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Highly efficient synthesis of cyclic ureas from CO_2 and diamines by a pure CeO_2 catalyst using a 2-propanol solvent†

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Pure cerium oxide (CeO_2) acts as an effective and reusable heterogeneous catalyst for direct synthesis of cyclic ureas from CO_2 and diamines even at a low CO_2 pressure of 0.3 MPa. 2-Propanol is the most preferable solvent to provide good selectivity. The system composed of a CeO_2 catalyst and a 2-propanol solvent is applied to various diamines to provide the corresponding cyclic ureas in high yields (78–98%), including six-membered-ring ureas that are difficult to be synthesized from CO_2. Based on the kinetic studies on the effect of CO_2 pressure and amine concentration and FTIR studies on adsorption of ethylenediamine and CO_2 onto CeO_2, the following mechanism for the synthesis of cyclic urea is proposed: (1) formation of carbamic acid and carbamate species on CeO_2, (2) decomposition of carbamic acid to a free amino group and CO_2, (3) nucleophilic attack of the amino group on the carbamate on CeO_2 to produce the cyclic urea and (4) desorption of the product and regeneration of CeO_2.

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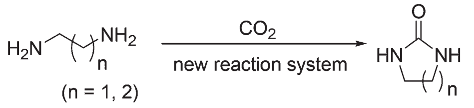
Introduction

Carbon dioxide is one of the greenhouse gases and its conversion to useful compounds will be an essential technology for the future sustainable society without the anxiety of global warming issues.[1] The reductive CO_2 conversion is one of the transformation methods of CO_2, but in general, the energy level of CO_2 is so low that the reductive conversion needs a larger energy input using highly reactive reducing agents such as H_2.[2–4] As an alternative method, non-reductive conversion is promising because the reaction can proceed with a low energy input. The compounds given by non-reductive conversion include carbonates, carbamates, ureas and so on.[1c,5] Among these compounds, ureas are an important class of carbonyl compounds and useful chemical intermediates in the synthesis of pharmaceuticals, agricultural chemicals and dyes as well as antioxidants in gasoline and additives in plastics. Cyclic ureas are heterocyclic motifs frequently observed in biologically active molecules, and in particular six-membered ring ureas are important[6–9] because of their antineoplastic,[7] antiviral[8] and anti-arrhythmic[9] activity. Therefore, an effective synthetic method of cyclic ureas from CO_2 and diamines is required (eqn(1)).



(1)

Conventionally cyclic ureas are synthesized by the reaction of diamines with several reagents such as phosgene, urea, carbonyldiimidazole,[10] trichloromethyl chloroformate,[11] organic carbonates,[6,12] dithiocarbonate,[13] carbonyl selenide[14] and CO.[15] However, these reagents are intrinsically very toxic or prepared from hazardous chemicals such as phosgene, CO and CS_2. From the environmental viewpoint, reaction of CO_2 with diamines will provide an attractive alternative method for the direct synthesis of cyclic ureas. Direct reaction of CO_2 with diamines to cyclic ureas has been conducted using various catalyst systems.[16–24] Effective homogeneous systems for this reaction such as Ph_3SbO/P_4S_{10},[16] PhTMG/DPPA[17] and Hünig's base[18] were reported, and recently Mizuno[19] reported that $TBA_2[WO_4]$ is an efficient homogeneous catalyst for the synthesis of cyclic ureas from diamines and CO_2 of atmospheric pressure. From the viewpoints of catalyst separation and recycling, heterogeneous catalysts or non-catalytic systems are preferable to homogeneous catalysts.[20–23] Arai[20] and Zhao[21] developed non-catalytic systems for the direct CO_2 conversion to cyclic ureas. However, these systems suffer from harsh reaction conditions such as high pressure (≥6.0 MPa) and high

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temperature (≥473 K), and cannot achieve a satisfactory yield of six-membered-ring urea in spite of such harsh conditions and the yields are below 86%. As for heterogeneous catalysts, only two effective catalysts were reported. Polyethylene-glycol-supported potassium hydroxide (KOH/PEG1000)[23] was an efficient catalyst at 8 MPa CO_2 pressure and 423 K, which suffered from high pressure, narrow scope of substrates and low yields of cyclic ureas (≤82%). Nanoparticulate CeO_2[22] prepared by a biopolymer-template process using mesoporous alginate aerogel was an efficient catalyst at 0.7 MPa CO_2 pressure and 433 K, however, this catalyst has drawbacks of narrow scope of substrates and low yields of cyclic ureas (≤37%). As above, there is no green system that can achieve satisfactory yields of cyclic ureas, particularly six-membered-ring ureas, at low pressure (<1.0 MPa) and moderate temperature (<453 K). Therefore, effective reaction systems are desired to be developed from the industrial and academic viewpoints.

Our research group has reported that pure CeO_2 activates CO_2 effectively and acts as an efficient heterogeneous catalyst for the direct synthesis of organic carbonates and carbamates from CO_2.[24] It has been also found that the solvent is clarified to be one of the most important factors to obtain high yield and selectivity.[25] In this paper, we demonstrate that the catalyst system composed of pure CeO_2 and 2-propanol solvent is effective for the direct synthesis of cyclic ureas from CO_2 and diamines under mild reaction conditions. This system can be applied to various diamines to afford the corresponding cyclic ureas in excellent yields, including six-membered-ring ureas. The reaction mechanism over CeO_2 is also discussed on the basis of the kinetics and FTIR studies.

Experimental

General

Preparation of a pure CeO_2 catalyst was carried out by calcination of cerium oxide HS (Daiichi Kigenso, Japan) for 3 hours under air at 873 K, which is an optimized calcination temperature of CeO_2 according to the result of carbonate synthesis.[24a] The specific surface area (BET method) of pure CeO_2 was 80 $m^2\ g^{-1}$. The purity of pure CeO_2 is 99.97%. All the chemicals for organic reactions were commercially available and were used without further purification.

Catalytic reaction

All the reactions were carried out in an autoclave reactor with an inner volume of 190 mL. The standard procedure for the cyclic urea synthesis from CO_2 and diamine (CO_2 + diamine) was as follows: CeO_2 catalyst (0.34 g, 2 mmol), diamine (10 mmol) and solvent (200 mmol) were put into the autoclave together with a spinner, and then the reactor was purged with CO_2 (Shimakyu Co. Ltd., >99.5%). After that, it was pressurized with CO_2 to the desired pressure (typically 0.5 MPa). The gas line was closed and then the reactor was heated to the reaction temperature. The mixture was constantly stirred during the reaction. After the reaction time, the reactor was cooled to room temperature and the gas was collected. Methanol and 1-hexanol were added to the liquid phase as a solvent and an internal standard substance for a quantitative analysis, respectively. The reactor was washed with methanol and water, and the liquids used in washing were added to the reaction mixture. The products in the liquid and the gas phases were analyzed by a gas chromatograph equipped with an FID or quadrupole mass spectrometer (GC-MS) using an InertCap for amines 5 MS/Sil capillary column (GL science Inc., length = 30 m, I.D. = 0.25 mm).

Conversion and selectivity to each product in the reaction of CO_2 + diamine were calculated on the basis of diamines as below.

$$\text{Conversion}/\% = \left(1 - \frac{\text{Amount of diamine after the reaction}}{\text{Amount of diamine before the reaction}}\right) \times 100$$

$$\text{Selectivity}/\% = \frac{\text{Amount of each product}}{\text{Amount of reacted diamine}} \times 100$$

The products which are not identified by GC-MS and NMR are denoted as “Others”. The amount of “Others” was calculated as below.

$$\text{Selectivity of others}/\% = \frac{\text{Amount of reacted diamine} - \text{Amount of identified products}}{\text{Amount of reacted diamine}} \times 100$$

The reaction rate (V/mmol $h^{-1}\ g^{-1}$) was calculated as below.

$$V\ (\text{mmol h}^{-1}\ \text{g}^{-1}) = \frac{\text{Amount of diamine before the reaction} \times \text{Conversion}/100 \times \text{Selectivity of product}/100}{\text{Time} \times \text{Amount of catalyst}}$$

The test of reusability of CeO_2 is conducted as follows: the used catalysts were collected by the decantation. The collected catalysts were washed with methanol and dried at 383 K for 2 h, followed by calcination in air at 873 K for 3 h. After this treatment, the recovered catalyst is applied to the successive reaction. Multiple runs were conducted at the same time under the same conditions to collect enough amount of the used catalyst, and the loss of the catalyst was compensated by reducing the number of runs.

Catalyst characterization. Diffuse reflectance infrared Fourier transform (DRIFT) spectra were recorded with a NICOLET 6700 spectrometer (Thermo Scientific) equipped with a liquid nitrogen-cooled MCT(HgCdTe) detector (resolution 4 cm^{-1}), using an *in situ* cell with ZnSe windows. An *in situ* cell was used for high-temperature and high-pressure gas flow systems. The measurement of the adspecies of ethylenediamine and CO_2 is carried out in the following method; ethylenediamine (ethylenediamine/metal oxides = 2 wt%) is added to the metal oxide (SiO_2 or pure CeO_2) and the admixture was stirred vigorously. About 30 mg of the mixture was transferred to the ceramic pan in an *in situ* FTIR cell connected to the flow system. The loaded sample was heated up to the desired temperature (303 K or 433 K) under N_2 flow (50 mL min^{-1}), and the spectrum of adsorbed ethylenediamine was measured. Next, CO_2 was introduced into ethylenediamine-treated CeO_2 in the flow, and then pressurized up to 5 MPa while the sample temperature was kept at the desired temperature. All the spectra were obtained 5 min after the introduction of CO_2. The spectra were obtained by subtraction of the spectrum derived from air and the apparatus.

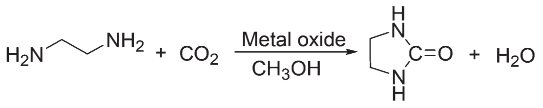
The surface area of CeO_2 was measured with the BET method (N_2 adsorption) using Gemini (Micromeritics). X-ray diffraction (XRD) patterns were recorded using a Rigaku Ultima IV with Cu Kα (40 kV, 40 mA) radiation.

Results and discussion

Catalytic performance in the reaction of CO_2 + ethylenediamine

First, various metal oxides were tested as catalysts for the formation of 2-imidazolidinone (**1**) from 0.5 MPa CO_2 and ethylenediamine at 433 K (Table 1). Formation of **1** hardly proceeded without a catalyst (Table 1, entry 12) under these conditions (yield 0.8% in 1 h). In the reported non-catalytic systems,[20,21] high CO_2 pressure (above 5 MPa) and high temperature (above 423 K) are required. For example, 96.9% yield of **1** was obtained in 24 h at 10 MPa CO_2 pressure and 453 K.[21] The effect of CO_2 pressure is very large, which means the necessity of high CO_2 pressure. Therefore, addition of an effective catalyst is indispensable to make the reaction conditions much milder. For various metal oxides, turnover frequency (TOF) was measured under the conditions in which the conversions were below 40%. TOF is calculated from the following equation: TOF = (amount of produced **1** (mol)/total amount of the metal atom (mol)). ZnO and CeO_2 gave higher conversion and TOF than the other metal oxides (Table 1, entries 1 and 3). As for selectivity, CeO_2 shows a higher value of 93% (Table 1, entry 1), however, the value shown by ZnO is very low (Table 1, entry 3, 68%). The results of the reaction at longer time were also compared between CeO_2 and ZnO catalysts (Table 1, entries 2 and 4). The reaction over pure CeO_2 smoothly proceeded to afford 94% yield in 12 h. On the other hand, the conversion over ZnO was saturated and the yield was decreased. In the case of ZnO, insoluble material was observed in the reaction mixture, particularly on ZnO, which implies that the polymerization reaction occurred. The produced polymer may cover the surface of ZnO, leading to deactivation of ZnO. From the above results, pure CeO_2 is the most effective catalyst for the direct synthesis of **1** from CO_2 and ethylenediamine among the various metal oxides tested and the yield of **1** was highest for the reported heterogeneous catalysts (KOH/PEG1000:[23] 82%, nanoparticulate CeO_2:[22] 37%). Low yield of nanoparticulate CeO_2 might be due to impurities such as Na because the nanoparticulate CeO_2 in the literature was prepared using sodium alginate.

Table 1 The results of the reaction of ethylenediamine and CO_2 in methanol over various metal oxides[a]



2-Imidazolidinone (**1**)

Entry	Catalyst	SA (m^2 g^{-1})	Conversion (%)	Selectivity (%)		TOF[b] (h^{-1})
				1	Others	
1	Pure CeO_2	78	22	93	7	4.0
2[c]			98	96	4	—
3	ZnO	5.8	40	68	32	5.4
4[d]			42	7	93	—
5	CaO	12	3.1	32	68	0.20
6	La_2O_3	7.0	5.0	16	84	0.16
7	TiO_2	48	2.0	95	5	0.38
8	MgO	37	2.6	23	77	0.12
9	ZrO_2	91	2.1	90	10	0.38
10	Pr_6O_{11}	33	5.5	13	87	0.14
11	Al_2O_3	182	0.8	88	12	0.14
12	None	—	0.8	87	13	—

[a] Reaction conditions: ethylenediamine (10 mmol), methanol (6.4 g), metal oxide (metal: 0.2 mmol), P_{CO_2} = 0.5 MPa, T = 433 K, t = 1 h. [b] Molar ratio of the converted substrate to the total amount of the metal atom per hour. [c] 12 h. [d] 4 h.

In order to verify whether the observed catalysis is derived from solid CeO_2 or leached Ce species in the solution, the direct synthesis of **1** from CO_2 and ethylenediamine was carried out under the above conditions for 1 h to reach 21% yield of the product, and then CeO_2 was removed from the reaction mixture by filtration (Fig. S1†). Then, the reaction was tested with the filtrate under the same conditions again. After 12 h, the conversion slightly increased and the increasing amount of **1** was 5.2% in 11 h (~0.5%/h), which is derived from a non-catalyzed reaction considering that **1** is produced at 0.8% yield in 1 h in the absence of the catalyst (Table 1, entry 12). This means that the catalytically active species are not due to the leached species from CeO_2. Therefore the observed catalysis is essentially heterogeneous. A further advantage of this catalytic system is its reusability. We studied the reuse of CeO_2 for the reaction of CO_2 + ethylenediamine (Fig. 1). The catalyst can be easily retrieved from the reaction mixture by decantation. CeO_2 was reused at least three times without marked loss of its catalytic activity and selectivity. Moreover, the specific surface area of CeO_2 hardly changed after the first and second uses (fresh: 80 m^2 g^{-1}, first use: 83 m^2 g^{-1}, second use: 83 m^2 g^{-1}), and XRD (Fig. S2†) and TG profiles (Fig. S3†) did not change after the first use, either. These results indicate that the structure of CeO_2 maintained through the recycle tests.

The reaction conditions for the synthesis of **1** from CO_2 and ethylenediamine on CeO_2 as a model reaction were optimized. The effect of reaction temperature was examined in a temperature range of 413–453 K (Fig. 2). Increase in the temperature

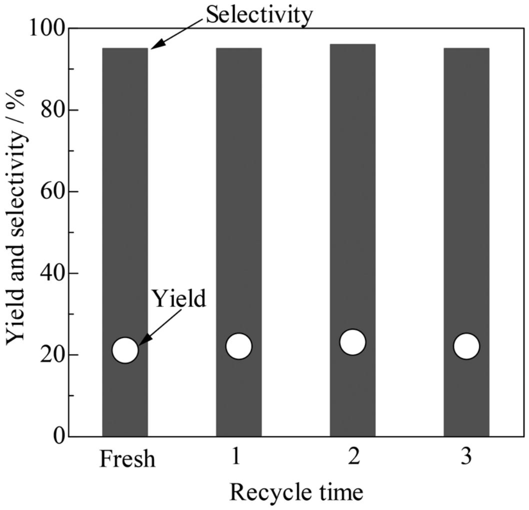


Fig. 1 Recycle test of CeO_2 for the synthesis of **1** from CO_2 and ethylenediamine. Reaction conditions: ethylenediamine (10 mmol), methanol (6.4 g), CeO_2 (0.085 g), P_{CO_2} = 0.5 MPa, T = 433 K, 1 h.

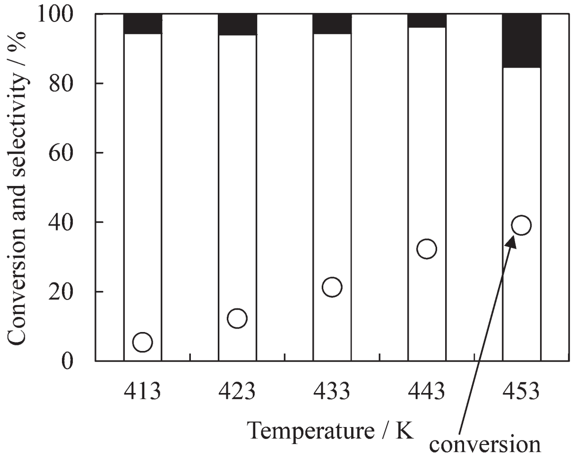


Fig. 2 Effect of temperature on formation of **1** (white bar; **1**, black bar; others). Reaction conditions: ethylenediamine (10 mmol), methanol (6.4 g), CeO_2 (0.085 g), P_{CO_2} = 0.5 MPa, T = 413–433 K, 1 h.

from 413 to 453 K raised the conversion from 5 to 39%. On the other hand, the selectivity was maintained to be very high up to 443 K, but was decreased at 453 K, accompanying that the *N*-alkylated product, a main byproduct, was formed. The effect of the concentration of ethylenediamine was examined by changing the amount of the diamine in a range 2.5–25 mmol (Table 2). The selectivity was high between 5 and 15 mmol (Table 2, entries 2–4), however, the selectivity became low when the diamine concentration is out of the range (Table 2, entries 5and 6). Ultimately, 10 mmol of the diamine to 6.4 g methanol was adopted. The effect of CO_2 pressure was examined by changing CO_2 pressure from 0.2 to 3.0 MPa (Fig. 3). At 1 h reaction time (Fig. 3a), the conversion was almost constant in the range of 1.0–3.0 MPa, but increased slightly as CO_2 pressure decreased from 1.0 to 0.2 MPa. On the other hand, the selectivity was almost constant except for 0.2 and 3.0 MPa of CO_2 pressure, where the selectivity is decreased owing to increase of byproducts including *N*-alkylated products. At 12 h reaction time (Fig. 3b), ethylenediamine is converted almost completely to **1** at more than 0.3 MPa CO_2 pressure with very high selectivity (>92%). However, at 0.2 MPa CO_2 pressure the conversion is 54% and the selectivity is also low. Note that CeO_2 achieved the high conversion and selectivity even at a very low CO_2 pressure of 0.3 MPa, where neither non-catalytic systems nor reported heterogeneous catalysts worked effectively: reported non-catalytic systems and reported heterogeneous catalysts required ≥8 MPa and ≥0.7 MPa CO_2 pressure, respectively. Ultimately, we selected 0.5 MPa CO_2 pressure in the following experiments.

Table 2 Effect of the concentration of ethylenediamine in the reaction of ethylenediamine and CO_2 over CeO_2 in methanol[a]

Entry	Diamine (mmol)	Conversion (%)	Selectivity (%) 1	Selectivity (%) Others	Reaction rate[b] (mmol h^{-1} g^{-1})
1	2.5	88	86	14	—
2	5	44	95	5	3.19
3	10	22	93	7	3.17
4	15	19	93	8	3.41
5	20	15	83	16	3.37
6	25	12	83	16	3.37

[a] Reaction conditions: ethylenediamine (2.5–25 mmol), methanol (6.4 g), CeO_2 (0.086 g), P_{CO_2} = 0.5 MPa, T = 433 K, t = 1 h. [b] Reaction rate was calculated under the reaction conditions where the conversion is below 50%.

Solvent effect and substrate scope of CeO_2 catalysts

The solvent effect for the synthesis of **1** from CO_2 and ethylenediamine was investigated and the results are listed in Table 3. Under the low conversion conditions, the catalytic performance is not influenced so significantly by the solvents (Table 3, entries 1, 3, 4, 6, 8 and 9), which indicates that the interaction of solvents with CeO_2 is weak. On comparing the details of the solvent effect, 1-propanol and 2-propanol provided slightly higher conversion and selectivity (Table 3, entries 4 and 6). Even under the high conversion conditions, 1-propanol and 2-propanol provide higher selectivity than methanol (Table 3, entries 2, 5 and 7), and these selectivities are almost 100%. To ascertain that these alcohols are truly efficient for improvement of selectivity, 2-propanol which is a cheap and fairly non-toxic solvent was applied to various cyclic urea syntheses.

Cyclic urea syntheses from CO_2 and various diamines were examined (Table 4). The effect of the solvent on selectivity was also examined using both methanol and 2-propanol. In the case of methanol as a solvent, ethylenediamine, 1,2-propanediamine and 2-methyl-1,2-propanediamine (Table 4, entries 1, 3 and 5) reacted to afford the corresponding cyclic ureas in high yields (86–94%). *N*-Alkyl ethylenediamines (Table 4, entries 7, 9 and 11) were also converted selectively. 1,3-Propanediamine and *N*-methyl-1,3-propanediamine were applied to provide the six-membered-ring ureas (Table 4, entries 15 and 17). However, *N,N*′-dimethylethylenediamine (Table 4, entry

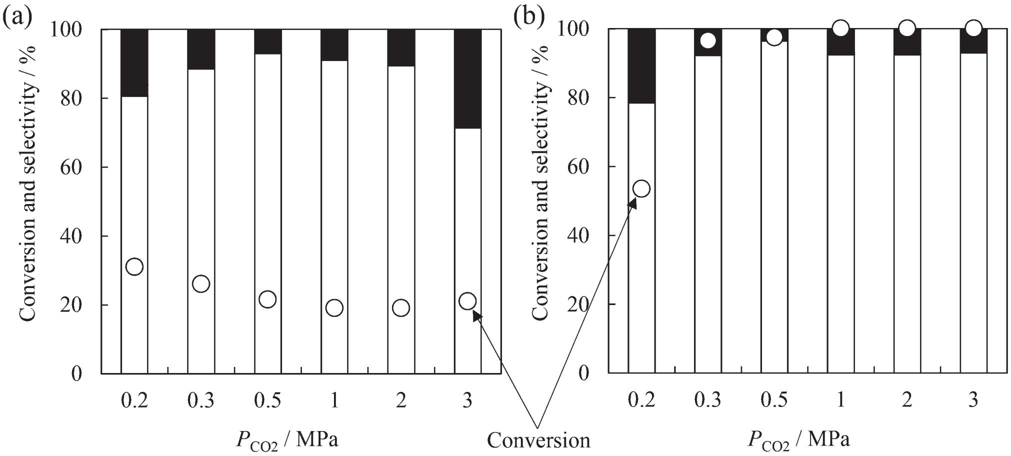


Fig. 3 Effect of CO_2 pressure on formation of **1** after (a) 1 h and (b) 12 h (white bar; **1**, black bar; others). Reaction conditions: ethylenediamine (10 mmol), methanol (6.4 g), CeO_2 (0.085 g), P_{CO_2} = 0.2–3.0 MPa, T = 433 K, 1 h or 12 h.

Table 3 Solvent effect for the reaction of ethylenediamine and CO_2 over CeO_2[a]

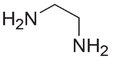
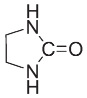
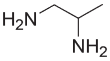
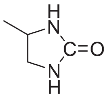
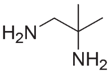
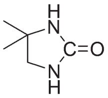
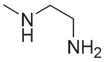
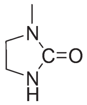
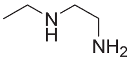
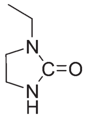
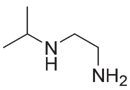
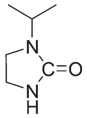
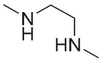
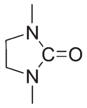
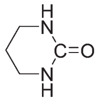
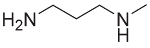
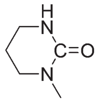
Entry	Solvent	Conversion (%)	Selectivity (%)	
			1	Others
1	Methanol	22	93	7
2[b]		98	96	4
3	Ethanol	21	95	5
4	1-Propanol	26	96	4
5[b]		97	98	2
6	2-Propanol	26	96	4
7[b]		97	99	1
8	Acetonitrile	20	70	30
9	1-Methyl-2-pyrrolidone	17	88	12

[a] Reaction conditions: ethylenediamine (10 mmol), solvent (200 mmol), CeO_2 (0.086 g), P_{CO_2} = 0.5 MPa, T = 433 K, t = 1 h. [b] CeO_2 (0.34 g), t = 12 h.

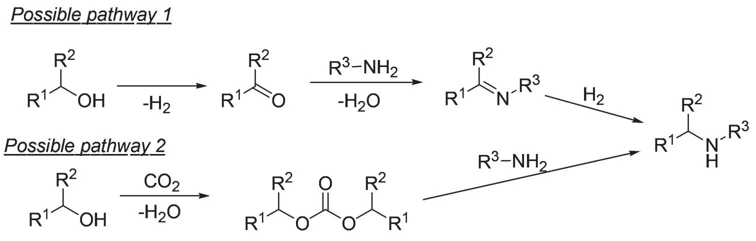
13) was converted in low yield (43%). Using 2-propanol as a solvent instead of methanol provided high yield (78%) with high selectivity (94%) (Table 4, entry 14). Other diamines (Table 4, entries 2, 4, 6, 8, 10, 12, 16 and 18) were also transformed using 2-propanol to afford the corresponding products in high yields (88–96%). These results indicate that 2-propanol is a more preferable solvent for the synthesis of various cyclic ureas. Note that 1,3-propanediamines (Table 4, entries 15–18), which are known to be more difficult substrates to give the cyclic urea, can be converted to the corresponding six-membered-ring ureas, which are core structures of important medicines for antineoplastic, HIV-1 and anti-arrhythmic.[6–9] These yields are higher than the previously reported non-catalyst systems (max yield: 86%) and there are no reports on heterogeneous catalysts. Therefore, this catalytic system composed of CeO_2 and 2-propanol solvent can be promising in the aspect of practical use.

To reveal the effect of the solvent, we focused on the byproduct in the synthesis of cyclic ureas. In this reaction system, the main side reaction is *N*-alkylation of amines with alcohols (Table 4), and CeO_2 will catalyze this reaction. *N*-Alkylation of amines with alcohols will be considered in the following two possible pathways (Scheme 1); (1) dehydrogenation of alcohol, nucleophilic addition of amine to a carbonyl group producing imine and hydrogenation of imine[26,27] and (2) *N*-alkylation with dialkylcarbonate.[28] The pathway (1) has been widely reported by transition-metal complexes such as Ir, Ru, Pd, *etc.*,[26] and strong bases[27] such as alkaline hydroxide or alkaline alkoxide are also known to catalyze the reaction pathway. However, these strong base catalysts require harsh reaction conditions such as high temperature (>473 K). Considering that the basicity of CeO_2 is lower than such strong bases and the temperature of the present reaction system is comparatively low (433 K), the contribution of the pathway (1) must be small. On the other hand, as described in the introduction, CeO_2 is an effective catalyst for the dialkylcarbonate synthesis from CO_2 and alcohols.[24a–d] It is reported that *N*-alkylation of amines by dialkylcarbonates proceeds at a low temperature of 363 K using base catalysts such as alkaline alkoxide.[28c] The reported results suggest that the pathway (2) will be valid as a side reaction in our catalyst system; dialkylcarbonate will be *in situ* produced on CeO_2 and the produced carbonate will play the role in the alkylation agent. The yields of *N*-alkylated products in methanol and in 2-propanol were compared (Table 4). The yields of *N*-alkylation products by methanol in entries 7, 11, 13 and 17 are 0.3%, 3%, 9% and 11%, respectively, and the yields of *N*-alkylation products by 2-propanol in entries 8, 12, 14 and 18 are almost 0%. *N*-Alkylation of amines was remarkably suppressed using 2-propanol as a solvent. Taking into consideration that *N*-alkylation of amines proceeds *via* the pathway (2) in Scheme 1, the bulky alkyl group of 2-propanol will inhibit the insertion of alcohol into CO_2 owing to the steric hindrances of the alkyl chain in the alcohol, which coincides with the previous result that secondary alcohol is less reactive for the synthesis of dialkylcarbonate than methanol on CeO_2.[24d] Therefore, the structure of an alcohol solvent is the most important factor to suppress the side reaction and achieve high yields of cyclic ureas.

Table 4 Scope of diamines for the cyclic urea synthesis[a]

							Yield	
Entry	Diamine	Cyclic urea	Solvent	Time	Conv. (%)	Selectivity to cyclic urea (%)	Cyclic urea (%)	*N*-Alkylated amine (%)
1			Methanol	12	98	96	94	Trace
2			2-Propanol	12	97	99	96	Trace
3			Methanol	12	97	97	94	n.a.[b]
4			2-Propanol	12	98	98	96	n.a.[b]
5			Methanol	12	90	96	86	n.a.[b]
6			2-Propanol	12	92	98	90	n.a.[b]
7			Methanol	24	86	94	81	0.3
8			2-Propanol	24	99	99	98	Trace
9			Methanol	24	83	94	78	n.a.[b]
10			2-Propanol	24	98	98	96	n.a.[b]
11			Methanol	24	81	93	75	3
12			2-Propanol	24	97	99	96	Trace
13			Methanol	24	55	78	43	9
14			2-Propanol	24	83	94	78	Trace
15			Methanol	24	86	81	70	n.a.[b]
16			2-Propanol	24	93	97	90	n.a.[b]
17			Methanol	24	81	85	69	11
18			2-Propanol	36	90	98	88	Trace

[a] Reaction conditions: substrate (10 mmol), solvent (200 mmol), CeO_2 (0.34 g), P_{CO_2} = 0.5 MPa, T = 433 K. [b] Not analyzed.



Scheme 1 Possible reaction pathways for *N*-alkylation of amine with alcohol on CeO_2.

FTIR study and kinetic study

To elucidate the reaction mechanism of cyclic urea synthesis from CO_2 and diamines over CeO_2, kinetic and FTIR studies were carried out. The adsorption order of the substrates in FTIR experiment obeyed the actual synthesis of cyclic ureas in an autoclave. At first, adspecies formed from the treatment of ethylenediamine with CeO_2 and SiO_2 at a low temperature of 303 K were observed by FTIR. Fig. 4 shows the spectra of ethylenediamine adspecies on SiO_2 and CeO_2. The main bands at 1574 cm^{-1} for CeO_2 and 1601 cm^{-1} for SiO_2 were observed and were assigned to N–H bending vibrations of adsorbed

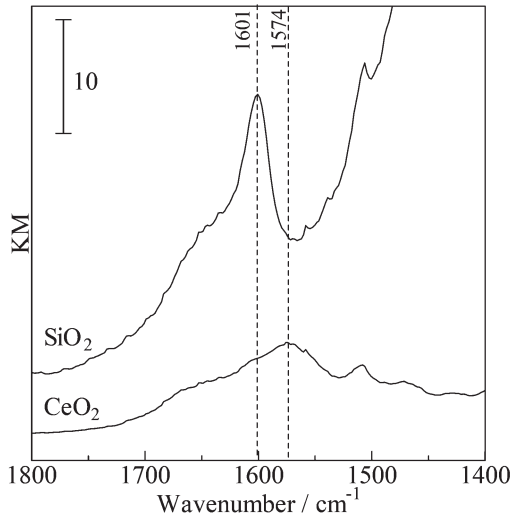


Fig. 4 FTIR spectra of adspecies of ethylenediamine on CeO_2 and SiO_2 at 303 K in the N–H bending vibration region.

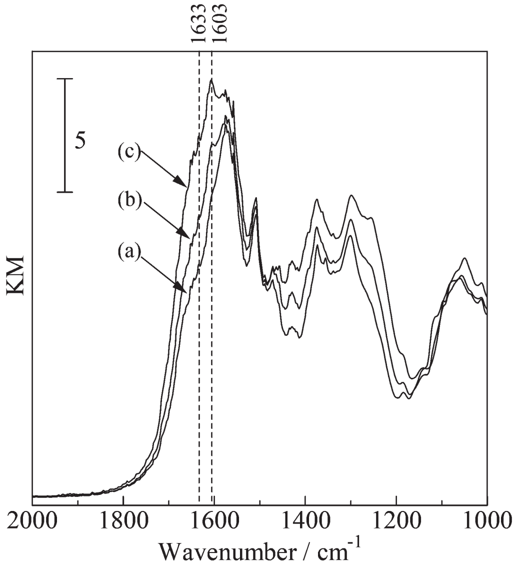
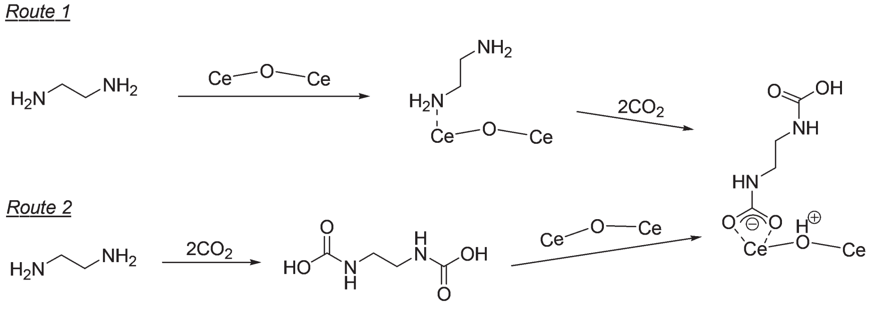


Fig. 5 FTIR spectra of adspecies on CeO_2. (a) CeO_2 treated with ethylenediamine at 303 K and after introduction of CO_2 of (b) atmospheric pressure and (c) 5 MPa at 303 K to (a).

ethylenediamine species. According to the previous report,[29] the NH_2 group produced by coordinatively bonded *n*-butylamine on Lewis acid sites shows bands around 1600–1565 cm^{-1}. In addition, the band for CeO_2 was at a lower wavenumber than that for SiO_2. These results indicate that ethylenediamine is coordinatively adsorbed on the Lewis acid sites on CeO_2. The observed large broad bands on SiO_2 below 1550 cm^{-1} are derived from the absorption of SiO_2 itself due to the stretching vibrations of Si–O–Si bridges.[30] Next, introduction of CO_2 into the ethylenediamine-treated CeO_2 was conducted at 303 K. Fig. 5 shows IR spectra change after introductions of atmospheric pressure (Fig. 5b) and 5 MPa CO_2 (Fig. 5c). New bands at 1603 and 1633 cm^{-1} were observed after CO_2 introduction and these bands increased with increasing CO_2 pressure. The band at 1603 cm^{-1} will be due to $\nu(CO_3)$ of hydrogen carbonate, which is derived from CO_2 adsorption on CeO_2 (Fig. S4†).[31] According to the literature,[32] the band around 1630 cm^{-1} can be assigned to carbamic acid or carbamate adspecies. Taking the basicity of CeO_2 into account, the carbamate species on CeO_2 will be formed by the reaction of diamine adsorbed on CeO_2 with CO_2. As shown in Scheme 2 route 1, diamine is adsorbed on CeO_2 and the diamine adspecies on CeO_2 reacts with CO_2 to give the carbamate adspecies on CeO_2 and a free carbamic acid. On the other hand, it is reported that CO_2 reacts with diamine at room temperature to readily produce dicarbamic acid without a catalyst.[33] Therefore, under the reaction conditions diamine may be firstly converted to dicarbamic acid before contacting CeO_2, and then the dicarbamic acid may be adsorbed on CeO_2 to provide the carbamate adspecies on CeO_2 (Scheme 2, route 2). Next, ethylenediamine-treated CeO_2 was measured at the reaction temperature of 433 K, followed by the introduction of atmospheric pressure and 5 MPa CO_2 on FTIR. As shown in Fig. 6a, ethylenediamine was not desorbed even at 433 K, which indicates that ethylenediamine is strongly adsorbed onto the CeO_2 surface at the reaction temperature. After CO_2 introduction, the main two bands at 1668 and 1572 cm^{-1} were increased with increase of CO_2 pressure (Fig. 6b and c). These bands were located at almost the same positions as those of **1** adsorbed on CeO_2 (Fig. S5†) and were assignable to the stretching vibrations of C═O and CO–N–H, respectively.[34] Therefore, the carbamate species on CeO_2 is easily converted to **1** at 433 K. A small band observed by treatment of ethylenediamine



Scheme 2 Formation route of carbamate species on CeO_2.

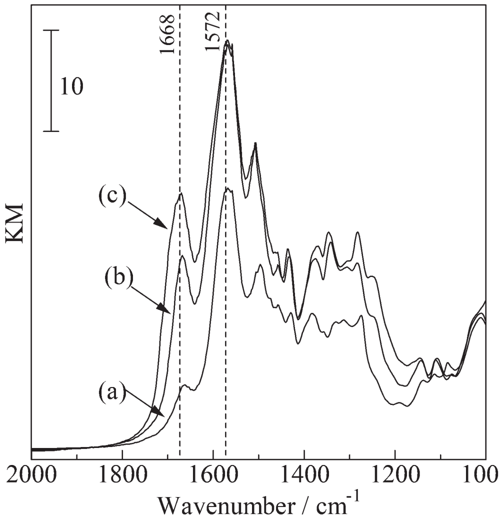


Fig. 6 FTIR spectra of adspecies on CeO_2. (a) CeO_2 treated with ethylenediamine at 433 K and after introduction of CO_2 of (b) atmospheric pressure and (c) 5 MPa at 433 K to (a).

in Fig. 6a will be produced by the reaction of ethylenediamine with CO_2 adspecies on the CeO_2 surface. Moreover, C═O stretching vibration (1668 cm^{-1}) of **1** adsorbed on CeO_2 had a lower wavenumber than that of liquid phase **1** (around 1686–1670 cm^{-1}), which indicates that **1** was adsorbed on CeO_2 at the carbonyl group (C═O) of **1**. The carbamate species on CeO_2 can be transformed into **1** not at 303 K but at 433 K, which suggests that cyclic urea formation from carbamate species on CeO_2 is a slower step in the reaction cycle, in that the step will be the rate-determining step.

Next, kinetics for the synthesis of **1** from CO_2 and ethylenediamine as a model reaction were studied. The dependence of the reaction rate on the ethylenediamine concentration or CO_2 pressure was examined using the results of Table 2 and Fig. 3. The reaction rate (V/mmol h^{-1} g^{-1}) for the effect of diamine concentration and CO_2 pressure was calculated under the reaction conditions where the conversion was below 50%. The reaction rate was plotted as a function of ethylenediamine concentration as shown in Fig. 7. The reaction order of ethylenediamine concentration is estimated to be +0.16, which indicates that free ethylenediamine is not involved in the rate-determining step or strongly adsorbed onto the CeO_2 surface. Fig. 8 shows the effect of CO_2 pressure on the reaction rate. The reaction order of −0.16 was obtained, which indicates that CO_2 does not affect the rate-determining step or slightly suppresses the reaction proceeding. The reactivity of *N*-alkyl diamines was also compared under the conditions where the conversion is below 30% (Table 5). The order of reactivity is as follows: ethylenediamine > *N*-methyl ethylenediamine ≈ *N*-isopropyl ethylenediamine. The amines having some alkyl groups at the N atom decrease the reactivity, which will be attributed to the steric hindrance of *N*-alkyl chains and/or basicity of amines. The alkyl chain of amines will inhibit the nucleophilic attack of amines, leading to the decrease of the reactivity. Basicity of amines is increased by the electron inductive effect

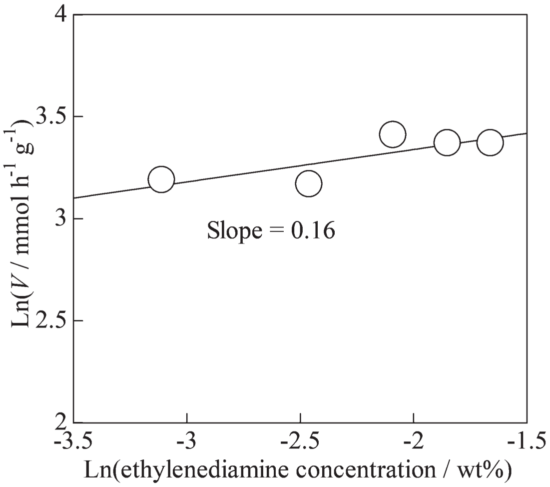


Fig. 7 Effect of amine concentration on the formation rate of **1** from CO_2 and ethylenediamine. Reaction conditions: ethylenediamine (5.0–25 mmol), methanol (6.4 g), CeO_2 (0.085 g), P_{CO_2} = 0.5 MPa, T = 433 K, 1 h.

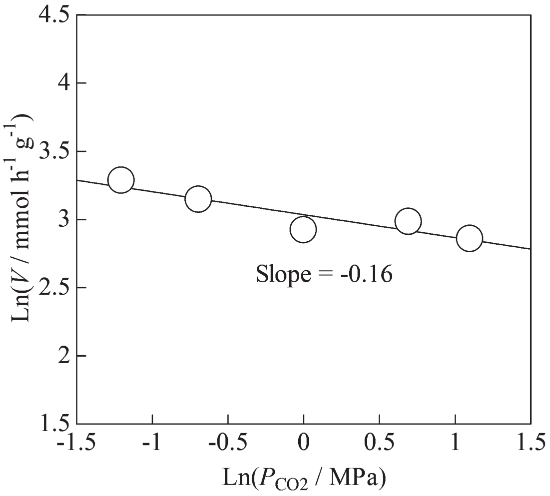
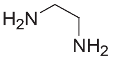
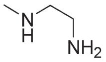
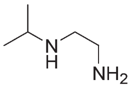


Fig. 8 Effect of CO_2 pressure on the formation rate of **1** from CO_2 and ethylenediamine. Reaction conditions: ethylenediamine (10 mmol), methanol (6.4 g), CeO_2 (0.085 g), P_{CO_2} = 0.2–3.0 MPa, T = 433 K, 1 h.

Table 5 Comparison of the initial reaction rate of *N*-alkyl diamines in 2-propanol solvent[a]

Entry	Diamine	Conv. (%)	Selectivity to cyclic urea (%)
1		26	96
2		15	93
3		17	94

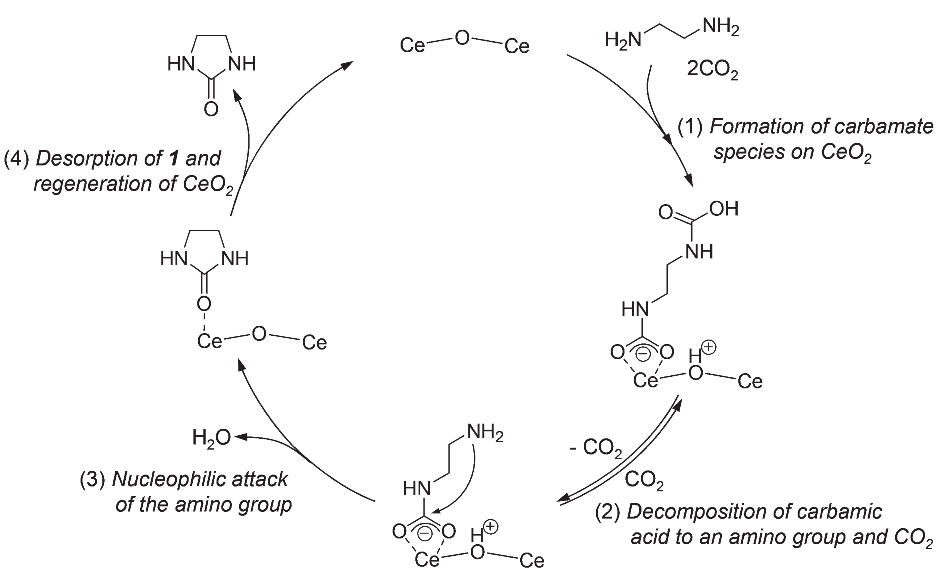
[a] Reaction conditions: substrate (10 mmol), 2-propanol (12 g), CeO_2 (0.086 g), P_{CO_2} = 0.5 MPa, T = 433 K, 1 h.

of an *N*-alkyl group, which will stabilize the carbamic acid. Stabilization of carbamic acid reduces the nucleophilicity of the N atom because nucleophilicity of carbamic acid is weaker than the free amine, leading to the decrease of the reactivity. This result shows that nucleophilic addition of amines is an important step in the reaction, which suggests that the nucleophilic attack of an amino group on the carbamate species on CeO_2 is the rate-determining step.

Reaction mechanism

On the basis of the above experimental results, we discuss the reaction mechanism on CeO_2 for the direct cyclic urea synthesis from CO_2 and diamine. From FTIR studies on adsorption of ethylenediamine at 303 and 433 K (Fig. 4 and 6a), ethylenediamine is adsorbed on Lewis acid sites of CeO_2 and did not desorb from CeO_2 even at 433 K, which indicates that ethylenediamine is strongly adsorbed on the Lewis acid sites of CeO_2 under the reaction conditions. Introduction of CO_2 into ethylenediamine-treated CeO_2 at a low temperature of 303 K demonstrates that ethylenediamine reacted with CO_2 on CeO_2 to afford carbamates species on CeO_2 at 303 K (Fig. 5) and the other amino group forms the carbamic acid. On the other hand, in general, ethylenediamine easily reacts with CO_2 at room temperature to provide dicarbamic acid. An adsorption of the carbamic acid on CeO_2 probably forms the carbamate species on CeO_2, too (Scheme 2). As shown in Table 3, the effect of solvents was hardly observed, which indicates that the interaction of alcohol with the CeO_2 surface is weaker than diamines and carbamates. In addition, dependence of the reaction rate on the ethylenediamine concentration was small (Fig. 7), which also supports that diamine is strongly adsorbed on CeO_2. Taking into account that diamine and CO_2 easily formed carbamate species on CeO_2 at 303 K, the carbamate species will cover the CeO_2 surface and prevent the adsorption of alcohol. Production of **1** was observed at the reaction temperature of 433 K by introduction of CO_2 into ethylenediamine-treated CeO_2 on FTIR (Fig. 6b and 6c). Considering that at 303 K the carbamate species was formed but **1** was not formed on CeO_2, **1** should be produced by the reaction of the carbamate species on CeO_2. In general, carbamic acid is decomposed to CO_2 and amine at above 383 K, which is much lower than the reaction temperature (433 K). Since the nucleophilicity of the N atom of carbamic acid is lower than that of the amine, the reaction proceeds through nucleophilic addition of a free amino group that is produced by the decomposition of carbamic acid, which is the rate-determining step. The comparison of reactivity for *N*-alkylated diamines presents that reactivity of *N*-alkylated substrates is lower than ethylenediamine (Table 5), which will be derived from steric hindrance and/or basicity of the *N*-alkylated amino group. This result shows that reactivity of an amino group is important for the reaction, which supports that nucleophilic addition of a free amino group to a carbamate moiety on CeO_2 is the rate-determining step. In addition, the reaction rate shows a little negative dependence on CO_2 pressure (Fig. 8). At high CO_2 pressure, carbamic acid will be more stable than at low CO_2 pressure because decomposition of carbamic acid is a reversible reaction, leading to the suppression of decomposition of carbamic acid. This result also supports that nucleophilic addition of a free amino group to a carbamate moiety on CeO_2 is the rate-determining step.

In summary, the proposed reaction mechanism for the synthesis of **1** from CO_2 and ethylenediamine as a model reaction is shown in Scheme 3: (1) adsorption of amine and CO_2 to afford carbamic acid and carbamate species on CeO_2, (2) decomposition of the carbamic acid to amine and CO_2, (3) nucleophilic addition of the amino group to the carbamate moiety on CeO_2, providing the cyclic urea, (4) desorption of product **1** and regeneration of CeO_2. The third step is the rate-determining step.



Scheme 3 Proposed reaction mechanism of cyclic urea from CO_2 and ethylenediamine by CeO_2.

Conclusion

We developed an effective and reusable catalyst system composed of pure CeO_2 and 2-propanol solvent for the direct synthesis of cyclic ureas from CO_2 and diamines. 2-Propanol is the best solvent to achieve high yields of cyclic ureas and the bulky alkyl group of 2-propanol will play an important role in the suppression of *N*-alkylation of amine, a main side reaction. The catalyst system can be applied to various diamines to afford the corresponding cyclic ureas, particularly six-membered ring ureas. On the basis of the kinetic studies such as the effect of CO_2 pressure and amine concentration and FTIR studies about the adsorption state of diamine and CO_2, the proposed reaction mechanism is as follows: (1) adsorption of amine and CO_2 to afford carbamic acid and carbamate species on CeO_2, (2) decomposition of the carbamate to a free amino group and CO_2, (3) nucleophilic attack of the amino group on the carbamate moiety, providing the cyclic urea, (4) desorption of product **1** and regeneration of CeO_2.

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