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# Ionic liquid-mediated catalytic oxidation of $\beta$ -caryophyllene by ultrathin 2D metal-organic framework nanosheets under 1 atm $O_2$

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# ABSTRACT

An ionic liquid (IL)-mediated facile method was established for the epoxidation of  $\beta$ -caryophyllene with molecular oxygen using ultrathin (~3–6 nm) 2D Cu-, Co- or Ce-based MOF nanosheets. Under the optimum conditions, high selectivity (92.4%) and excellent yield (86.7%) for  $\beta$ -caryophyllene epoxide were obtained over ultrathin (~5.5 nm) **Cu-TCPP** nanosheets (**TCPP** = tetrakis(4-carboxyphenyl)porphyrin) with the aid of [C<sub>12</sub>mim]Cl at 313 K and 1 atm O<sub>2</sub>. Notably, a small amount of [C<sub>12</sub>mim]Cl (1-dodecyl-3-methylimidazolium chloride, 5.0 mol %) played pivotal roles in forming a favorable microenvironment *in-situ*, thus significantly improving the catalytic performances of above-mentioned **Cu-TCPP** nanosheets containing PVP stabilizer. Moreover, ultrathin **Cu-TCPP** nanosheets showed better stability during  $\beta$ -caryophyllene transformation in the presence of amphiphilic [C<sub>12</sub>mim]Cl, as supported by TEM and XRD analyses. Importantly, the addition of TBHP (*tert*-butyl hydroperoxide, 13.0 mol %) initiator is also crucial for the aerobic oxidation of  $\beta$ -caryophyllene *via* **Cu-TCPP** nanosheets/[C<sub>12</sub>mim]Cl/TBHP/O<sub>2</sub> nanosystem. Further insights into the synergistic effects and free radical mechanism were achieved by fluorescence, DRUV-Vis, UV-vis and XPS measurements.

# 1. Introduction

Transformation of terpenes is an important strategy in the modern synthesis of natural products and key intermediates owing to their relatively low cost, renewability and convenience [1,2]. Particularly,  $\beta$ -carvophyllene is one of the most abundant bicyclic sesquiterpene presented in different plants derivatives such as copaiba oil [3], S. odoratissima essential oil [4] and heavy turpentine [5]. As a result, a series of value-added epoxide, alcohol, acid or ester compounds can be readily obtained from  $\beta$ -caryophyllene [3,6,7]. Among them,  $\beta$ -caryophyllene epoxide that exhibits significant anticancer. anti-inflammatory and repellent activities [8,9] has been used in the food industry and in the preparation of a variety of valuable products [7, 10,11]. Therefore, numerous methods for  $\beta$ -caryophyllene epoxidation have been explored employing *m*-CPBA or  $H_2O_2$  as the oxidant in the presence of Vilsmeier reagent (N-methylpyrrolidone with POCl<sub>3</sub>), peroxyphosphotungstomolybdate cetylpyridinium (Cat-PMo<sub>2</sub>W<sub>2</sub>O<sub>24</sub>), supported Eco-Mn<sub>OX3</sub> catalyst, or lipases [12-15].

Metal-organic frameworks (MOFs) have attracted special attention in heterogeneous catalysis due to their fascinating features such as extraordinarily high surface area, tailorable structure or morphology, and facile separation [16–19]. Recently, Hatton et al. investigated the oxidation of  $\beta$ -caryophyllene with H<sub>2</sub>O<sub>2</sub> utilizing hybrid material like chromium(III) terephthalate (MIL101)/phosphotungstic acid (PTA) and  $\beta$ -caryophyllene epoxide was afforded in high yield [20].

Compared with bulk MOF materials, ultrathin two-dimensional (2D) MOF-based nanocatalysts have garnered greater interest owing to the intriguing merits including more accessible active sites and shorter diffusion length [21,22]. Consequently, single-layered (~1 nm) 4-mer-captopyridine-stabilized Zn<sub>2</sub>(PdTCPP) MOF nanosheets [23], functional Fe<sup>II</sup>-metal-organic layers (MOLs) (~1.4 nm in thickness) [24], ultrathin Zr-porphyrinic MOF nanosheets (~1.5 nm) [25], NUS-8 (Zr) MOF nanosheets (~3 nm) [26], Au NPs/Cu-TCPP(Co) hybrid nanosheets (~3.5 nm) [27], Pt NPs embedded MOF nanosheets (i.e. Pt@NiNSMOFs, ~3.7 nm) [28], Co-TCPP(Fe) nanosheets (~5.6 nm) [29], etc., have been developed for selective transformations. Furthermore, O<sub>2</sub> is an

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Fig. 1. TEM (A) and SEM (B) images of Cu-TCPP nanosheets; AFM image and corresponding height profile of Cu-TCPP nanosheets (C); TEM image of bulk Cu-TCPP (D); XRD patterns (E) and FT-IR spectra of Cu-MOFs (F).

ideal oxidant from the economic and environmental viewpoints [30]. However, the facile and highly efficient epoxidation of  $\beta$ -caryophyllene with O<sub>2</sub> over ultrathin 2D MOF nanosheets has been rarely reported.

Cu-, Co- or Ce-based nanomaterials can mimic natural enzymes and many related MOFs have therefore been studied in a series of aerobic oxidation processes [31–34]. However, it is still a challenge to achieve perfect stability and catalytic activity when using pristine MOFs [35,36]. Ionic liquids (ILs) have demonstrated their crucial roles in biomass conversion reactions [37,38] and nanocatalysis [39,40]. Herein, ultrathin 2D Cu-, Co- or Ce-based MOF nanosheets were fabricated and conveniently used for the IL-assisted conversion of  $\beta$ -caryophyllene with molecular oxygen under mild conditions. Impressively, the unique **Cu-TCPP** nanosheets/[C<sub>12</sub>mim]Cl/TBHP/O<sub>2</sub> synergistic system was found to be especially efficient during the catalytic epoxidation of  $\beta$ -caryophyllene at 313 K under 1 atm O<sub>2</sub>, which may open a new and facile avenue for **Cu-TCPP** nanosheets-based biomimetic oxidations. In particular, possible free radical mechanism was proposed and validated by fluorescence and other spectral methods.

#### 2. Experimental section

# 2.1. Materials

 $[C_4mim][HSO_4]$ ,  $[C_4mim]_2CO_3$  and amino acid ionic liquids like  $[C_4mim][Ala]$ ,  $[C_4mim][Cys]$  and  $[C_4mim][Pro]$  were prepared as previously described [37].  $\beta$ -Caryophyllene and other commercially available chemicals were used without further purification.

# 2.2. Instrumentation

FT-IR spectra of catalysts were collected on a NEXUS spectrometer. Thermogravimetric (TG) analysis was performed using a Netzch STA 409PC instrument (Germany). BET surface area and other textural properties were determined by  $N_2$  adsorption-desorption method at 77 K

on a Micromeritics TriStar 3000 apparatus. Diffuse reflectance UV-vis (DRUV-vis) and UV-vis spectra were recorded by a Hitachi UV-3310 or a Shimadzu UV-2450 spectrophotometer, respectively. Fluorescence measurement was performed on a Hitachi F-7000 fluorometer (Japan). Transmission electron microscopy (TEM) image was obtained on a JEM-2100 instrument (JEOL, Japan) operated at 200 kV. Field Emission Scanning Electron Microscope (FESEM) measurement was carried out with Nova NanoSEM230. Atomic force microscopy (AFM) images were acquired with a NanoManVS instrument. XPS was carried out on an Xray photoelectron spectrometry (ESCALAB 250Xi, ThermoVG Scientific) using monochromated Al Ka excitation. XRD data were collected by a Y-2000 diffractometer (Cu K $\alpha$  radiation,  $\lambda = 0.154178$  nm) in the 2 $\theta$  range from 5° to 40°. Gas chromatography analysis was performed using GC-2010plus equipped with a DB-17 (30 m  $\times$  0.32 mm  $\times$  0.50 µm) column. Mass spectra were measured by an America Varian Saturn 2100 T GC-MS spectrometer.

# 2.3. Synthesis of Cu-, Co- and Ce-MOF nanosheets

**Cu-TCPP** nanosheets could be synthesized following a reported procedure with minor modifications [41]. Typically, 24.0 mg (0.099 mmol) Cu(NO<sub>3</sub>)<sub>2</sub>·3H<sub>2</sub>O, 100  $\mu$ L CF<sub>3</sub>COOH (1.0 M) and 100 mg PVP (polyvinylpyrrolidone) were mixed with DMF (30 mL) and EtOH (10 mL) in a 100 mL Teflon-lined stainless-steel autoclave. Then, 44.0 mg (0.056 mmol) TCPP dissolved in a mixture of DMF (15 mL) and ethanol (5 mL) was added dropwise into the aforementioned solution under stirring and then heated at 353 K for 7 h. The resulting **Cu-TCPP** nanosheets were washed twice with EtOH and collected by centrifugation. Finally, the product was obtained after drying under vacuum at 333 K for 12 h.

**M-TCPP** nanosheets (M = Co and Ce) were prepared by a modified method reported in the literature [41–43]. Briefly, Co(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O (8.8 mg, 0.03 mmol), CF<sub>3</sub>COOH (30  $\mu$ L, 1.0 M) and PVP (40.0 mg) in 24 mL of the mixture of DMF and EtOH (v:v = 3:1) were dissolved in a 50 mL



Fig. 2. TEM image (A), AFM image and corresponding height profile of Co-TCPP nanosheets (B); TEM image of bulk Co-TCPP (C); TEM image (D), AFM image and corresponding height profile of Ce-TCPP nanosheets (E); TEM image of bulk Ce-TCPP (F).

Teflon-lined stainless-steel autoclave. Then TCPP (8.0 mg, 0.01 mmol) dissolved in 8 mL of the mixture of DMF and EtOH (v:v = 3:1) was added dropwise under stirring. After that, the solution was sonicated for 20 min. The mixture was heated to 353 K and kept at the temperature for 30 h. The resulting **Co-TCPP** nanosheets were washed twice with EtOH, centrifuged, and finally collected after drying under vacuum at 333 K for 12 h.

Similarily, Ce(NO<sub>3</sub>)<sub>3</sub>·6H<sub>2</sub>O (13.0 mg, 0.03 mmol), CF<sub>3</sub>COOH (30 µL, 1.0 M) and PVP (40.0 mg) in 24 mL of the mixture of DMF and EtOH (v:v = 3:1) were dissolved in a 50 mL Teflon-lined stainless-steel autoclave. Then TCPP (8.0 mg, 0.01 mmol) dissolved in 8 mL of the mixture of DMF and EtOH (v:v = 3:1) was added dropwise under stirring. After that, the solution was sonicated for 20 min. The mixture was heated to 353 K and kept at the temperature for 30 h. The resulting **Ce-TCPP** nanosheets were washed twice with EtOH, centrifuged at 8000 rpm for 10 min, and finally collected after drying under vacuum at 333 K for 12 h.

### 2.4. Synthesis of bulk Cu-, Co- and Ce-MOFs

Bulk **M-TCPP** MOFs (M = Cu, Co and Ce) were synthesized according to ref [41]. Some details about the preparation and characterization of catalysts are described in the Supporting information.

### 2.5. Catalytic reaction

The oxidation of  $\beta$ -caryophyllene was carried out in a 10 mL threenecked flask and 1 atm O<sub>2</sub> was supplied continuously by a commonly used water-seal system [44]. In a typical procedure, appropriate amounts of  $\beta$ -caryophyllene, MOF catalyst, solvent, TBHP (*tert*-butyl hydroperoxide) and IL were added into a flask. The mixture was magnetically stirred at 313 K under 1 atm O<sub>2</sub> atmosphere. Subsequently, H<sub>2</sub>O was added and the resulting solution was extracted with EtOAc. The organic layer was analyzed by GC. The identification of compounds was done by GC-MS and the retention times were compared to those of the commercially available reagents. The MOF catalyst can be easily collected by centrifugation and reused after washing with EtOH and drying under vacuum.

# 3. Results and discussion

# 3.1. Catalyst characterization

The morphology of obtained 2D Cu-TCPP nanosheets with few layers was well characterized by transmission electron microscopy (TEM) and scanning electron microscopy (SEM) (Fig. 1A and B), indicating an obvious sheet-like structure with good flexibility [45]. The Tyndall light scattering effect of ultrathin Cu-TCPP nanosheets exhibited in EtOH (inset in Fig. 1A) also confirmed their colloidal state [41,45]. In contrast, bulk Cu-TCPP presented a 2D stacking morphology with opaque property (Fig. 1D). Furthermore, AFM analysis clearly supported the successful fabrication of ultrathin Cu-TCPP nanosheets with the thickness of  $\sim$ 5.5 nm (Fig. 1C). The powder X-ray diffraction (XRD) patterns of Cu-TCPP nanosheets and bulk Cu-TCPP were illustrated in Fig. 1E, implying the crystal nature of these two MOF samples since four characteristic peaks around  $2\theta = 7.68^{\circ}$ ,  $9.00^{\circ}$ ,  $12.06^{\circ}$  and  $19.40^{\circ}$  could be ascribed to (110), (002), (210) and (004) planes, respectively [41]. The observed red-shifts of  $v_{C=0}$  (from 1653 cm<sup>-1</sup> to 1618 cm<sup>-1</sup>) and  $v_{C=N}$  (from 1290 cm<sup>-1</sup> to 1284 cm<sup>-1</sup>) stretching vibrations in PVP (Fig. 1F) also validated the formation of Cu-TCPP nanosheets [41]. Furthermore, the disappearance of the COO- band at 1699 cm<sup>-1</sup> indicates the more complete deprotonation of TCPP ligands in Cu-TCPP nanosheets compared with bulk Cu-TCPP [46]. The TG curve of Cu-TCPP nanosheets is shown in Fig. S1 and important physical properties are presented in Fig. S2 and Table S1.

The shape of 2D **Co-TCPP** and **Ce-TCPP** nanosheets was clearly displayed by the TEM (Fig. 2A and D) and SEM images (Fig. S3). Their

# Table 1

Oxidation of β-caryophyl	ene with O <sub>2</sub> over	Cu-, Co- or Co	e-based MOFs. <sup>a</sup>
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(1)		(2) (3)			
	Catalyst	Solvent ( $\varepsilon^{\rm b}$ , mL)	Conv. (%)	Sel. (%) (2)	(2) Yield (%) (3)
1	Cu-TCPP <sup>c</sup>	DMSO (45.0, 0.5)	81.1	90.7	6.6 73.6
2		DMSO (45.0, 1.0)	92.6	92.3	6.5 85.5
3		DMSO (45.0,1.5)	80.1	92.1	7.5 73.8
4		DMSO (45.0, 2.0)	74.8	91.7	6.2 68.6
5		DMSO (45.0, 2.5)	69.0	91.6	6.4 63.2
6		DMSO (45.0, 3.0)	62.3	90.2	7.3 56.2
7		THF (7.6, 2.0)	97.5	87.2	8.5 85.0
8		Acetonitrile (38.0, 2.0)	65.8	90.3	7.9 59.4
9		Acetone (20.7, 2.0)	65.2	91.3	7.1 59.5
10		Ethyl acetate (6.0, 2.0)	57.0	84.4	11.5 48.1
11		Methanol (32.6, 2.0)	34.1	83.5	8.9 28.5
12		DMF (36.1, 2.0)	20.5	90.9	7.6 18.6
13	Bulk Cu-TCPP	DMSO (45.0, 1.0)	66.9	90.4	8.9 60.5
14	Co-TCPP <sup>c</sup>	DMSO (45.0, 1.0)	49.1	90.9	8.1 44.6
15	Bulk Co-TCPP	DMSO (45.0, 1.0)	41.5	90.6	7.2 37.6
16	Ce-TCPP <sup>c</sup>	DMSO (45.0, 1.0)	21.7	88.4	8.1 19.2
17	Bulk Ce-TCPP	DMSO (45.0, 1.0)	11.3	88.7	7.4 10.0

<sup>a</sup> β-Caryophyllene (1.0 mmol), catalyst (6.0 mg), O<sub>2</sub> (1 atm), [C<sub>12</sub>mim]Cl (0.05 mmol) as the additive, 70% TBHP (0.13 mmol), 313 K, 24 h. <sup>b</sup> Solvent dielectric constant ( $\varepsilon$ ).

Solvent directific constant (r).

<sup>c</sup> Cu-TCPP, Co-TCPP and Ce-TCPP are 2D MOF nanosheets.

corresponding colloidal suspensions in EtOH both showed a strong Tyndall effect (insets in Fig. 2A and D), which was different from their related bulk MOF samples (Fig. 2C and F). Additionally, AFM images acquired from **Co-TCPP** and **Ce-TCPP** nanosheets implied that the thickness of ultrathin **Co-TCPP** and **Ce-TCPP** nanosheets is ~4.8 or 3.7 nm, respectively (Fig. 2B and E).

# 3.2. Transformation of $\beta$ -caryophyllene over 2D MOF nanosheets

In order to achieve outstanding oxidation performance, the influence of 2D MOF nanosheets and solvents on  $\beta$ -caryophyllene transformation were first examined in the presence of amphiphilic [C<sub>12</sub>mim]Cl.

As shown in Table 1, ultrathin 2D MOF nanosheets or bulk MOFs possess adequate reactivity towards β-caryophyllene oxidation because efficient conversion of substrate (11.3%-92.6%) and fairly good selectivity (88.4%–92.3%) for  $\beta$ -caryophyllene epoxide (entries 1–6, 13–17) were observed in DMSO under very mild conditions, i.e. at 313 K using 1 atm O<sub>2</sub> as the oxygen source. As desired, ultrathin Cu-TCPP nanosheets provided better performance than bulk Cu-TCPP, similar to those of the Co-TCPP and Ce-TCPP nanosheets (entries 2, 13-17). Notably, 2D Cu-TCPP nanosheets seemed to be more superior to Co-TCPP and Ce-TCPP nanosheets in the aerobic epoxidation (entries 2, 14 and 16) perhaps due to the nature of metal centers and stability of metal active species [32, 47,48]. According to recent work by Zhou [23] and Wang [25], a polar aprotic solvent like acetonitrile is profitable for the catalytic oxidation with MOF nanosheets under an oxygen atmosphere. Herein, we found that polar aprotic solvents such as DMSO, CH<sub>3</sub>CN and acetone are suitable for  $\beta$ -caryophyllene transformation (entries 4, 8 and 9). Additionally, the optimal amount of DMSO (entry 2) was more favorable for the formation of  $\beta$ -caryophyllene epoxide, affording excellent selectivity (92.3%) and high yield (85.5%). Interestingly, less polar and aprotic medium like THF also offered intriguing results (entry 7) owing to its extraordinary dissolving power for polar and nonpolar molecules [49]. In contrast, decreased reactivity and selectivity were exhibited in ethyl acetate (entry 10). Moreover, the epoxidation proceeded poorly in CH<sub>3</sub>OH and DMF (entries 11 and 12).

To further investigate the impact of ionic liquids on  $\beta$ -caryophyllene

Table 2	
Influence of II	on the oxidation of B-carvonhyllen

Influence of IL on the oxidation of	β-caryophyl	llene over <b>Cu-TCPP</b> nano	sheets."
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Entry	Additive (mmol)	Conv. (%)	Sel. (%) (2)	(2) Yield (%) (3)
1	[C <sub>12</sub> mim]Cl (0.01)	74.9	90.8	8.0 68.0
2	[C <sub>12</sub> mim]Cl (0.025)	85.3	91.7	7.8 78.2
3	[C <sub>12</sub> mim]Cl (0.03)	87.0	92.0	7.7 80.0
4	[C <sub>12</sub> mim]Cl (0.04)	90.3	92.2	7.5 83.3
5	[C <sub>12</sub> mim]Cl (0.05)	92.6	92.3	6.5 85.5
6 <sup>b</sup>	[C <sub>12</sub> mim] Cl (0.05)	93.8	92.4	7.3 86.7
7	[C <sub>12</sub> mim]Cl (0.06)	91.7	90.4	8.3 82.9
8	[C <sub>12</sub> mim]Cl (0.075)	84.1	90.2	8.1 75.9
9	[C <sub>12</sub> mim]Cl (0.10)	75.0	89.8	8.2 67.4
10	[C <sub>4</sub> mim]Cl (0.05)	79.4	91.2	7.1 72.4
11	[C <sub>8</sub> mim]Cl (0.05)	84.8	92.0	7.2 78.0
12	[C <sub>14</sub> mim]Br (0.05)	85.6	91.4	7.4 78.2
13	[C <sub>16</sub> mim]Cl (0.05)	87.5	90.4	7.8 79.1
14	None	4.8	83.9	8.0 4.0
15	[C <sub>4</sub> mim][HSO <sub>4</sub> ] (0.05)	70.5	92.0	7.1 64.9
16	[C <sub>4</sub> mim][BF <sub>4</sub> ] (0.05)	68.1	91.2	6.6 62.1
17	[C4mim][Cys] (0.05)	48.2	86.0	9.0 41.5
18	[C <sub>4</sub> mim][Ala] (0.05)	28.0	84.8	10.3 23.7
19	[C <sub>4</sub> mim][Pro] (0.05)	9.5	86.4	7.5 8.2

 $^a$   $\beta\mbox{-}Caryophyllene$  (1.0 mmol),  $Cu\mbox{-}TCPP$  nanosheets (6.0 mg),  $O_2$  (1 atm), 70% TBHP (0.13 mmol), DMSO (1.0 mL), IL as the additive, 313 K, 24 h.  $^b$  Reaction time =27 h.

oxidation, a series of ILs were then evaluated. As shown in Table 2, significantly enhanced transformation of  $\beta$ -caryophyllene can be achieved utilizing **Cu-TCPP** nanosheets as the catalyst in the presence of different imidazolium ILs (Table 2, entries 1–5, 7–13). In particular, [C<sub>12</sub>mim]Cl possessing a proper alkyl chain was more beneficial (entries 5, 10–13). Of note, the amount of [C<sub>12</sub>mim]Cl also played an important role in improving the performance of **Cu-TCPP** nanosheets (entries 1–5, 7–9). When 5.0 mol % [C<sub>12</sub>mim]Cl was used, 92.6% conversion of substrate and 92.3% selectivity to  $\beta$ -caryophyllene epoxide can be obtained over **Cu-TCPP** nanosheets (entry 5). In sharp contrast, the reaction could not occur smoothly in the absence of [C<sub>12</sub>mim]Cl and poor conversion (4.8%) was observed (entry 14) owing to the characteristics



Fig. 3. Variation of the yield of  $\beta$ -caryophyllene epoxide with time. Reaction conditions:  $\beta$ -caryophyllene (1.0 mmol), **Cu-TCPP** catalyst (6.0 mg), O<sub>2</sub> (1 atm), [C<sub>12</sub>mim] Cl (0.05 mmol), 70% TBHP (0, 0.07, 0.13 or 0.2 mmol), DMSO (1.0 mL), 313 K.



Fig. 4. Recycling of Cu-TCPP nanosheets. Reaction conditions: the first experiment was scaled up using 7 mmol  $\beta$ -caryophyllene, 42 mg fresh Cu-TCPP nanosheets catalyst, 0.35 mmol [C<sub>12</sub>mim]Cl, 0.91 mmol 70% TBHP, 1 atm O<sub>2</sub>, and 7 mL DMSO. In the following experiments, oxidation of substrate was carried out based on the recovered Cu-TCPP nanosheets. Reaction time =27 h, temp. = 313 K.

of **Cu-TCPP** nanosheets bearing PVP since surfactant may block the active sites [26], thus confirming the availability of IL for tuning the catalytic properties of PVP-containing nanosystems [50]. However,



Fig. 5. XPS spectra of the fresh and used Cu-TCPP nanosheets.

other alkylimidazole-based ILs, such as [C<sub>4</sub>mim][HSO<sub>4</sub>], [C<sub>4</sub>mim][BF<sub>4</sub>], [C<sub>4</sub>mim][Cys], [C<sub>4</sub>mim][Ala] and [C<sub>4</sub>mim][Pro], provided obviously lower or even poor conversion of substrate (entries 15–19). Using **Cu-TCPP** nanosheets as the catalyst, prolonged reaction time was also necessary to reach satisfactory results (entry 6).

Radical initiator is of specific importance for the selective oxidation with molecular oxygen under mild conditions over a copper catalyst [51]. The effect of some peroxides, including TBHP, DTBP (di-*tert* butyl peroxide), BPO (benzoyl peroxide) and *m*-CPBA (*m*-chloroperoxybenzoic acid) [51,52], on the aerobic oxidation of  $\beta$ -caryophyllene was thus carefully investigated. As exhibited in Table S2, good conversion of  $\beta$ -caryophyllene (93.8%) and 92.4% selectivity for  $\beta$ -caryophyllene epoxide could be gained using TBHP as initiator. In comparison, the presence of other peroxides mentioned above resulted in rather low conversion of substrate (2.0%–11.3%). Additionally, an appropriate amount of TBHP (13.0 mol %) could be more beneficial to the transformation of  $\beta$ -caryophyllene, as illustrated in Fig. 3.

In order to establish the optimal reaction conditions, some crucial parameters, i.e. the catalyst amount and temperature, were also explored. As shown in Fig. S4, a suitable amount of **Cu-TCPP** nanosheets (6.0 mg) afforded very good  $\beta$ -caryophyllene epoxide yield (86.7%) and selectivity (92.4%). As shown in Fig. S5, **Cu-TCPP** nanosheets provided significantly advantageous epoxide yield at a relatively low temperature (313 K). More interestingly, the efficient epoxidation of  $\beta$ -caryophyllene proceeded smoothly and selectively over **Cu-TCPP** nanosheets at lower temperatures (298–308 K), thus demonstrating the great potential of **Cu-TCPP** nanosheets for biomimetic activation of O<sub>2</sub> under very mild conditions [27,53].



Fig. 6. TEM images of fresh (A) and recovered Cu-TCPP nanosheets (B and C, with or without [C<sub>12</sub>min]Cl).



Fig. 7. XRD patterns of fresh (a) and recovered Cu-TCPP nanosheets (b and c, with or without  $[C_{12}min]Cl$ ).

### 3.3. Stability of Cu-TCPP nanosheets

Due to the facile decomposition or deactivation, superior stability is still quite desirable for porphyrinic frameworks-based biomimetic oxidation [54,55]. Hence, the recyclability of **Cu-TCPP** nanosheets was tested. As depicted in Fig. 4, **Cu-TCPP** nanosheets exhibited good reusability and up to 83.1% yield of  $\beta$ -caryophyllene epoxide was maintained in seven consecutive runs. Indeed, the excellent stability of **Cu-TCPP** nanosheets was also supported by XPS (Fig. 5) and FT-IR



**Fig. 8.** Fluorescence spectra of **Cu-TCPP** nanosystem containing 8 mg terephthalic acid (TA) before and after adding TBHP (**A**) or DTBP (**B**): (**a**) 0 min; (**b**) 5 min; (**c**) 10 min; (**d**) 15 min; (**e**) 20 min; (**f**) 30 min; (**g**) 40 min. Analysis conditions: **Cu-TCPP** 6 mg, DMF 2.0 mL, TBHP (**A**) or DTBP (**B**) 0.13 mmol,  $[C_{12}mim]Cl$  0.05 mmol,  $\lambda_{ex} = 365$  nm.

(Fig. S6) measurements. As exemplified in Figs. 6 and 7, recovered **Cu-TCPP** nanosheets displayed a clear morphology or structure more similar to those of the fresh sample in the presence of  $[C_{12}mim]Cl$ , thus implying enhanced stability. Importantly, the improved stability of **Cu-TCPP** nanosheets may be ascribed to the critical role of  $[C_{12}mim]Cl$  since IL can significantly tune the microenvironment of MOFs [37,40, 56].

# 3.4. Mechanistic considerations

To provide further insight into the reaction mechanism for the mild and highly selective aerobic epoxidation of  $\beta$ -caryophyllene by **Cu-TCPP** nanosheets/[C<sub>12</sub>mim]Cl/TBHP/O<sub>2</sub> nanosystem, additional spectroscopic analyses were performed.

Reactive radical species like HO' may play a decisive role during the activation of molecular oxygen under mild conditions [57,58]. Interestingly, terephthalic acid (TA) can serve as a simple yet highly sensitive fluorescent probe for radical detection [59]. As demonstrated in Fig. 8A, the fluorescence intensity at around 453 nm increased steadily with time in the presence of TBHP initiator, indicating that HO' and *t*-BuO' can be formed gradually and the epoxidation of  $\beta$ -caryophyllene thus proceeds smoothly *via* a Cu-promoted synergistic radical process [57,60]. On the contrary, only very slight fluorescence enhancement at ~453 nm was



Fig. 9. (A) DRUV-vis spectra of Cu-TCPP nanosheets (a) and Cu-TCPP nanosheets treated with  $O_2$  (b) or  $[C_{12}min]Cl + O_2$  (c). Treatment conditions: Cu-TCPP nanosheets (12 mg),  $O_2$  (1 atm),  $[C_{12}min]Cl$  (0.05 mmol, if necessary), 18 h, 313 K, analysis after centrifugation and drying. (B) UV-vis spectra of Cu-TCPP nanosheets (a),  $[C_{12}min]Cl$  (b), Cu-TCPP nanosheets +  $O_2$  (c), and Cu-TCPP nanosheets +  $[C_{12}min]Cl + O_2$  (d) in DMSO. Cu-TCPP nanosheets (0.4 mg),  $O_2$  (1 atm),  $[C_{12}min]Cl$  (1.8 × 10<sup>-3</sup> mmol).

Wavelength/nm



**Scheme 1.** Plausible pathways for β-caryophyllene transformation over **Cu-TCPP** nanosheets.

observed after adding DTBP capable of generating *t*-BuO' (Fig. 8B) [61], which is well consistent with the poor product yield (10.3%) listed in Table S2. Therefore, these foregoing results reveal the importance of TBHP and related free radicals (HO' and *t*-BuO') during  $\beta$ -caryophyllene epoxidation over **Cu-TCPP** nanosheets.

Amphiphilic IL [C<sub>12</sub>mim]Cl could be utilized as a multifunctional modifier [37,38]. As shown in Fig. 9A, a small blue shift of the Soret band from 466 nm to 452 nm together with decreased absorbance in the DRUV-Vis spectrum (Fig. 9A, b and c) implied the host-guest interactions between Cu-TCPP nanosheets and [C12mim]Cl [62,63]. Furthermore, the good compatibility between IL and PVP may also favor the formation of a new microenvironment around Cu-TCPP nanosheets in the presence of [C<sub>12</sub>mim]Cl [50], which is critical for the active sites within the parent **Cu-TCPP** nanosheets [26,56]. Indeed, the appearance of a band at  $\sim 1159 \text{ cm}^{-1}$  after regeneration (Fig. S6) can be due to the imidazole moiety binding to the Cu-TCPP nanosheets surface [64], confirming the in-situ construction of [C12mim]Cl-based microenvironment around Cu-TCPP nanosheets. [C12mim]Cl-induced change in the unique microenvironment of the Cu active sites was also exhibited in the UV-vis spectra since a new band at 311 nm and an obvious increase of the Q absorption around 546 nm could be seen from Fig. 9B [41], indicating favorable O<sub>2</sub> binding and activation [65,66].

The plausible mechanistic pathways are illustrated in Scheme 1. The XPS spectra for Cu-TCPP nanosheets showed the characteristic Cu  $2p_{3/2}$ ,  $2p_{1/2}$  and shake-up satellite peaks at ~934.7, 954.5 and 944.1 eV (Fig. 5), evidencing the existence of the  $Cu^{2+}$  species [67]. Therefore, HO' and t-BuO' might be readily generated from TBHP via Cu-TCPP nanosheets [60]. Meanwhile, a new microenvironment around Cu-TCPP nanosheets can be constructed in-situ with the aid of [C12mim]Cl, which will be beneficial for enhanced  $O_2$  binding. Thus,  $\beta$ -caryophyllene epoxide (2) could be conveniently formed with high selectivity through a Cu<sup>2+</sup>-mediated cooperative radical pathway under very mild conditions [57]. Notably, Cu-TCPP nanosheets displayed surprisingly high stability as well as excellent efficiency due to the amphiphilic nature of [C<sub>12</sub>mim]Cl, and particularly the perfect compatibility among [C<sub>12</sub>mim] Cl, PVP and Cu-TCPP nanosheets. Additionally, humulene oxide (3) can be obtained from  $\beta$ -caryophyllene epoxide (2) involving a radical isomerization route [11].

#### 4. Conclusions

In this study, a novel synergistic system, i.e. **Cu-TCPP** nanosheets/ [ $C_{12}$ mim]Cl/TBHP/O<sub>2</sub>, was conveniently constructed and successfully utilized for the highly efficient epoxidation of  $\beta$ -caryophyllene under mild conditions. High selectivity (up to 92.4%) and 86.7% yield for  $\beta$ -caryophyllene epoxide were achieved over ultrathin (~ 5.5 nm) **Cu-TCPP** nanosheets with the help of 5.0 mol % [C<sub>12</sub>mim]Cl and 13.0 mol % TBHP at 313 K under 1 atm O<sub>2</sub>. Inspiringly, PVP-stabilized **Cu-TCPP** nanosheets were endowed with enhanced stability and O<sub>2</sub> binding owing to the formation of the new microenvironment around **Cu-TCPP** nanosheets *in-situ* in the presence of [C<sub>12</sub>mim]Cl, as confirmed by TEM, XRD, DRUV-Vis and UV-vis techniques. In addition, free radicals (HO' and *t*-BuO') from TBHP played an important role in the cooperative aerobic oxidation process and were well characterized by means of fluorescence approach. This unique **Cu-TCPP** nanosheets/[C<sub>12</sub>mim]Cl/TBHP/O<sub>2</sub> nanosystem may hold great promise for the facile fabrication of new platforms for biomimetic oxidations with superior performance.

# Credit author statement

Yi Xiao and Dulin Yin conceived the idea for this work. Shiye Li, Lihan Shi and Li Zhang carried out the experiments. Hongmei Huang, Liqiu Mao, Rong Tan, Zaihui Fu, and Ningya Yu provided guidance with regard to the catalyst performance and characterizations. Yi Xiao and Shiye Li wrote the manuscript.

#### **Declaration of Competing Interest**

The authors reported no declarations of interest.

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# Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.mcat.2020.111196.

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