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Author(s)	Liu, R.; Yoshida, H.; Fujita, S.; Lu, N.; Tu, W. H.; Arai, M.
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Selective photoreduction of CO₂ to CO in CO₂-dissolved expanded liquid phase with heterogeneous CO₂-philic Pd complex catalysts

R. Liu,^a H. Yoshida,^a S. Fujita,^a N. Lu,^{*b} W. H. Tu,^b M. Arai^{*a}

^a Division of Chemical Process Engineering, Faculty of Engineering, Hokkaido University, Sapporo 060-8628, Japan. E-mail: marai@eng.hokudai.ac.jp (M. Arai), Tel & Fax: +81-11-706-6594

^b Institute of Organic and Polymeric Materials, National Taipei University of Technology, Taipei 106, Taiwan. E-mail: normanlu@mail.ntut.edu.tw (N. Lu), Tel: +886-2-2771-2171, Fax: +886-2-2731-7174

ABSTRACT

Novel CO₂-philic Pd complexes, PdCl₂[4,4'-bis(R_fCH₂OCH₂)-2,2'-bpy] (bpy: 2,2'-bipyridine) where R_f = *n*-C₁₀F₂₁, *n*-C₁₁F₂₃, were anchored onto a silica support modified with long fluorinated hydrocarbon chains (C₆F₁₃) by mixing these complex and the support in DMSO at 413 K. These immobilized Pd complex catalysts were applied for the photoreduction of CO₂ in DMF or organic solvents using triethylamine as a hydrogen donor at 323 K. The rate of CO₂ reduction and the selectivity to CO were observed to depend on several factors including CO₂ pressure, solvent, Pd complex structure, and Pd loading. With the most active catalyst, the selective photoreduction of CO₂ to CO can be achieved in DMF at a CO₂ pressure of 4 MPa and the performance observed is much better compared to the literature results. The features of the supported

Pd complexes and the multiphase reaction media were characterized by UV-Vis absorption and others to discuss the reasons for their high performance.

Keywords:

Heterogeneous catalysis; Palladium; Reduction; Catalyst design; Photocatalysis; Expanded liquid

1. Introduction

The photochemical transformation of CO₂ into valuable organic compounds and fuels has grown into an intense area of research owing to the global warming problem and the fossil fuels shortage [1,2]. The photocatalytic reduction of CO₂ using photosensitive transition metal complexes has widely been investigated in homogeneous systems because metal complexes have high quantum efficiency and selectivity for the production of carbon-containing species, relative to semiconductors [3-6]. The photoreduction of CO₂ with metal complexes have extensively been performed in organic solvents at room temperature and ambient pressure with a sacrificial electron donor such as triethanolamine (TEOA) and triethylamine (TEA) [7,8] However, the catalytic performance observed so far is still low and one of possible reasons is the limited concentration of CO₂ in organic solvents under the conditions used. The solubility of CO₂ in conventional organic solvents is typically on the order of 0.1-0.3 M under ambient conditions [9]. The concentration of CO₂ plays a significant role in determining the rate of photoreduction of CO₂. It was reported that when Re(bpy)(CO)₃Cl complex was used, a key intermediate of Re(bpy)(CO)₃(CO₂) complex for the production of CO was shown to decay with a first-order dependence on the

concentration of CO₂ [10]. An obvious approach to overcome the problem of low CO₂ concentration is to perform the reactions at high pressures.

The pressurization of a conventional organic solvent with a high pressure CO₂ will result in an increase in the concentration of CO₂ in the liquid phase and an expansion of its volume. Such a liquid phase is called as a CO₂-dissolved expanded liquid phase (CXL) [11]. In recent years, CXLs have been recognized as an innovative and ecologically benign reaction media for chemical synthetic reactions [12,13]. This is because CXLs have several advantages including high miscibility of metal complexes and gaseous reactants such as H₂, O₂, and CO, high diffusion rate, low viscosity, and tunable solvent properties changing from neat organic solvents through supercritical carbon dioxide (scCO₂) [14]. These properties may easily be varied by CO₂ pressure. In addition to those physical impacts, dense phase CO₂ can also have chemical effects on organic reactions through molecular interactions with substrates, intermediates, and catalysts [15,16]. Those attractive features of CXLs as promising reaction media are demonstrated in review articles [17,18]. For example, the authors have revealed the chemical function of dense phase CO₂ in CXLs for hydrogenation, oxidation, hydroformylation, acid-catalyzed reaction, Heck reaction, and Diels-Alder reaction [19]. However, only a few reports have been focused on photochemical CO₂ reduction in CXLs even in dense phase CO₂ systems [20-28]. Mizuno et al. studied the photoreduction of high pressure CO₂ with TiO₂ powder in aqueous solution [23-26]. They found that an increase in CO₂ pressure significantly accelerated the CO₂ reduction and improved the CO₂ reduction selectivity [23]. In 2000, Hori et al. gave the first example of photochemical reduction of CO₂ to CO by CO₂-soluble rhenium phosphite complexes such as [Re(bpy)(CO)₃{P(OC₆H₁₃)₃}][B(3,5-(CF₃)₂-C₆H₃)₄] in liquid CO₂ [27]. The turnover number for CO formation at a CO₂ pressure of 1.36 MPa was 3.8

times larger compared to that for the photoreduction of CO₂ using [*fac*-Re(bpy)(CO)₃P(O^{*i*}Pr)₃]⁺ at ambient pressure. They pointed out that the high CO₂ concentration enhanced the reaction of one-electron-reduction catalytic species with CO₂ and prevented the deactivation of the catalyst [28]. Those observations have stimulated us to study the photoreduction of CO₂ to CO in CXLs by using Pd complexes of CO₂-philic nature.

In the present work, CO₂-philic Pd complexes anchored on a silica support were used for the photoreduction of CO₂ in CXLs using dimethylformamide (DMF) and other solvents. Novel CO₂-philic Pd complexes, PdCl₂[4,4'-bis(R_fCH₂OCH₂)-2,2'-bpy] (bpy: 2,2'-bipyridine) where, R_f = *n*-C₁₀F₂₁ and R_f = *n*-C₁₁F₂₃, were prepared and then anchored (immobilized) onto a silica support modified with long fluorinated hydrocarbon chains. The immobilized Pd complex catalysts prepared were shown to be very active for the selective photoreduction of CO₂ to CO in DMF using TEA as a sacrificial agent, compared to the previous reactions reported in the literature. A high turnover frequency of 65 h⁻¹ was obtained for the selective production of CO from CO₂ reduction at 323 K with a catalyst in which the Pd complex of R_f = *n*-C₁₁F₂₃ was loaded in 2 wt% onto the fluorinated SiO₂ support. The immobilization of the fluorinated Pd complexes onto the fluorinated support improves their CO₂ photoreduction activity, CO selectivity, and stability, compared to the free Pd complexes, which were observed to change into metallic Pd particles during the reaction. Several variables determining the rate of CO₂ reduction and the CO selectivity have been studied, including CO₂ pressure, structure of Pd complex, loading of Pd complex, and organic solvent.

2. Experimental Section

2.1. Catalyst Preparation and Characterization

The synthesis of fluorinated Pd complexes, $\text{PdCl}_2[4,4'\text{-bis}(\text{R}_f\text{CH}_2\text{OCH}_2)\text{-2,2'}\text{-bpy}]$ (bpy: 2,2'-bipyridine) where, $\text{R}_f = n\text{-C}_{10}\text{F}_{21}$ and $\text{R}_f = n\text{-C}_{11}\text{F}_{23}$, was reported elsewhere [29,30], which will be abbreviated as Pd-F₂₁ and Pd-F₂₃, respectively, in the following. A fluorinated silica support, silica gel 60 C₈-reversed phase perfluorinated (synonym: perfluorinated silica gel 60), was purchased from Fluka. This silica support will be abbreviated as F-SiO₂. The size of silica particles was in the range of 0.035-0.070 mm.

The Pd complexes were anchored onto the fluorinated silica as follows. A 2 wt% Pd-F₂₁ supported sample was prepared by dissolving 5 mg Pd-F₂₁ and 250 mg support in 2 cm³ DMSO. The whole solution was stirred at about 140 °C for several hours and then the temperature was cooled down to room temperature, yielding a light yellow solid anchored on the fluorinated silica surface. This sample indicated FTIR (Perkin Elmer RXI FTIR spectrometer) absorption bands of 1625.6 w (ν bpy), 1550.0 w (ν bpy), 1258.0 vw (ν CF₂) and 1097.1 w (ν CF₂). A sample of 2 wt% Pd-F₂₃ on F-SiO₂ was prepared by dissolving 2 mg Pd-F₂₃ and 100 mg support in 2 cm³ DMSO, followed by the same procedure as for Pd-F₂₁/F-SiO₂. The resulting yellow solid sample showed FTIR absorption bands (those only shown for anchored Pd-F₂₃ but not for F-SiO₂) at frequencies (cm⁻¹) of 1627.6 w (ν bpy), 1447.0 w (ν bpy), 1218.0 vw (ν CF₂) and 1089.4 w (ν CF₂). Other 10 wt% supported Pd complex samples were also prepared in similar procedures.

The samples of Pd-F₂₁ and Pd-F₂₃ on F-SiO₂ prepared were examined by field emission scanning electron microscopy (SEM, JEOL 6335F) equipped with an energy dispersive X-ray (EDX) analysis. The unsupported and anchored fluorinated Pd

complexes were also examined by diffuse reflectance UV/Vis absorption measurements with a Shimadzu UV-3100PC spectrophotometer. BaSiO₄ was used as a reference and the absorption spectra were obtained by using the Kubelka-Munk function.

2.2 Photoreduction of CO₂

Using those supported and free fluorinated Pd complex catalysts prepared, the reaction runs were carried out in a laboratory designed high pressure stainless steel reactor of 50 cm³ with a quartz window (diameter 1 cm). In a typical run, a catalyst (20 mg), an organic solvent (10 cm³) and triethylamine (TEA, 2 cm³) were introduced into the reactor. The reactor was flushed with 1 MPa CO₂ three times to remove air. The reactor was placed on a heating plate and wrapped by a heating tape. The temperature was monitored by a thermocouple embedded in the reactor wall. The reactor was heated while stirring by a magnetic stirrer. When the temperature reached to 323 K, CO₂ was introduced up to the desired pressure. The reaction mixture was illuminated by a 500 W high-pressure Hg lamp (Ushio USH-500SC). This lamp emits the light predominantly in the wavelength range of 360-370 nm, 400-410 nm, and 430-440 nm. After the reaction, the pressure was reduced carefully by a back pressure regulator and the gases (CO₂, CO, CH₄, H₂) evolved were collected in a gas trap. The amounts of CO, CH₄, and CO₂ were determined by a gas chromatograph (Shimadzu GC-8A, Porapak Q packed column, FID detector, N₂ carrier) with a methanizer converting those gases into CH₄, and that of H₂ by a gas chromatograph (Shimadzu GC-8A, molecular sieve 5A packed column, TCD detector, N₂ carrier). The liquid phase was analyzed by a gas chromatograph (Shimadzu GC-14B, Porapak T packed column, FID detector, He carrier). Under the reaction conditions used, no other hydrocarbons such as HCOOH, CH₃OH and HCHO were

detected. For comparison, a physical mixture of the Pd complex and the F-SiO₂ support was tested for the CO₂ photoreduction. The complex and the support were charged into the reactor with DMF and TEA. After the mixture was stirred for 30 min at room temperature, the reactor was heated to the reaction temperature and then introduced with CO₂ at the desired pressure in the same manners as above-mentioned.

2.3. Phase behavior observation

The phase behavior is one of important factors determining the reaction rate and the product selectivity for multiphase reactions. It was examined by visual observation using an autoclave with a transparent glass window. A certain volume of organic liquid was added to the autoclave for the liquid/autoclave volume ratio to be similar to that used in photoreduction of CO₂ reaction runs. The autoclave was heated to 323 K (reaction temperature) and CO₂ was introduced to the desired pressure under stirring. The phase behavior was visually examined in different solvents at different CO₂ pressures.

3. Results and discussion

3.1. Catalysts Prepared

Heterogeneous Pd catalysts were prepared using fluorinated Pd complexes and silica support modified with long fluorinated hydrocarbon chains (F-SiO₂). The fluorinated Pd complex was anchored onto the F-SiO₂ support by mixing a solution of the complex in DMSO with F-SiO₂ support at 413 K as shown in Fig. 1. Yellow and

light yellow powder samples were obtained with Pd-F₂₃ and Pd-F₂₁, respectively, and the DMSO solvent was clear, indicating that the Pd complexes were successfully anchored onto the F-SiO₂. The catalysts were prepared from Pd-F₂₁ and Pd-F₂₃ complexes different in the length of fluorinated tail with a Pd loading of either 2 wt% or 10 wt%.

Fig. 1

The Pd-F₂₁ and Pd-F₂₃ anchored F-SiO₂ were examined by SEM-EDX. The results obtained are given in Supplementary Information. The EDX analysis results clearly show that both Pd-F₂₁ and Pd-F₂₃ complex are immobilized onto F-SiO₂ support. It was also observed that the percentage of either F or Si atoms accounted for *ca* 50% and that of either Pd or Cl atoms only accounted for less than 1 %.

Fig. 2 shows the diffuse reflectance UV-Vis spectra for unsupported and anchored fluorinated Pd complexes. The unsupported Pd-F₂₁ and Pd-F₂₃ complexes exhibit almost the same absorption bands in the high-energy region ($\lambda < 350$ nm) but the absorption intensity of the former is a little stronger than that of the latter (Fig. 2A). A high energy absorption band at round 260 nm is assigned to the π - π^* transition introduced by the bipyridine moieties. Another absorption band at ~ 310 nm and weak intense low-energy band around 360-420 nm may be ascribed to spin-allowed metal-to-ligand charge transfer (MLCT) transitions that involve a Pd 5d π orbital as the donor orbital and a π^* bipyridine orbital as the acceptor orbital. No absorption is observed for the fluorinated silica alone (Fig. 2B-a). The main absorption bands of 2 wt% Pd-F₂₁/F-SiO₂ and 2 wt% Pd-F₂₃/F-SiO₂ are blue shifted by about 15 nm and the intensities of these absorption bands are stronger compared with the spectra of the free complexes. When the Pd loading is raised to 10 wt%, the main absorption band is

further blue shifted for the supported Pd-F₂₃ sample but not changed for the Pd-F₂₁ sample. The long wavelength absorption is extended to 600 nm for the supported Pd complexes from 380 nm for the free samples. Those changes in the UV-Vis spectra indicate the presence of interactions of the Pd complexes with the F-SiO₂ support through its long fluorinated tails, which may modify their photocatalytic activities, as described later.

Fig. 2

3.2. Photoreduction of CO₂ with a Pd-F₂₃/F-SiO₂ Catalyst

The CO₂ photoreduction was examined with 2 wt% Pd-F₂₃/F-SiO₂ using TEA as sacrificial agent in the presence of dense phase CO₂ and/or an organic solvent of DMF. Table 1 show the results obtained under different conditions (in different reaction systems as illustrated in Fig. 3). In all cases, CO, a two-electron reduction product of CO₂, was mainly formed with a small amount of H₂ from the sacrificial agent. In DMF/TEA solution under ambient CO₂ pressure (entry 1), which is a widely used reaction system in the literature, the rate of CO production was 14.8 h⁻¹. When a high CO₂ pressure of 4 MPa was used in the absence of DME, a larger CO₂ production rate of 41.5 h⁻¹ was observed (entry 2). In this case, CH₄, an eight-electron reduction product, was also produced at a rate of 5 h⁻¹, along with H₂ at a rate of 8.8 h⁻¹ from TEA due to the electron donor-acceptor interaction between CO₂ and TEA [31]. It is noteworthy that the CO production rate was enhanced to 65.8 h⁻¹ in the presence of DMF as well (entry 3), in which no CH₄ was detected and the H₂ production was also suppressed. A large amount of CO₂ is soluble in DMF at a pressure of 4 MPa, producing an expanded

liquid phase (Fig. 3c). The CO₂ concentration is large and the liquid phase is more CO₂-philic, which is favorable for promoting the CO₂ reduction and allowing the CO₂-philic Pd complex to work more effectively. According to the literature [28], the concentration of CO₂ in a similar DMF/TEOA solution at 5.57 MPa was 12.5 M, about 95 times higher than that at ambient pressure. It is assumed that the concentration of CO₂ in the DMF/TEA solution is much larger due to the stronger electron donor-acceptor interaction with more basic TEA relative to TEOA [28,31]. Table 1 indicates that a higher CO₂ pressure of 8 MPa decreases the rate of CO production (entry 4). At 8 MPa, the liquid phase of DMF and TEA are soluble and diluted in the dense phase CO₂ and this is a significant reason for the lowered rate of CO production of 11.0 h⁻¹. Thus, the reaction system including both DMF and CO₂ at a medium pressure is beneficial for the photoreduction of CO₂ to CO, which is illustrated in Fig. 4.

Table 1, Fig. 3

The influence of CO₂ pressure was further studied for the reaction system of Fig. 4. The rate of CO production was strongly dependent on the pressure, as shown in Fig. 5, which was largely enhanced by three times with increasing pressure up to about 4 MPa. The CO production markedly decreased when the CO₂ pressure went over 4 MPa. A marginal amount of H₂ was also detected and simply decreased with CO₂ pressure up to 10 MPa, in contrast to the change of CO production. The phase behavior observations at different CO₂ pressures indicate that the volume of the DMF/TEA liquid mixture was expanded with increasing pressure, which was 1.8 times larger at 4 MPa compared with the volume at ambient pressure. The liquid and gas phases were observed to change into a single phase with a small further increase in the pressure. One can say, therefore, that the raising CO₂ pressure is positive for enhancing the CO₂

photoreduction to CO for the CO₂-dissolved expanded liquid phase but negative for the single fluid phase.

Fig. 4, Fig. 5

Furthermore, the authors tested other organic solvents as well, including *N*-methyl-2-pyrrolidone (NMP), tetrahydrofuran (THF), and acetonitrile (MeCN). The results of CO₂ photoreduction obtained with these solvents are given in Table 2. DMF was the best solvent with which the CO production rate was 65.8 h⁻¹ with no CH₄ formation (entry 1). With either NMP or THF, the rate of CO production was less than 1/2 of the rate with DMF and the CO selectivity was about 70% (entries 2, 3). The rate of photoreduction of CO₂ with MeCN was even smaller compared to the other solvents and the reaction was more selective to CH₄ than CO (entry 4). When these solvents were pressurized by CO₂, their volumes were observed to expand to a similar extent; the volume of a mixture of solvent and TEA (solvent vs. TEA volume ratio of 5) increased by about 60% at a CO₂ pressure of 4 MPa. Here, the authors will further discuss the results of Table 2 using one of solvent polarity parameters, Reichardt E_T(30) value [32]. The E_T(30) of dense phase CO₂ at 353 K and at 0.5 g cm⁻³, for example, is around 31.5 kcal mol⁻¹ [33]. One can say that, phenomenally, a large rate of CO₂ photoreduction to CO is achieved in a solvent of which E_T(30) value is close to E_T(30) of CO₂ (entry 1); DMF has an E_T(30) of 30.6 kcal mol⁻¹. Such an organic solvent may be suitable for the effective actions of both a CO₂-philic catalyst and a reactant of CO₂. In smaller E_T(30) solvents of NMP (28.2 kcal mol⁻¹) and THF (16.4 kcal mol⁻¹), the overall rate of CO₂ conversion and the selectivity to CO were both lowered (entries 2, 3). In MeCN having an E_T(30) of 36.5 kcal mol⁻¹, the rate and the selectivity were markedly decreased (entry 4). When the solvent properties become less CO₂-philic (dense phase CO₂-like), the rate

of catalytic CO₂ conversion is assumed to decrease due to less effective actions of the catalyst and CO₂ molecules. At present, no explanation is given for the change of the product selectivity. The structure of a reaction intermediate complex including Pd catalyst, CO₂, and TEA would depend on the properties of a solvent used.

Table 2

3.3. Comparison between Supported and Unsupported Pd-F₂₃ and Pd-F₂₁ Complexes

Under standard conditions using DMF, TEA, and 4 MPa CO₂, immobilized (anchored) and unsupported Pd-F₂₃ and Pd-F₂₁ complexes were compared in the performance for the photoreduction of CO₂. The comparison was made by using the same amount (1.5 μmol) of Pd complexes used for the reactions conducted. The results obtained are summarized in Table 3, which shows that CO is the main product with a marginal formation of H₂ from the sacrificial agent for all the reaction runs under the conditions used. The activity of the anchored Pd complex is much higher than that of the unsupported free counterpart for both Pd-F₂₃ (entries 1, 3, 7) and Pd-F₂₁ (entries 2, 4, 8). The maximum TOF of CO formation (65.8 h⁻¹) was obtained with 2 wt% Pd-F₂₃/F-SiO₂ (entry 1), about 6 times larger than that the unanchored counterpart (entry 7). Among the anchored catalysts (entries 1-4), a smaller loading (2 wt%) and a longer fluorinated tail (Pd-F₂₃) gave a more active catalyst. For the free Pd-F₂₃ and Pd-F₂₁ complexes, some black Pd particles were observed to form after the reactions and this should be a main reason for their low activities. It was further found that a larger amount of Pd particles was formed at a higher CO₂ pressure of 8 MPa and CO was little detected with the free complexes. For the Pd complexes anchored on F-SiO₂ support,

which was yellow in color, the liquid phase after the reaction runs was clear and no black Pd particles were seen. Thus, the anchored complexes are stably supported on the support and this hinders the Pd complexes from dissolving into the liquid phase and decomposing to metallic Pd particles. In addition, a physical mixture of Pd-F complex and F-SiO₂ was also tested under the same conditions. These physically mixed catalysts indicated larger activities (entries 5, 6) compared with the free complexes but smaller activities compared with the anchored complexes. For the physically mixed catalysts, the liquid phase was changed in color from clear to light grey after the reaction, indicating the formation of a small amount of Pd particles. There might be a possibility, however, that the free Pd complexes became anchored onto the surface of F-SiO₂ during the reaction even at a lower reaction temperature of 323 K (compared to the anchoring at 413 K), which is responsible for the larger activities of the physically mixed catalysts compared to the free complexes.

Table 3

For further checking the stability of the anchored Pd complex, the photoreduction of CO₂ was tested for longer reaction times under the standard conditions with 2 wt% Pd-F₂₃/F-SiO₂. The amount of CO was observed to increase linearly during the reaction up to 48 h (Fig.. 6). After the reaction for 18 h, the catalyst was separated from the reaction mixture and the liquid phase was tested for further reaction. No reaction occurred and no UV-Vis absorption band appeared. These results indicate that no Pd complex is leaching from the surface of F-SiO₂ and the activity of the anchored Pd complex catalysts is durable for the reduction of CO₂.

Fig. 6

To confirm that CO originates from CO₂ photoreduction, blank experiments were made. No carbon species was detected under dark conditions in the presence and absence of catalyst and under light illumination conditions in the absence of CO₂. No CO was detected with F-SiO₂ alone on photoirradiation. All these results indicate that CO is evolved through photoreduction of CO₂ catalyzed by the fluorinated Pd complexes but not originates from the organic components of F-SiO₂.

3.4. Comparison between the Present and Previous Catalysts

There are only a few reports concerned with metal complexes anchored onto solid supports for photoinduced activation and reduction of CO₂ [34-41]. Table 4 shows the comparison among different anchored Pd complexes in the performance for the photoreduction of CO₂ at ambient pressure. Rhenium tricarbonyl diimine complexes are well-known two electron reduction photocatalysts for converting CO₂ to CO. Ishitani et al. synthesized a mesoporous biphenyl-silica (Bp-PMO) anchored *fac*-[Re(bpy)(CO)₃(PPh₃)]CF₃SO₃ (Re/Bp-PMO) by co-condensation method [36]. The TOF of CO production was 0.1 h⁻¹ with Re/Bp-PMO in MeCN with TEOA as sacrificial agent (entry 1). It was found that the photocatalytic CO evolution from CO₂ was enhanced by a factor of 4.4 compared with the homogeneous complex because Bp-PMO could promote the harvest of light and protect the Re complex against a decomposition by UV irradiation. Hirose and co-workers studied the photoreduction of CO₂ with Ru/Nf-Co complex, in which a photosensitizer of [Ru(bpy)₃]²⁺ was fixed to cation exchange Nafion, and [Co(bpy)₃]²⁺ as a homogeneous catalyst (entry 2) [37]. They pointed out that the lifetime of the partially heterogeneous photocatalyst could be prolonged relative to the counterpart homogeneous metal complex due to retardation of

the decomposition of $[\text{Ru}(\text{bpy})_3]^{2+}$. This was because the complex could not move from the ion exchange polymer surface and so dissociation of the ligands was suppressed. Unfortunately, the rate of CO production from CO_2 was quite low (TOF, 0.04 h^{-1}) and 2.5 times larger amount of H_2 was also produced from sacrificial agent. It was claimed that the low CO productivity in the heterogeneous system was caused by the decrease in the electron transfer from the Ru complex on the polymer surface to the Co complex in the solution. Ramaraj et al. investigated metal phthalocyanines adsorbed onto a Nafion membrane, which behaved as a p-type photocatalyst, for photoreduction of CO_2 in acidic aqueous solution containing TEOA as a hole scavenger [38,39]. HCOOH , another two electron reduction product, was mainly produced with a TOF of 3.0 h^{-1} with ZnPC/Nf (zinc phthalocyanine adsorbed on Nafion membrane). Recently, Motohiro et al. synthesized a hybrid photocatalyst consisting of a ruthenium complex and p-type photoactive N-doped Ta_2O_5 by a direct assembly method and used for the reduction of CO_2 in MeCN/TEOA under visible light irradiation [40,41]. The electron transfer from Ta_2O_5 to Ru complex leads to the two electron reduction of CO_2 to HCOOH . However, when metal complexes are fixed to a solid matrix, dissociation of ligands from a metal ion could be suppressed due to restricted mobility. The development of more efficient heterogeneous catalysts including anchored metal complex catalysts is desirable for the efficient multielectron photoreduction of CO_2 .

In the present work, the authors designed novel heterogeneous CO_2 -philic Pd complex catalysts (Pd-F/F-SiO_2) through immobilizing fluorinated Pd complexes onto the surface of silica support functionalized with long fluorinated hydrocarbon chains. Palladium catalyst, rather than the commonly Re and Ru, was selected because it is more selective to hydrocarbon species for the reduction of CO_2 [42,43]. The

recombination of H atom is retarded on the Pd surface decreasing the production of H₂ from hydrogen donor such as TEA [44,45]. The present Pd-F/F-SiO₂ shows a much higher rate of CO production of 14.8 h⁻¹ when the photoreduction of CO₂ was carried out in DMF/TEA solution under ambient CO₂ pressure (entry 5). It was assumed the anchored Pd complex was more efficient and suitable for the photoreduction of CO₂ due to its unique properties: 1) good light harvesting as evidenced by UV-Vis measurement of Fig. 2, 2) good mobility and action of the CO₂-philic Pd complex in the CO₂-dissolved liquid phase, 3) good stability and durability of the anchored Pd complex for which interactions with F-SiO₂ suppress its leaching and decomposition, 4) easy desorption of the byproduct of H₂O to the solution promoting the reaction.

Table 4

4. Conclusions

The selective photoreduction of CO₂ to CO can be achieved in CO₂-dissolved expanded DMF solvent with TEA as an electron donor and novel heterogeneous CO₂-philic Pd complex catalysts. The catalysts used are fluorinated Pd complexes anchored onto a silica support modified by long fluorinated hydrocarbon chains. A high TOF of 65 h⁻¹ and the 100% selectivity to CO were obtained with the most active catalyst at a temperature of 323 K and at a CO₂ pressure of 4 MPa. This excellent performance, compared to the literature data, may result from an effective combination of the CO₂-dissolved DMF and the CO₂-philic Pd catalyst. In this multiphase catalytic reaction system designed, the CO₂ concentration in DMF can be enhanced, the anchored fluorinated Pd complex can work well in the CO₂-philic medium, and the Pd complex

catalyst can be well stabilized, which prevents the immobilized active Pd species from leaching and decomposing to inactive metallic Pd species. It is further suggested that the light harvesting can be enhanced and the light of a wider range of wavenumber can be used with the anchored Pd complexes compared to the unsupported free complexes.

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Tables and Figures:

Table 1

Results of photocatalytic reduction of CO₂ in four different reaction systems

Entry	Solvent	CO ₂ pressure (MPa)	System ^a	TOF (h ⁻¹)			Selectivity (%)	
				CO	CH ₄	H ₂	CO	CH ₄
1	DMF	0.1	a	14.8	nd	3.2	100.0	0
2	CO ₂	4	b	41.7	5	8.8	89.4	10.6
3	CO ₂ -DMF	4	c	65.8	nd	0.5	100.0	0
4	CO ₂ -DMF	8	d	11.0	nd	nd	100.0	0

Reaction conditions: 2 wt% Pd-F₂₃/F-SiO₂ 20 mg, DMF 10 cm³, TEA 2 cm³, 323 K, 18 h.
nd: not detected. TOF: turnover frequency = (moles of product formed)/((moles of Pd complex used)(reaction time)). [a] shown in Figure 3.

Table 2Results of photoreduction of CO₂ in CO₂ expanded different organic solvents

Entry	Solvent	E _T (30) (kcal mol ⁻¹)	TOF (h ⁻¹)			Selectivity (%)	
			CO	CH ₄	H ₂	CO	CH ₄
1	DMF	30.6	65.8	nd	0.5	100	0
2	NMP	28.2	29.0	10.8	1.0	72.9	27.1
3	THF	16.4	24.2	8.8	1.4	73.3	26.7
4	MeCN	36.5	6.3	12.6	2.1	33.3	66.7

Reaction conditions: 2 wt% Pd-F₂₃/F-SiO₂ 20 mg, CO₂ 4 MPa, solvent 10 cm³, TEA 2 cm³, 323 K, 18 h. nd: not detected. TOF: turnover frequency = (moles of product formed) / ((moles of Pd complex used)(reaction time))

Table 3Results of photoreduction of CO₂ with different Pd complex in CXLs

Entry	Catalyst	Amount of catalyst	TOF (h ⁻¹)	
			CO	H ₂
Heterogeneous				
1	2 wt% Pd-F ₂₃ /F-SiO ₂	20 mg	65.8	0.5
2	2 wt%Pd-F ₂₁ /F-SiO ₂	20 mg	21.7	0.7
3	10 wt%Pd-F ₂₃ /F-SiO ₂	20 mg	44.9	1.0
4	10 wt%Pd-F ₂₁ /F-SiO ₂	20 mg	19.2	1.5
5	10 wt%Pd-F ₂₃ + F-SiO ₂	20 mg	35.1	0.4
6	10 wt%Pd-F ₂₁ + F-SiO ₂	20 mg	14.5	0.3
Homogeneous				
7	Pd-F ₂₃	1.5 μmol	9.6	0.3
8	Pd-F ₂₁	1.5 μmol	11.5	0.1

Reaction conditions: CO₂ 4 MPa, DMF 10 cm³, TEA 2 cm³, 323 K, 18 h. TOF: turnover frequency = (moles of product formed)/((moles of Pd complex used)(reaction time)).

Table 4 Comparison of the present heterogeneous Pd complex with other anchored metal complex in the literature for photoreduction of CO₂ under ambient CO₂ pressure

Entry	Catalyst	Temperature	Solvent	Product	TOF (h ⁻¹)	Ref.
1	^a Re/Bp-PMO	293 K	MeCN	CO	0.1	[32]
2	^b Ru-Co/Nf	Room temp.	DMF+H ₂ O	CO	0.04	[33]
3	^c ZnPC/Nf	Room temp.	H ₂ O	HCOOH	3.00	[34,35]
4	^d Ru/N-Ta ₂ O ₅	Room temp.	MeCN	HCOOH	2.0	[36,37]
5	^e PdF/F-SiO ₂	323 K	DMF	CO	14.8	Present work

[a] Re/Bp-PMO: mesoporous biphenyl-silica (Bp-PMO) anchored fac-[Re(bpy)(CO)₃(PPh₃)]CF₃SO₃, 300 W Xe lamp equipped with a mirror module and a band-pass filter (280 or 365 nm, half-width of 10 nm), sacrificial agent TEOA.

[b] Ru-Co/Nf: a partially heterogeneous system, [Ru(bpy)₃]²⁺ as a photosensitizer was fixed to cation exchange Nafion while [Co(bpy)₃]²⁺ was used a homogeneous catalyst. 500 W Xe lamp with an IR-cut filter, sacrificial agent TEOA.

[c] ZnPC/Nf: Zinc phthalocyanine (ZnPC) adsorbed Nafion membrane, 500 W W-Hg lamp with a water filter and a Pyrex-glass filter to cut off IR and UV radiation, sacrificial agent TEOA.

[d] Ru/N-Ta₂O₅: [Ru(dcbpy)₂(CO)₂]²⁺ anchored on p-type N-doped Ta₂O₅ functionalized with an PO₃H₂. 500 W Xe lamp with filter to produce light in the range 410 ≤ λ ≤ 750 nm. sacrificial agent TEOA.

[e] PdF/F-SiO₂: 2 wt% Pd-F₂₃/F-SiO₂, sacrificial agent TEA.

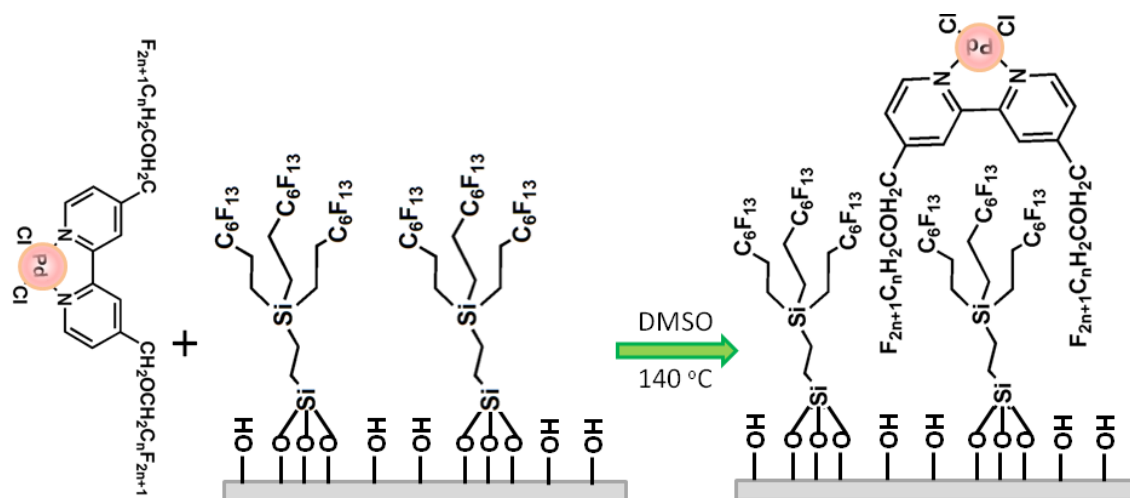


Fig. 1. Synthesis of CO₂-philic photocatalysts through anchoring of fluorinated Pd complexes onto the fluorinated silica.

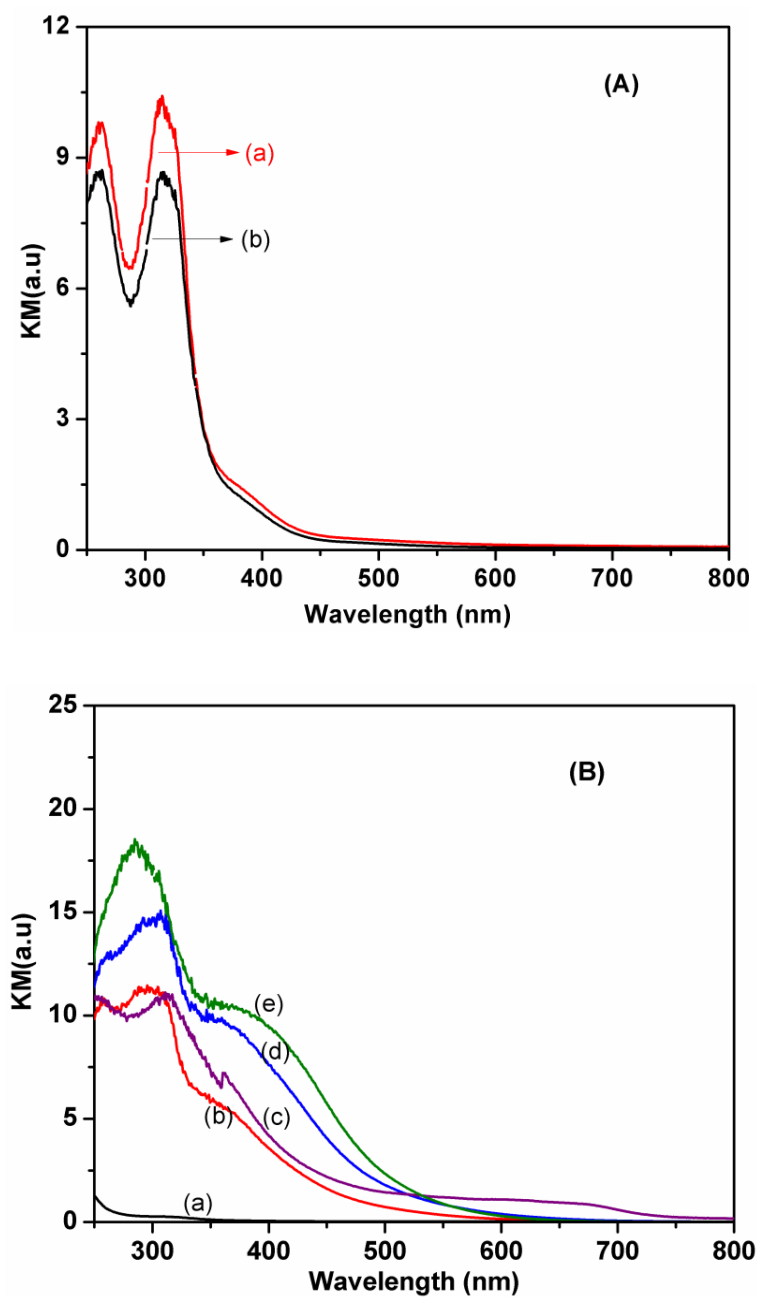


Fig. 2. Diffuse reflectance UV-Vis spectra of (A) unsupported Pd complexes (a) Pd-F₂₁, (b) Pd-F₂₃; (B) F-SiO₂ supported Pd complexes (a) F-SiO₂, (b) 2 wt% Pd-F₂₁/F-SiO₂, (c) 10 wt% Pd-F₂₁/F-SiO₂, (d) 2 wt% Pd-F₂₃/F-SiO₂, and (e) 10 wt% Pd-F₂₃/F-SiO₂.

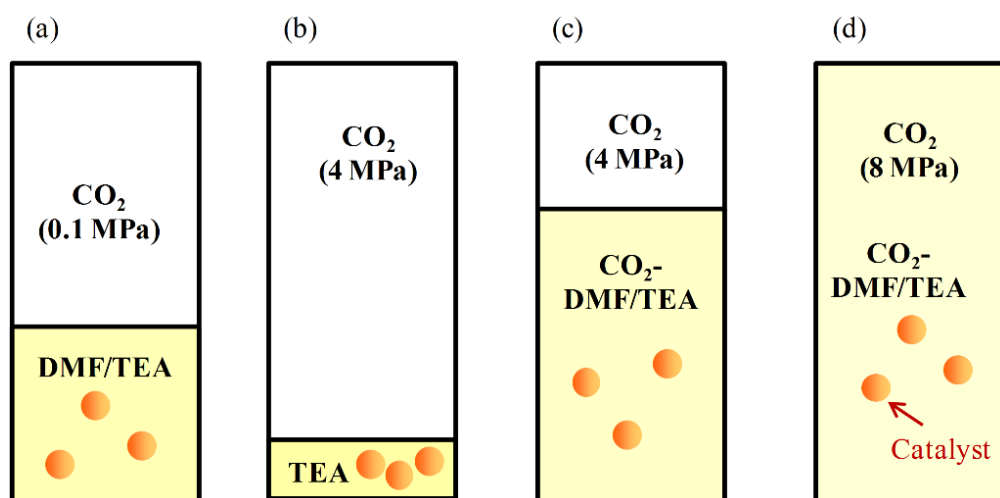


Fig. 3. Phase behavior of different reaction systems for photoreduction of CO_2 .

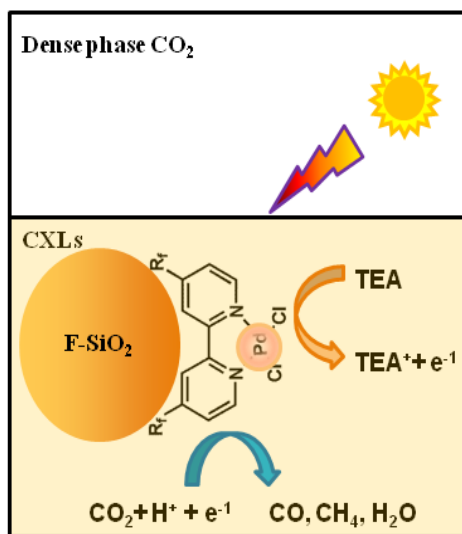


Fig. 4. Photoreduction of CO_2 with the CO_2 -philic heterogeneous Pd complex anchored on fluorinated silica using TEA as electron donor in a CO_2 -dissolved liquid phase.

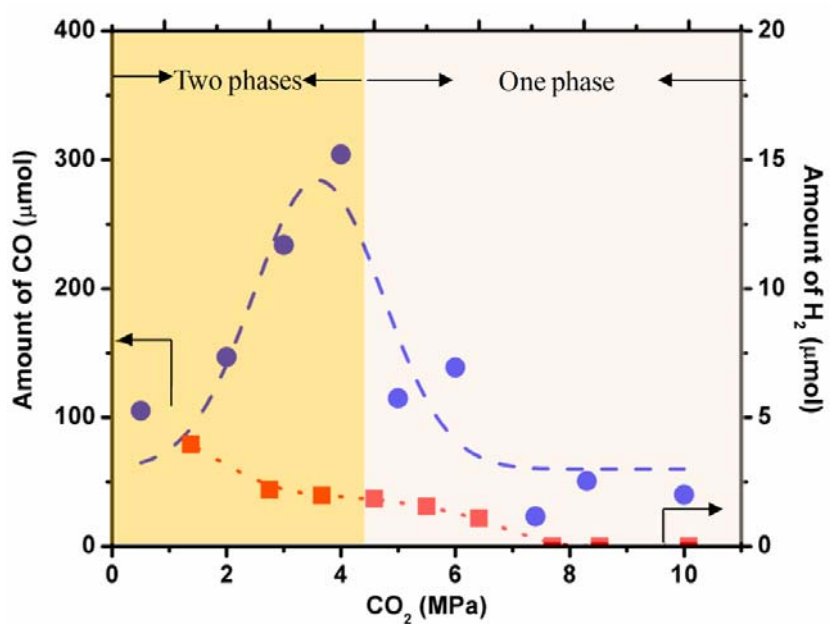


Fig. 5. Effect of CO₂ pressure on the photoreduction of CO₂ with 2 wt% Pd-F₂₃/F-SiO₂ in CO₂-expanded DMF. Reaction conditions: 2 wt% Pd-F₂₃/F-SiO₂ 20 mg, DMF 10 cm³, TEA 2 cm³, 323 K, 18 h.

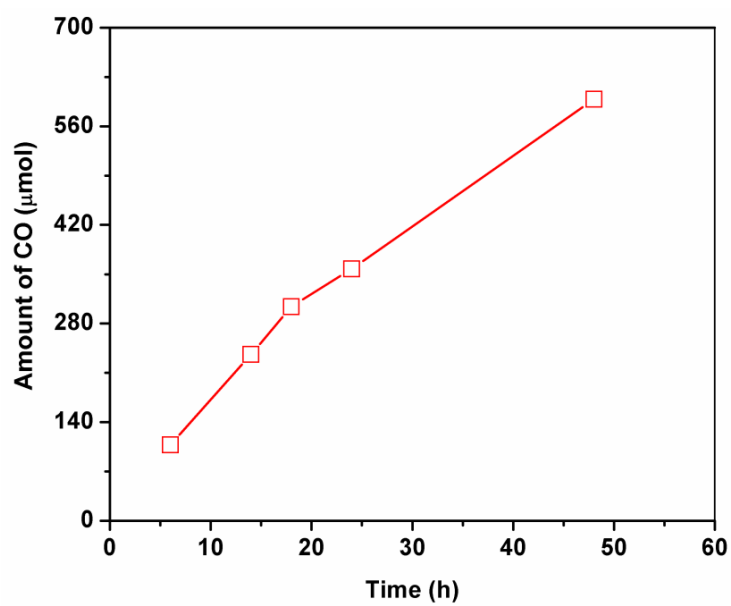


Fig. 6. Time profile of photoreduction of CO₂ with 2 wt% Pd-F₂₃/F-SiO₂ in CO₂-expanded DMF. Reaction conditions: 2 wt% Pd-F₂₃/F-SiO₂ 20 mg, CO₂ 4 MPa, DMF 10 ml, TEA 2 ml, 323 K.