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Carbon dioxide and water: An effective multiphase medium for selective hydrogenation of nitriles with a Pd/Al₂O₃ catalyst

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(ABSTRACT)

The effectiveness of a multiphase medium including CO₂ and water was studied for the selective hydrogenation various nitriles of 2-phenylethyl cyanide (PEC), cinnamonnitrile, *n*-hexanenitrile (HN) and 4-cyanobiphenyl with a conventional Pd/Al₂O₃ catalyst. Such a multiphase reaction medium was observed to have different impacts changing from one nitrile to another and the selective production of primary amine was achieved with PEC and HN but not with the other nitriles. Possible reasons for the substrate-dependent effects of CO₂ and water were discussed.

Keywords: Multiphase media, Selective hydrogenation, Nitriles, Selectivity control, Water

1. Introduction

Single phase and multiphase reaction media using dense phase CO₂ at low and high pressures is useful for organic synthetic reactions, in which CO₂ acts as promoter, controller and/or solvent in different manners affecting reaction rate, product selectivity and/or catalyst life [1-6]. When a liquid reaction mixture is pressurized by CO₂, CO₂ molecules can be dissolved in the liquid phase, interact with organic substrates and/or intermediates, and then change their reactivity. As a result, CO₂ can act as a reaction promoter/modifier for several synthetic reactions although CO₂ is not involved as a reactant in the reactions [7, 8]. One of interesting applications of CO₂ is the preparation of CO₂-responsive materials, in which CO₂ modifies the properties of reaction media and reversible heterogeneous and homogeneous reaction systems using molecular catalysts may be tailored. These will make it possible to effectively make product isolation and catalyst separation and recycling of practical importance [9, 10]. Water is also an interesting functional solvent in organic synthetic reactions, as demonstrated for several reactions using molecular catalysts [11, 12]. The presence of water - organic interface is one of important factors responsible for the promotion effects that appear in the presence of water. In addition, water is also shown to be a powerful solvent for hydrogenation reactions with supported noble metal catalysts due to its unique solvent properties [13, 14].

Those results suggest that it is interesting to apply both CO₂ and water as effective green components for the design of useful multiphase reaction media [7, 8]. The authors indicated for hydrogenation of nitrobenzene with a Ni/Al₂O₃ catalyst that the rate of hydrogenation was enhanced and the selectivity to the desired product of aniline is 100% at any conversion level in the presence of CO₂ [15, 16]. Furthermore, on the addition of water into this multiphase medium, the effect of CO₂ pressurization can appear at a low pressure of about 1 MPa [17]. The multiphase reaction medium including CO₂ and H₂O was shown to be effective for the selective hydrogenation of nitriles to primary amines, as demonstrated for benzonitrile (BN) [18] and benzyl cyanide (BC) [19] with a 5 wt.-% Pd/Al₂O₃ catalyst. In the present work, the versatility of such a multiphase medium has further been studied with other nitriles of 2-phenylethyl cyanide (PEC), cinnamitrile (CN), 4-cyanobiphenyl (CBP) and hexanenitrile (HN) using the same supported Pd catalyst. The effectiveness of CO₂ - H₂O medium has been found to change from one nitrile to another. Possible reasons for the substrate-dependent effects of CO₂ and water will be discussed.

2. Experimental

2.1. Multiphase hydrogenation

Hydrogenation of various nitriles was carried out with a commercial Pd/Al₂O₃ catalyst 50 mg (Wako) in a Teflon lined autoclave (100 cm³) at 323 K [18, 19]. The reactor was charged with 1 mmol substrate, 5 cm³ solvent (toluene or hexane), 5 cm³ water, and 50 mg catalyst. Then, the reactor was flushed with H₂ (99.99%) three times to remove the air, closed, and heated in a heating mantle to a reaction temperature of 323 K. After the reaction temperature was attained, 4 MPa H₂ (99.99%) was introduced followed by the introduction of CO₂ (99.99%) to the desired total pressure with a high pressure liquid pump (JASCO SGF-GET). The reactions were carried out while stirring the reaction mixture with a magnetic stirrer. After the reaction, the reactor was cooled in an ice water bath and depressurized carefully to atmospheric pressure. The reaction mixture was analyzed by gas chromatography (GL Sciences GC-390B) using a capillary column (GL Sciences TC 1701) and a flame ionization detector. The total conversion was determined from the initial and final amounts of substrate. The products were identified by GC-MS (Shimadzu 17A). The following substrates were used: benzyl cyanide, 2-phenylethyl cyanide, cinnamionitrile (Aldrich), *n*-Hexanenitrile, and 4-cyanobiphenyl (TCI). Under the reaction conditions used, average mass balance of (total moles of products detected) / (initial moles of substrate used) was 94%.

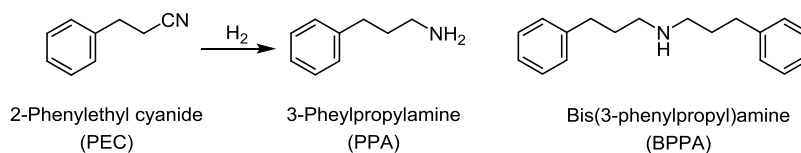
2.2. High pressure FTIR measurement

Molecular interactions between CO₂ and organic substrates were examined by in situ high-pressure FTIR spectroscopy in attenuated total reflection (ATR) mode in similar manners as used previously [20, 21]. An organic substrate was introduced into a cell, it was heated to the reaction temperature, it was pressurized by CO₂ at desired pressures, and the liquid phase dissolving CO₂ was subjected to FTIR-ATR measurements.

3. Results and discussion

Table 1 gives the results of PEC hydrogenation in different reaction media. The secondary amine was selectively obtained in a conventional organic solvent of toluene, toluene + CO₂, toluene + H₂O irrespective of conversion levels under the conditions used (entries 1 - 3). In contrast, the primary amine, 3-phenylpropylamine (PPA), was produced in

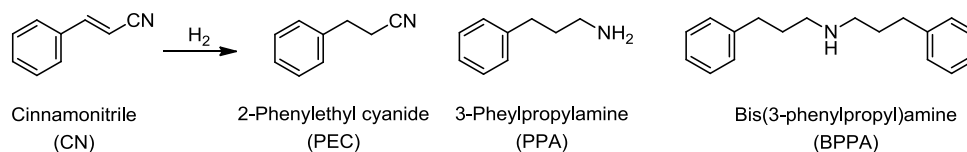
a larger selectivity of 82% when both CO₂ and H₂O were included (entry 4). The presence of CO₂ and/or H₂O decreased the conversion of PEC, which may be explained as follows: when the liquid reaction mixture (toluene, PEC) is pressurized by CO₂, a certain amount of CO₂ molecules is dissolved into the liquid phase and CO₂ acts as a diluent, causing the dilution of reacting species. The comparative reaction was also tested in the presence of N₂ instead of 1 MPa CO₂. A higher N₂ pressure of 4 MPa was used because the solubility of N₂ in organic liquids is smaller than that of CO₂ [22, 23]. The reaction results were observed to be little influenced by the presence of 4 MPa N₂ as compared to the results in the absence of CO₂ (entry 1). The amounts of N₂ and CO₂ dissolved in the liquid reaction mixture at 4 MPa and 1 MPa, respectively, are unknown at present. After considering the dissolution of a certain amount of N₂ that would cause the dilution of reacting species, the authors speculate that the dissolution of N₂ and CO₂ have different impacts on the reaction; some dissolved CO₂ molecules come in contact with the substrate having a polar –CN group although no strong interactions appear under the reaction conditions used as indicated by FTIR (data shown in Fig. 1 later). This might be a microscopic description of the macroscopic dilution effects of CO₂ observed. Microscopic structure around an organic substrate molecule depends on the nature of solvent [24] and also probably on the nature of gaseous species (CO₂, N₂ in the present case). In contrast, N₂ is unlikely to show such an impact due to its non-polar nature. The reaction occurs in organic phase in the absence of H₂O but, when H₂O is used, the main reaction locus changes from the organic phase to the interfacial layer between the organic and aqueous phases, which include the substrate and the catalyst of hydrophilic nature, respectively. It may be more difficult for the two reacting species to contact with one another at the interface. Those impacts of CO₂ and H₂O should result in a decrease in the conversion. However, the desired product of PPA was obtained in a larger selectivity (entry 4), which may be explained by considering a few factors. The PPA molecule is soluble in H₂O and exists in the form of stable carbamate salt with CO₂ in the aqueous phase. The acidic nature of H₂O caused by the dissolution of CO₂ should also contribute to stabilize the carbamate species. When water is pressurized by CO₂ at pressures of 1–8 MPa, the pH value decreases to about 3 [25, 26]. The transfer of PPA molecules into the aqueous phase may reduce the chance of PPA to react with intermediate species in the organic phase yielding the secondary amine. The formation of such carbamate species with CO₂ was indicated for several amines in the literature [18, 27, 28]. The acidic nature of H₂O would also have resulted in the higher conversion of PEC in *n*-hexane - CO₂ - H₂O than that in *n*-hexane - H₂O.

Table 1Results of PEC hydrogenation in different reaction media including CO₂ and/or H₂O

Entry	Medium	Time (min)	Conversion (%)	Selectivity (%)	
				PPA	BPPA
1	Toluene	60	71	0	> 99
2	Toluene - CO ₂	60	48	0	> 99
3	Toluene - H ₂ O	60	6	0	> 99
4	Toluene - CO ₂ - H ₂ O	60	32	82	18

Reaction conditions: PEC 1 mmol (0.131 g), 5 wt.-% Pd/Al₂O₃ catalyst 65.6 mg, toluene 10 cm³ (for 1, 2) and 5 cm³ (for 3, 4), H₂O 5 cm³ (for 3, 4), 323 K, H₂ 4 MPa, CO₂ 1 MPa

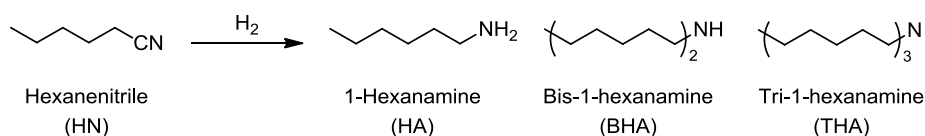
The results of CN hydrogenation are presented in Table 2, indicating that H₂ was selectivity added to C=C bond but not to C≡N bond and so PEC was exclusively obtained in four different reaction media (entries 1 - 4) under the conditions used. The rate of hydrogenation of C=C bond is larger than that of C≡N bond. It is expected, for the toluene - CO₂ - H₂O medium, that the product of PEC would further be hydrogenated to PPA for a longer reaction time, according to the results of Table 1. The presence of H₂O has negative and positive impacts in the toluene - H₂O and toluene - CO₂ - H₂O media, respectively, on the CN conversion, as mentioned for the results of PEC (Table 1).

Table 2Results of CN hydrogenation in different reaction media including CO₂ and/or H₂O

Entry	Medium	Time (min)	Conversion (%)	Selectivity (%)		
				PEC	PPA	BPPA
1	Toluene	30	>99	> 99	0	0
2	Toluene - CO ₂	30	>99	> 99	0	0
3	Toluene - H ₂ O	30	56	> 99	0	0
4	Toluene - CO ₂ - H ₂ O	30	87	> 99	0	0

Reaction conditions: CN 1 mmol (0.129 g), 5 wt.-% Pd/Al₂O₃ catalyst 64.5 mg, toluene 10 cm³ (for 1, 2) and 5 cm³ (for 3, 4), H₂O 5 cm³ (for 3, 4), 323 K, H₂ 4 MPa, CO₂ 1 MPa

An aliphatic nitrile of HN was also examined, for which *n*-hexane was used instead of toluene due to its solubility. The results obtained in different reaction media are presented in Table 3. The primary amine was not detected to form in *n*-hexane and *n*-hexane - CO₂ (entries 1, 2) and the conversion of HN in *n*-hexane - H₂O was very small (entry 3) under the conditions used. Although the rate of HN conversion was small, the primary amine of HA was selectively formed in *n*-hexane - CO₂ - H₂O medium (entry 4). The rate of HN conversion in *n*-hexane - CO₂ - H₂O is again larger than that in *n*-hexane - H₂O.

Table 3Results of HN hydrogenation in different reaction media including CO₂ and/or H₂O

Entry	Medium	Time (min)	Conversion (%)	Selectivity (%)		
				HA	BHA	THA
1	<i>n</i> -Hexane	60	87	0	18	82
2	<i>n</i> -Hexane - CO ₂	60	52	0	38	62
3	<i>n</i> -Hexane - H ₂ O	180	<0.1	0	0	0
4	<i>n</i> -Hexane - CO ₂ - H ₂ O	300	32	> 99	0	0

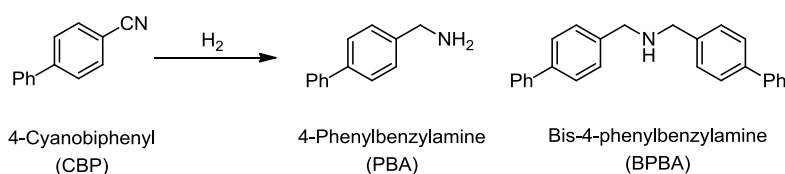
Reaction conditions: HN 1 mmol (0.0972 g), 5 wt.-% Pd/Al₂O₃ catalyst 48.6 mg, *n*-hexane 10 cm³ (for 1, 2) and 5 cm³ (for 3, 4), H₂O 5 cm³ (for 3, 4), 323 K, H₂ 4 MPa, CO₂ 1 MPa

Finally, a large aromatic nitrile of CBP was tested and the results obtained are given in Table 4. The primary amine was exclusively formed in toluene, toluene - CO₂, and toluene - H₂O (entries 1 - 3). In this hydrogenation, the primary amine, 4-phenylbenzylamine (PBA), is less soluble in H₂O and so it stays in the organic phase; however, its selectivity is high at relatively high conversion levels, suggesting that the second step of PBA transformation to the secondary amine (Bis-4-phenylbenzylamine, BPBA) is slower compared to the first one of hydrogenation of CBP to PBA. This may be due to difference in the structure between CBP and PBA molecules; CN group is bonded to the phenyl ring in a large conjugated system in the former but not NH₂ group in the latter. The differences in the rate of CBP conversion among these media were not so large as compared to the results of PEC (Table 1) and HN (Table 3). The dissolution of CO₂ causes the dilution of reacting species in the organic phase (toluene) as above-mentioned but, concurrently, it assists the dissolution of a gaseous reactant of H₂. That is, the pressurization with CO₂ has positive and negative impacts depending on the type and nature of reactions and reaction conditions. For the present case of toluene - CO₂ in which the CBP conversion is slightly larger than that in neat toluene (entries 1, 2), positive impact should be larger than that of negative one. For the toluene - CO₂ - H₂O medium, CBP

was observed to be consumed in a conversion of 32% but PBA and BPBA were not detected to form and products were unable to identify at present.

Table 4

Results of CBP hydrogenation in different reaction media including CO₂ and/or H₂O



Entry	Medium	Time (min)	Conversion (%)	Selectivity (%)	
				PBA	BPBA
1	Toluene	60	70	> 99	0
2	Toluene - CO ₂	60	76	> 99	0
3	Toluene - H ₂ O	60	61	> 99	0
4	Toluene - CO ₂ - H ₂ O	60	34	0	0

Reaction conditions: CBP 0.5 mmol (0.0895 g), 5 wt.-% Pd/Al₂O₃ catalyst 44.8 mg, toluene 10 cm³, H₂O 5 cm³ (for 3, 4), 323 K, H₂ 4 MPa, CO₂ 1 MPa

Furthermore, molecular interactions of CO₂ with the substrates (PEC, CN, HN, CBP) were measured by *in situ* high-pressure FTIR in attenuated total reflection mode (ATR) at a reaction temperature of 323 K [20, 21]. Fig. 1 shows FTIR spectra collected at different CO₂ pressures. The peaks of the absorption bands of stretching vibration of nitrile group were located at 2220 - 2250 cm⁻¹ depending on the structure of substrates examined. The absorption peak was blue-shifted with increasing CO₂ pressure for all substrates in common although the extent of blue-shift depended on the substrates. Those results indicate that C≡N bond becomes stronger through interactions with CO₂ and its reactivity is likely to be reduced. At a low CO₂ pressure of 1 MPa used in the present reaction runs, however, such an effect of CO₂ should not be taken into consideration.

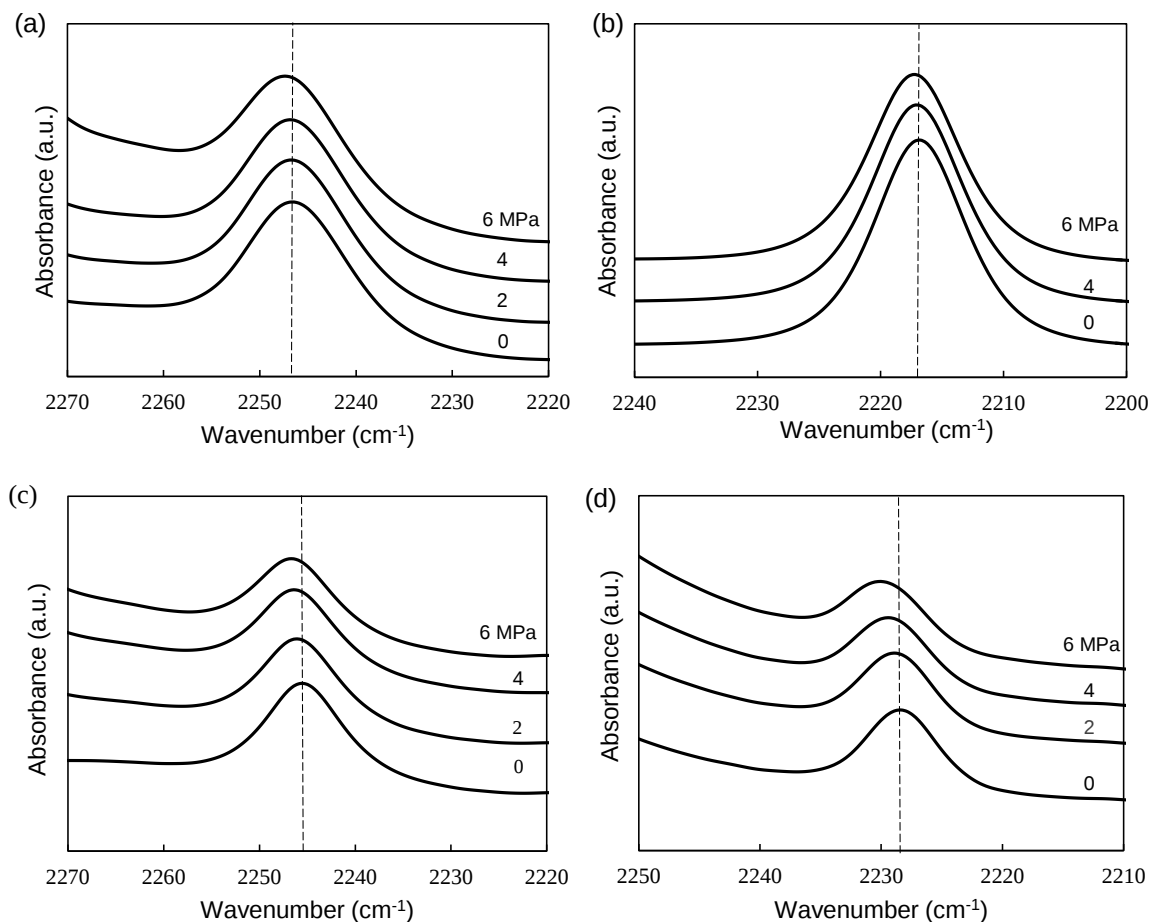


Fig. 1. *In-situ* high pressure FTIR-ATR spectra collected at 323 K for (a) neat PEC, (b) neat CN, (c) neat HN and (d) CBP in toluene under compressed CO₂ at pressures given.

Interactions of organic substrates with another component of H₂O would have impacts on the reaction. In hydrogenation of nitrobenzene with a Ni/Al₂O₃ catalyst, the reactivity of N-O bond of the substrate is lowered by interactions with CO₂ while that of an intermediate of phenylhydroxylamine is enhanced [15, 16]. In addition, interactions with H₂O also have an impact of enhancing the reactivity of the intermediate, as indicated by FTIR-ATR [17]. This leads to the complete (100%) selectivity to the desired product of aniline at any conversion level. For the present H₂O - nitrile substrates, unfortunately, it is difficult to make similar FTIR-ATR measurements with homogeneous aqueous solutions because of their low solubility in H₂O.

4. Conclusions

The organic solvent (toluene, n-hexane) - CO₂ - H₂O medium has been demonstrated to be effective for the selective hydrogenation of nitriles to corresponding primary amines with aromatic and aliphatic nitriles of PEC and HN, similar to BN and BC, but, unfortunately, not for CBP. The rate of nitrile conversion in this multiphase medium is smaller than that in neat organic solvents. This should result from the dilution of reacting species in the liquid phase by the dissolution of CO₂, the change of reaction locus from the organic phase to the organic - aqueous interfacial layer, and the decreased reactivity of nitrile group via interactions with CO₂ molecules. It is interesting to apply the multiphase reaction medium including CO₂ and H₂O for other synthetic reactions. A few positive examples are reported for hydrogenation of nitro [17] and carbonyl [29] substrates and dehydration of 1, 4-butanediol to tetrahydrofuran [30].

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