaction condition, achieving 95% substrate conversion and 97:3 regioselectivity, with 9% dimers yield. When $V(acac)_3$ was employed for the reaction alone, 35% substrate conversion and 27% oxazolidinone yield were obtained, and compared to the catalytic activity of TBAB alone and $V(acac)_3$-TBAB, it can be concluded that $V(acac)_3$ and TBAB catalyzed the reaction synergistically.

The influences of tetrabutylammonium halide (TBAX) anions were then studied. The combination of tetrabutylammonium chloride (TBAC), TBAB, or tetrabutylammonium iodide (TBAI), with one of the better-performing complexes, $V(acac)_3$, $VO(acac)_2$, $La(acac)_3$, or $MoO_2(acac)_2$, was applied to the reaction, respectively (Table 2, entries 1—12). For comparison, their combination with the less active $Al(acac)_3$ and TBAX for the reaction alone has also been investigated (Table 2, entries 13—18). As we know, the anion of TBAX acts as a nucleophile in the ring-opening of aziridine and its nucleophilicity would affect its performance (Scheme 2). In most cases of the synthesis of cyclic carbonates from CO_2 and epoxides, the order of catalytic activity coincides with that of the nucleophilicity of anions, in the order of $I^->Br^->Cl^-$.[44] However, this was not the case here. In general, with the better-performing $MO_x(acac)_n$-TBAX, the aziridine conversions were not significantly altered and were all in the range of 85%—98%. Different combinations resulted in different activity orders. When combined with $V(acac)_3$ or $VO(acac)_2$, the conversions of aziridine varied in the order of $Cl^->Br^->I^-$, and while combined with $La(acac)_3$ or $MoO_2(acac)_2$, the lowest conversion appeared with TBAB. When $Al(acac)_3$-TBAX or TBAX alone catalyzed the reaction, the aziridine conversions varied in the order of $I^->Cl^->Br^-$.

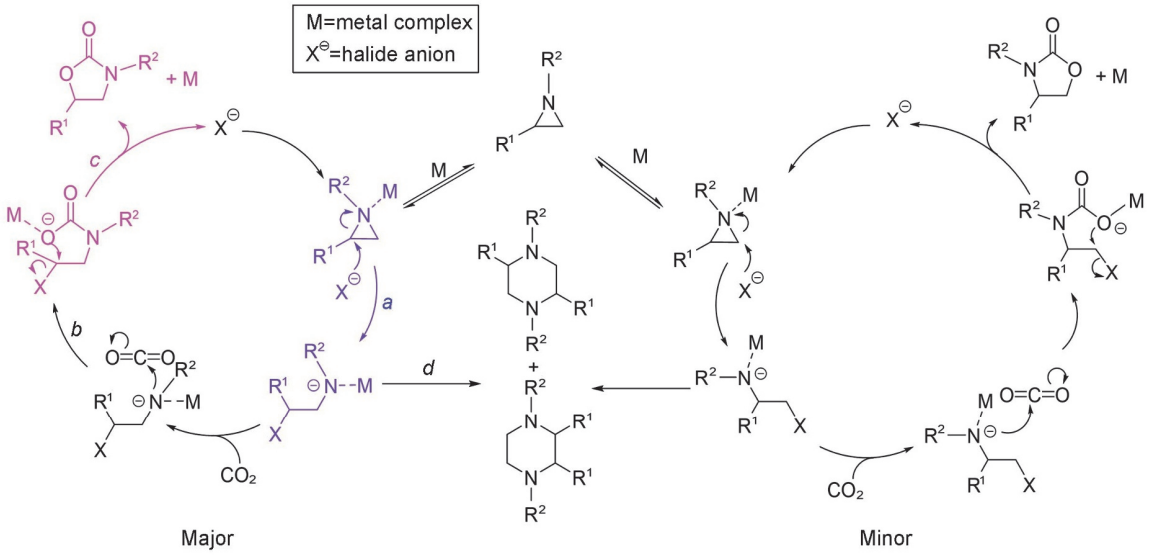
As shown in the proposed mechanism (Scheme 2), in the ring-opening step (Step *a*), X^- acted as a nucleophile to attack the C atom on the ternary ring, thereby causing the break of the C—N bond. So the order of reactivity in this step should be consistent with that of the nucleophilicity as $I^->Br^->Cl^-$.

https://doi.org/10.1007/s40242-024-3253-z

Table 2 Changing the anion of TBAX for the the synthesis of oxozolidnone from CO_2 and aziridine[a]

Entry	$MO_x(acac)_n$	Cocat.	Conv.[b] (%)	Oxazolidone[b]		Dimers yield[b] (%)
				Yield (%)	Regiosel.	
1	$V(acac)_3$	TBAC	98	96	92:8	2
2	$V(acac)_3$	TBAB	95	86	97:3	9
3	$V(acac)_3$	TBAI	85	62	98:2	23
4	$VO(acac)_2$	TBAC	97	93	92:8	4
5	$VO(acac)_2$	TBAB	91	78	98:2	12
6	$VO(acac)_2$	TBAI	88	64	98:2	24
7	$La(acac)_3$	TBAC	91	88	92:8	3
8	$La(acac)_3$	TBAB	90	82	96:4	7
9	$La(acac)_3$	TBAI	92	62	97:3	30
10	$MoO_2(acac)_2$	TBAC	99	96	91:9	2
11	$MoO_2(acac)_2$	TBAB	88	74	98:2	14
12	$MoO_2(acac)_2$	TBAI	96	54	98:2	42
13	$Al(acac)_3$	TBAC	15	15	95:5	0
14	$Al(acac)_3$	TBAB	11	11	95:5	0
15	$Al(acac)_3$	TBAI	26	22	97:3	4
16	/	TBAC	16	16	94:6	0
17	/	TBAB	11	11	95:5	0
18	/	TBAI	30	28	98:2	2

a. Reaction condition: 1-ethyl-2-phenyl-aziridine (2 mmol), $MO_x(acac)_n$ (0.04 mmol, 2%, molar fraction), TBAX (0.04 mmol, 2%, molar fraction), 1 atm (101325 Pa) of CO_2, 40 °C, 24 h; *b*. determined by GC.



Scheme 2 Proposed mechanism of reaction catalyzed by $MO_x(acac)_n$-TBAX

However, after the insertion of CO_2, it should undergo the ring-closing step of intermediate carbamate salt to form oxazolidinone (Step *c*). In this step, X^- departed from the intermediate, and thus the reactivity depended on the leaving capacity of X^-, which was in the order of Cl^->Br^-> I^-. Taking the above two factors into account, we believe that the overall reactivity was affected by two aspects of the properties of X^-: nucleophilicity and leaving capacity. Therefore, when TBAX was used alone, the catalytic activity of Br^- with moderate nucleophilicity and moderate leaving capacity was lower than that of I^- and Cl^-. The addition of better-performing $MO_x(acac)_n$ might amplify the influence of leaving capacity for the reaction, and as observed, almost TBAC showed the best catalytic activity among the three TBAXs (Table 2, entries 1, 4, 7, 10).

It is worth mentioning that the yields of dimers **4** and **5** gradually increased following the sequence of Cl^-<Br^-<I^-, resulting in a gradual decline in reaction selectivity (Table 2,

https://doi.org/10.1007/s40242-024-3253-z

entries 1—3, 4—6, 7—9, 10—12), and this phenomenon had rarely been adequately described in previous literature.[25,27] Take $V(acac)_3$ as an example, when TBAC, TBAB, or TBAI was employed as the cocatalyst for the reaction, the yields of dimers were 2%, 9%, and 23%, respectively (Table 2, entries 1—3). This value even rose to 42% when $MoO_2(acac)_2$-TBAI was employed as the catalyst, and while using $MoO_2(acac)_2$-TBAC, it was only 2%. It indicated that after the ring-opening of aziridine, two competitive reactions occurred: one being the insertion of CO_2 (Step *b*), and the other one being the formation of dimers (Step *d*). The generation of large amounts of dimers might be attributed to the rate gap between the ring-opening of aziridines and the insertion of CO_2, which was widened gradually following the order of nucleophilicity as in $Cl^-<Br^-<I^-$. When using TBAI, the rapid ring-opening reaction might lead to the accumulation of excess ring-opening products, and thus it was likely to form more dimers (Step *d*).

As to the regioselectivity of oxazolidinones in the product, the ratio of 5-substituted to 4-substituted oxazolidinone in the presence of TBAC was generally slightly lower than that in the presence of TBAB or TBAI. With the better-performing $MO_x(acac)_n$, the regioselectivity values were almost 92:8 and 98:2 in the presence of TBAC and TBAI, respectively, while the value obtained with TBAB was somewhere in between.

Due to its high substrate conversion and good selectivity, TBAC was selected as the cocatalyst for the following study. The Influences of reaction parameters, such as catalyst loading, reaction time and reaction temperature were then studied (Table 3).

As expected, with the reduction of catalyst loading, the substrate conversion decreased, but the reaction selectivity and oxazolidinone regioselectivity remained basically unchanged (Table 3, entries 1—3). When the proportion of catalyst was reduced to 0.5% (mass fraction), the conversion of substrate still reached 46% (Table 3, entry 3), indicating the high activity of this catalyst system.

The investigation of reaction performance with different time periods was conducted at 40 °C with 1% (molar fraction) catalyst loading (Table 3, entries 2, 4—6). With the extension of time, the conversion of substrate increased, accompanied by an increase in the amount of dimers, but the regioselectivity of oxazolidinones also remained unchanged.

The influence of reaction temperature was then studied (Table 3, entries 7—13). The aziridine can also be smoothly converted into oxazolidinones at 20 and 30 °C (Table 3, entries 7 and 8). The substrate conversion could still achieve 63%, when the reaction was carried out at 30 °C for 24 h with 2% (molar fraction) catalyst loading. Then the reaction temperature was gradually increased from 40 °C to 90 °C with 1% (molar fraction) catalyst loading and 8 h reaction time (Table 3, entries 4, 9—13). Higher temperatures led to higher substrate conversion, which were 92%, 96%, and 98% at 70, 80, and 90 °C, respectively. The temperature of 80 °C is believed to be already high enough under the current reaction condition, while the incremental benefits of further heating remain inconspicuous. The increase in reaction temperature had no effect on the formation of by-product dimers, but the regioselectivity of 5-oxazolidinone to 4-oxazolidinone decreased slightly, which was decreased gradually from 95:5 at 20 °C to 89:11 at 90 °C.

Table 3 Effect of reaction parameters for the synthesis of oxozolidnone from CO_2 and aziridine[a]

Entry	$MO_x(acac)_n$	Ratio of Cat. (%, mass fraction)	Temp./°C	Time/h	Conv.[b] (%)	Oxazolidone[b]		Dimers yield[b] (%)
						Yield (%)	Regiosel.	
1	$V(acac)_3$	2	40	24	98	96	92:8	2
2	$V(acac)_3$	1	40	24	75	72	92:8	3
3	$V(acac)_3$	0.5	40	24	46	44	92:8	2
4	$V(acac)_3$	1	40	8	18	18	92:8	0
5	$V(acac)_3$	1	40	12	31	31	93:7	0
6	$V(acac)_3$	1	40	18	51	50	92:8	1
7	$V(acac)_3$	2	20	24	23	22	95:5	1
8	$V(acac)_3$	2	30	24	63	61	93:7	2
9	$V(acac)_3$	1	50	8	52	52	91:9	0
10	$V(acac)_3$	1	60	8	65	64	90:10	1
11	$V(acac)_3$	1	70	8	92	90	90:10	2
12	$V(acac)_3$	1	80	8	96	93	90:10	2
13	$V(acac)_3$	1	90	8	98	96	89:11	2
14	$VO(acac)_2$	1	80	8	99	98	91:9	1
15	$MoO_2(acac)_2$	1	80	8	95	90	91:9	5

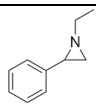
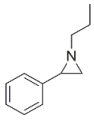
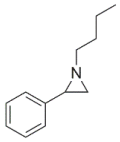
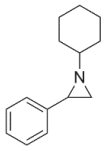
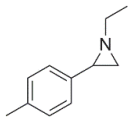
a. Reaction condition: 1-ethyl-2-phenyl-aziridine (2 mmol), 1 atm of CO_2, catslyst system: $MO_x(acac)_n$+TBAC; *b*. determined by GC.

https://doi.org/10.1007/s40242-024-3253-z

The catalytic activities of $VO(acac)_2$-TBAC and $MoO_2(acac)_2$-TBAC at 80 °C were also investigated under the same reaction condition mentioned above. $VO(acac)_2$-TBAC showed excellent performance here, with 99% aziridine conversion, 98% oxazolidinones yield, and 91:9 oxazolidinone regioselectivity (Table 3, entry 14). With $MoO_2(acac)_2$-TBAC, 95% aziridine conversion, 90% oxazolidinones yield, and 91:9 oxazolidinone regioselectivity were obtained (Table 3, entry 15).

The effects of substituents on the nitrogen atom and 2-carbon atom of aziridine have been systematically described in some literature.[22,29,31,34] Here we implemented a small range of substrate extensions. As shown in Table 4, the reactivity decreased with the increase in alkyl chain length from two to four on the nitrogen atom (Table 4, entries 1—3).

Table 4 Conversion of CO_2 with various aziridines[a]

Entry	Substrate	Conv.[b] (%)	Oxazolidone[b]		Dimers yield[b] (%)
			Yield (%)	Regiosel.	
1		69	67	92:8	2
2		57	56	93:7	1
3		42	41	98:2	<1
4		96	95	100:0	1
5		95	94	97:3	<1

a. Reaction condition: aziridine (2 mmol), $VO(acac)_2$ (0.02 mmol, 1%, molar fraction), TBAC (0.02mmol, 1%, molar fraction), 1 atm (101325 Pa) of CO_2, 40 °C, 24 h; *b*. determined by GC.

The steric hindrance caused by substituents on the nitrogen atom led to higher regioselectivity (Table 4, entries 1—4), as 100:0 oxazolidinone regioselectivity was obtained by replacing the linear alkyl groups with cyclohexyl group (Table 4, entry 4). Also, in this case, the conversion of aziridine was as high as 96% with 95% yield of oxazolidinone (Table 4, entry 4). When the phenyl group at the 2-position of the aziridine was replaced by *p*-tolyl group, the conversion of aziridine was enhanced from 69% to 95% (Table 4, entries 1 and 5), and it might contribute to the electron-donating effect of methyl on the *p*-position of the aryl ring, which had been discussed comprehensively through the Hammett correlation of reaction rates for aziridine substrate with electron-donating and -withdrawing groups at the *p*-position of the aryl ring.[23]

Although the presence of TBAI, leading to more dimers, was not beneficial to the reaction, it gave us the chance to investigate the ring-opening step of aziridine by demonstrating its existence. Therefore, reactions in the presence of TBAI under various conditions were investigated and the results are shown in Table 5. The reactions were firstly carried out at 40 °C for 24 h with 2% (mass fraction) catalyst loading (Table 5, entries 1—4). As mentioned above, dimers appeared in the product mixture catalyzed by $V(acac)_3$-TBAI and TBAI alone, for which the yields of dimers were 23% with 62% oxazolidinones yield, and 2% with 28% oxazolidinone yield, respectively (Table 5, entries 1 and 2). We assumed that if the reaction was carried out without CO_2, only dimers would be produced, without any oxazolidinones, since, after the ring-opening of the ternary ring (Scheme 2, Step *a*), the insertion of CO_2 (Scheme 2, Step *b*) could not occur without CO_2, thus the formation of dimers (Scheme 2, Step *d*) would be the unique route. Therefore, CO_2 was replaced by N_2 with TBAI as catalyst alone, and as expected only dimers were generated (Table 5, entry 3).

In addition, it was shown that the conversion of the substrate with CO_2 (the conversion of the substrate was 30%) was significantly higher than that with N_2 (the conversion of the substrate was 1%), which indicated that CO_2 might

Table 5 Reactions for mechanism study[a]

Entry	Cat.	Gas	Ratio. of Cat. (%, molar fraction)	Temp./°C	Time/h	Conv.[b] (%)	Oxazolidone[b]		Dimers yield[b] (%)
							Yield (%)	Regiosel.	
1	$V(acac)_3$+TBAI	CO_2	2	40	24	85	62	98:2	23
2	TBAI	CO_2	2	40	24	30	28	98:2	2
3	TBAI	N_2	2	40	24	1	0	/	1
4	/	CO_2	/	40	24	3	3	94:6	0
5	TBAI	CO_2	1	80	6	40	16	98:2	24
6	TBAI	N_2	1	80	6	14	0	/	14
7	/	CO_2	/	80	6	5	4	97:3	1

a. Reaction Conditions: 1-ethyl-2-phenyl-aziridine (2 mmol), 1 atm (101325 Pa) of CO_2; *b*. determined by GC.

https://doi.org/10.1007/s40242-024-3253-z

promote the ring-opening of aziridine. So we continued to investigate the reaction performance without any auxiliary catalysts, only CO_2 and aziridine were added to the vial, and 3% of the aziridine was converted to oxazolidinones (Table 5, entry 4). Since 1% and 3% were small data, in order to rule out the possibility of experimental accidents or errors, the reaction condition was set to 80 °C, 6 h, and 1% (molar fraction) catalyst loading to expand the progress of the reaction (Table 5, entries 5—7). Similar trends were observed. When the reaction was carried out with TBAI and CO_2, 40% conversion of aziridine with 16% yield of oxazolidinones was obtained, and while CO_2 was replaced by N_2, 14% aziridine was converted and all the products were dimers. In the absence of any catalysts, CO_2 itself could promote the reaction, producing 4% yield of oxazolidinones and 1% yield of dimers. Catalyst-free reactions had been reported in some literature,[45−47] and Dou *et al*.[47] suggested that CO_2-derived nucleophiles in the form of the zwitterionic adduct from CO_2 and aziridine induced the ring-opening of aziridine. And as we know, CO_2 played a similar role in reactions catalyzed by the CO_2 adduct of carbenes.[32,33] Metal complexes could also assist CO_2 in the ring-opening process,[23] and a derivative from CO_2, metal complex and aziridine was thought to be formed to facilitate the ring-opening of aziridine. In our reaction, $V(acac)_3$ alone could also facilitate the formation of oxazolidinones (Table 1, entry 14), possibly because CO_2 derivative acted as a nucleophile.

Therefore, the proposed mechanism of the $MO_x(acac)_n$-TBAX-catalyzed reaction was shown in Scheme 2. Based on the above results and relevant descriptions in the literature,[21,22,32,33,47] we believed that besides this pathway of using X^- as a nucleophile, there should be another pathway using CO_2 in derived form as a nucleophile. Since the nucleophilicity of X^- was obviously stronger than that of CO_2 derivative, when X^- was present, the ring-opening of aziridine was mainly promoted by X^-, and while X^- was absent, the nucleophilic ring-opening caused by CO_2 derivative could not be ignored.

4 Conclusions

In summary, $MO_x(acac)_n$ was demonstrated to be highly effective with TBAX for the synthesis of oxazolidinone from CO_2 and aziridine under conditions of atmospheric pressure and mild temperature. The produced oxazolidines consisted of two isomers, 5-substituted (major) and 4-substituted (minor) oxazolidinone, and dimers of aziridine as by-products were formed in some cases. The anion X^- of TBAX affected the reaction performance, especially the formation of dimers. It was believed that overall reaction activity was influenced by a balance of two abilities of anions: the nucleophilicity of X^- in the ring-opening of aziridine as in the order of $I^->Br^->Cl^-$, and their leaving capacity in the ring-closing of intermediate carbamate salt as in the order of $Cl^->Br^->I^-$. Meanwhile, the higher the nucleophilicity of anions, the more the dimers of aziridines formed. This might be contributed to the rate gap between the ring-opening of aziridines and the insertion of CO_2, which was widened gradually following the order of nucleophilicity as in $Cl^-<Br^-<I^-$. Reaction parameters, such as catalyst loading, reaction time, and temperature were studied. When the reaction was carried out at 80 °C with 1% (molar fraction) $VO(acac)_2$-TBAC for 8 h, 99% conversion of aziridine and 98% yield of oxazolidinones with 91:9 5-substituted to 4-substituted oxazolidinone were obtained.

The formation of dimers was a competitive reaction for the synthesis of oxazolidinone, and when CO_2 was replaced by N_2, the products were all dimers without any oxazolidinone. At the same time, it was observed that the reactivity in N_2 atmosphere was lower than that in CO_2 atmosphere, indicating that CO_2 could promote the reaction. Thus the reaction was further carried out without any catalyst, and the oxazolidinones were still obtained from CO_2 and aziridine. This suggested that there should be an alternative pathway, in which CO_2 derivative acted as a nucleophile in the ring-opening step of aziridine, and the reaction caused by this pathway could not be ignored when conventional nucleophiles, such as TBAX were absent. More dynamic details are being studied.

Acknowledgements

This work was supported by the Program for Public Technology of Jiaxing Province, China (No. 2023AD11041), the Natural Science Foundation of Zhejiang Province, China (No. LY22E020009), the National Undergraduate Training Programs for Innovation of China (No. 202110354038) and the Student Research Training Program of Jiaxing University, China (No. 8517231462).

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Lindsey R., *Climate Change: Atmospheric Carbon Dioxide*, https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide (accessed 25/07/2023).
[2] Global Monitoring Laboratory, *Trends in Atmospheric Carbon Dioxide*, https://www.esrl.noaa.gov/gmd/ccgg/trends (accessed 25/07/2023).
[3] Zahasky C., Krevor S., *Energ. Environ. Sci.*, **2020**, *13*, 1561
[4] Burkart M., Hazari D. N., Tway C. L., Zeitler E. L., *Acs Catal.*, **2019**, *9*, 7937.
[5] Wang L., Qi C. R., Xiong W. F., Jiang H. F., *Chin. J. Catal.*, **2022**, *43*, 1598.
[6] Zhang Z., Deng Y., Zhang Q. F., Yu D. G., *Chem. J. Chinese Universities*, **2022**, *43*, 20220255.
[7] Zhou C., Li M., Yu J. T., Sun S., Cheng J., *Chin. J. Org. Chem.,*

2020, *40*, 2221.
[8] Ran C. K., Xiao H. Z., Liao L. L., Ju T., Zhang W., Yu D. G., *Natl. Sci. Open*, **2023**, *2*, 20220024.
[9] Foti C., Piperno A., Scala A., Giuffre O., *Molecules*, **2021**, *26*, 4280.
[10] Pons A., Delion L., Poisson T., Charette A. B., Jubault P., *Acc. Chem. Res.,* **2021**, *54*, 2969.
[11] Cannizzaro C. E., Ashley J. A., Janda K. D., Houk K. N., *J. Am. Chem. Soc.,* **2003**, *125*, 2489.
[12] Fournier A. H., Robillard G., Devillers C. H., Plasseraud L., Andrieu J., *Eur. J. Org. Chem.,* **2016**, *21*, 3514.
[13] Zhu H. T., Chen P. H., Liu G. S., *J. Am. Chem. Soc.,* **2014**, *136*, 1766.
[14] Liu X. F., Wang M. Y., He L. N., *Curr. Org. Chem.,* **2017**, *21*, 698.
[15] Ye J. H., Ju T., Huang H., Liao L. L., Yu D. G., *Acc. Chem. Res.*, **2021**, *54*, 2518.
[16] Ye J. H., Song L., Zhou W. J., Ju T., Yin Z. B., Yan S. S., Zhang Z., Li J., Yu D. G., *Angew. Chem. Int. Ed.*, **2016**, *55*, 10022.
[17] Zhang Z., Ye J. H., Wu D. S., Zhou Y. Q., Yu D. G., *Chem. Asian J.*, **2018**, *13*, 2292.
[18] Zhu X. Y., Ran C. K., Wen M., Guo G. L., Liu Y., Liao L. L., Li Y. Z., Li M. L., Yu D. G., *Chin. J. Chem.*, **2021**, *39*, 3231.
[19] Arshadi S., Banaei A., Ebrahimiasl S., Monfared A., Vessally E., *RSC Adv.,* **2019**, *9*, 19465.
[20] Chen Y. J., Ren Q. G., Zeng X. J., Tao L. M., Zhou X. T., Ji H. B., *Chem. Eng. Sci.,* **2021**, *232*, 116380.
[21] Chen Y. J., Luo R. C., Yang Z., Zhou X. T., Ji H. B., *Sustain. Energ. Fuels*, **2018**, *2*, 125.
[22] Sengoden M., North M., Whitwood A. C., *Chemsuschem.*, **2019**, *12*, 3296.
[23] Adhikari D., Miller A. W., Baik M.-H., Nguyen S. T., *Chem. Sci.,* **2015**, *6*, 1293.
[24] Xie Y., Lu C., Zhao B., Wang Q., Yao Y., *J. Org. Chem.,* **2019**, *84*, 1951.
[25] Bresciani G., Zacchini S., Marchetti F., Pampaloni G., *Dalton Trans.,* **2021**, *50*, 5351.
[26] Wang T., Mu Z., Ding X., Han B., *Chem. Res. Chinese Universities*, **2022**, *38*, 446.
[27] Bresciani G., Bortoluzzi M., Pampaloni G., Marchetti F., *Org. Bio. Chem.,* **2021**, *19*, 4152.
[28] Zhao Y. N., Yang Z. Z., Luo S. H., He L. N., *Catal. Today.*, **2013**, *200*, 2.
[29] Yang Z. Z., He L. N., Peng S. Y., Liu A. H., *Green Chem.,* **2010**, *12*, 1850.
[30] Damiano C., Sonzini P., Manca G., Gallo E., *Eur. J. Org. Chem.,* **2021**, *19*,2807.
[31] Sonzini P., Damiano C., Intrieri D., Manca G., Gallo E., *Adv. Synth. Catal.,* **2020**, *362*, 2961.
[32] Ueno A., Kayaki Y., Ikariya T., *Green Chem.,* **2013**, *15*, 425.
[33] Liu A. H., Dang Y. L., Zhou H., Zhang J. J., Lu X. B., *Chemcatchem.*, **2018**, *10*, 2686.
[34] Du Y., Wu Y., Liu A. H., He L. N., *J. Org. Chem.,* **2008**, *73*, 4709.
[35] Helal A., Fettouhi M., Arafat M. E., Khan M. Y., Sanhoob M. A., *J. CO_2 Util.,* **2021**, *50*, 101603.
[36] Liu A. G., Chen Y., Liu P. D., Qi W., Li B., *Inorg. Chem. Front.,* **2022**, *9*, 4425.
[37] Wang X., Gao W. Y., Niu Z., Wojtas L., Perman J. A., Chen Y. S., Li Z., Aguila B., Ma S. Q., *Chem. Commun.,* **2018**, *54*, 1170.
[38] Shi Y., Zhao J., Xu H., Hou S.L., Zhao B., *Sci. China Chem.*, **2021**, *64*, 1316.
[39] Aresta M., Dibenedetto A., Angelini A., *Chem. Rev.,* **2014**, *114*, 1709.
[40] Vigato R. A., Peruzzo V., Tamburini S., *Coord. Chem. Rev.,* **2009**, *253*, 1099.
[41] Yang Z. Z., Li Y. N., Wei Y. Y., He L. N., *Green Chem.,* **2011**, *13*, 2351.
[42] Wang H. M., Zhang Z. L., Wang H. L., Guo L. P., Li L., *Dalton Trans.,* **2019**, *48*, 15970.
[43] Kumar S., Jain S. L., Sain B., *Catal. Lett.*, **2012**, *142*, 615.
[44] Guo L. P., Lamb K. J., North M., *Green Chem.,* **2021**, *23*, 77.
[45] Phung C., Ulrich R. M., Ibrahim M., Tighe N. T. G., Lieberman D. L., Pinhas A. R., *Green Chem.,* **2011**, *13*, 3224.
[46] Phung C., Tantillo D. J., Hein J. E., Pinhas A. R., *J. Phys. Org. Chem.,* **2018**, *31*, e3735.
[47] Dou X. Y., He L. N., Yang Z. Z., Wang J. L., *Synlett.*, **2010**, *14*, 2159.

https://doi.org/10.1007/s40242-024-3253-z