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A Study of Amidocarbonylation Reactions Catalyzed by Pd/HZSM-5

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A HZSM-5-supported palladium catalyst, which was prepared by the conventional impregnation method, was utilized in amidocarbonylation reactions. Several important parameters were optimized to give moderate to excellent yields. The catalyst recycling of Pd/HZSM-5, for the first time, was achieved for at least four run times without depreciation of catalytic activity. The studies of TEM images revealed that agglomeration of the palladium species of Pd/HZSM-5 catalyst was avoided after reaction, which was quite different from the case of Pd/C catalyst.

The synthesis of various functionalized *N*-acylamino acids have been realized via amidocarbonylation. In this one-step reaction, *N*-acyl-α-amino acid was obtained from cheap materials, i.e., an aldehyde, an amide, and carbon monoxide, without stoichiometric by-products in the presence of transition-metal catalysis.

Several transition metals can be applied as the catalysts in amidocarbonylation. The first cobalt-complex was discovered by Wakamatsu et al. in 1971,[1] and subsequently palladium-catalyzed amidocarbonylation was reported by Beller et al.[2] in 1997. The latter group also examined the catalytic activities of rhodium, iridium, and ruthenium complexes in this type of reaction.[3] Recently, platinum-catalyzed amidocarbonylation was reported by Sagae et al.[4] Among them, palladium demonstrated the highest activity. For practical application, however, the homogeneous palladium catalysts are expensive and unrecoverable. To solve these problems the heterogeneous catalyst Pd/C in amidocarbonylation was improved by Beller et al.[5] and another heterogeneous catalyst (polymer incarcerated palladium) was reported by Kobayashi et al.[6] The heterogeneous catalyst could be recoverable by filtering, but no experimental evidence on the reuse of catalysts have been provided in the literature.[5,6] From an economic point, the reuse of expensive palladium catalysts is very important. In the present study, Pd/HZSM-5 catalyst was prepared by the conventional impregnation method and applied in the amidocarbonylation. The catalyst recycling of Pd/HZSM-5 catalyst, for the first time, was achieved without loss of catalytic activity in four run times. This finding makes amidocarbonylation greatly attractive in practical application.

Experimental

Catalyst Preparation. HZSM-5 support with the SiO_2/Al_2O_3 ratio = 30 was purchased from PQ Corporation (Netherlands). The preparation of 10 wt % Pd/HZSM-5 catalyst as follow: 0.185 g of $PdCl_2$ was solved in 20 mL of water (5 mL of hydrochloric acid was necessary to make the solution of $PdCl_2$) and 1.0 g of HZSM-5 powder was dipped into the solution for 3 days. The solution was baked, the $PdCl_2$/HZSM-5 powder was added into 25 mL of ethanol, and then 2.0 mL of 85% hydrazine hydrate was added under stirring into the mixture of ethanol and $PdCl_2$/HZSM-5 powder. After reduction, the black precipitate was filtered and washed with ethanol several times, and then dried in vacuum before use in the reaction.

The 10 wt % Pd/C catalyst was obtained from Shanghai Chemical Company.

Amidocarbonylation. All of the aldehydes and solvents were dried and distilled before use. Acetamide and LiBr were dried in an oven (120 °C) for 4 h.

A 100 mL autoclave with a magnet-driven stirrer was used for pressurized reaction conditions.

General Procedure: 30 mmol aldehyde and amide were dissolved in 60 mL of solvent, 1.0 mol % 10 wt % Pd/HZSM-5, 6.0 mol % H_2SO_4, and 35 mol % LiBr were allowed to react under 6.0 MPa CO at a designed temperature for 16 h. As the reaction finished, Pd/HZSM-5 was filtered and the volatile components were removed in vacuum; the residue was taken up into a 50 mL saturated aqueous solution of $NaHCO_3$. Washing with 50 mL of chloroform and 50 mL of ethyl acetate, the aqueous solution was adjusted to pH 2 with 50% phosphoric acid. The precipitate was filtered off and washed with water. The aqueous phase was extracted with ethyl acetate (80 mL, 3 times) and the combined organic phase was dried over $MgSO_4$. Then, the organic solvent was removed under vacuum, the residue and the precipitate were combined and dried in the oven. The purity of the products, as measured by HPLC, was greater than 97%.

The procedure of catalyst recycling is as follows: after reaction, 10 wt % Pd/HZSM-5 catalyst was filtered off and washed by fresh NMP, and then the catalyst was dried at 55 °C for 8 h before the next run.

The purity of the product was measured by HPLC (Aglient 1100 series) equipped with a C_{18} column: The mobile phase was methanol and the flow rate was 1.0 mL min^{-1}. The TEM images of the 10 wt % Pd/HZSM-5 and 10 wt % Pd/C were taken by a JEM-200CX. The leaching of Pd/HZSM-5 and Pd/C to the organic solvent were measured by a Thermo Jarrell Ash Corporation's IRIS Intrepid II (detecting limit was 5 ppm).

Results and Discussion

In the present work, amidocarbonylation of isovaleraldehyde catalyzed by Pd/HZSM-5 was performed under similar reaction conditions to those described in the references (Scheme 1).[5]

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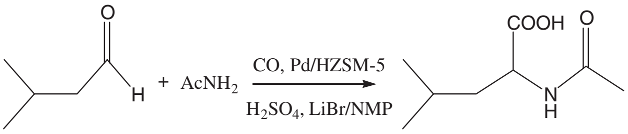


Scheme 1.

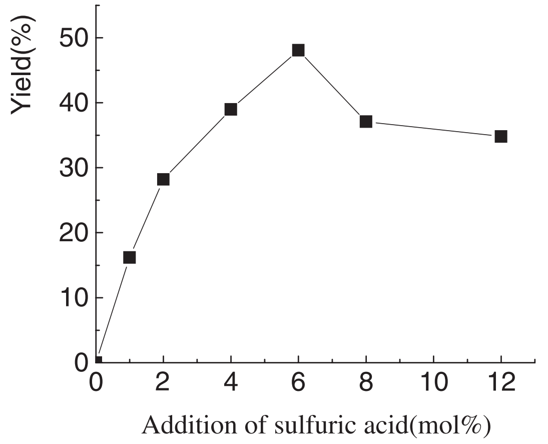


Fig. 1. Influence of H_2SO_4 concentration in the amidocarbonylation catalyzed by Pd/HZSM-5. Reaction conditions: 30 mmol isovaleraldehyde and amide, 60 mL NMP, 1.0 mol % Pd/HZSM-5, and 35 mol % LiBr were treated with 6.0 MPa CO at 90 °C for 16 h, without addition of PPh_3.

According to the reaction mechanism proposed by Beller et al.,[7] the co-catalyst H_2SO_4 was necessary for the formation of an α-haloamide intermediate, which leads to the formation of *N*-acyl-α-amino acid. The influence of the concentration of H_2SO_4 on catalytic performance was studied and the results revealed that more than 4.0 mol % of acid is necessary, as shown in Fig. 1.

Almost no *N*-acylleucine was obtained without adding H_2SO_4 into the catalyst system. With increasing the H_2SO_4 concentration, the yield of *N*-acylleucine gradually increased till the addition of H_2SO_4 reached 6.0 mol %. However, the yields of *N*-acylleucine were slightly decreased when the concentration of H_2SO_4 exceeded 6.0 mol %. These results were analogous to those reported by Beller et al.[7] in the amidocarbonylation of propionaldehyde.

The solvent was an important parameter in this reaction.[6,7] Kobayashi et al.[6] found that the mixture solvents accelerated the amidocarbonylation. Therefore, in the present study several types of solvent mixture were examined (see Table 1). The results showed that the mixture solvent NMP/toluene = 3 (Entry 3) exhibited the best performance (56.0% yield without adding PPh_3), which is applicable for further study.

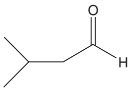
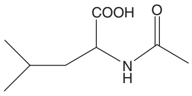
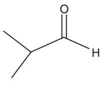
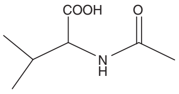
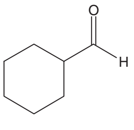
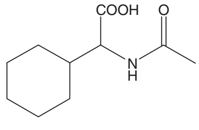
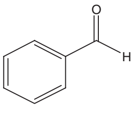
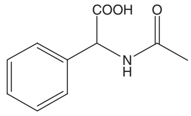
According to the reference,[5] the phosphine ligand was not necessary in the amidocarbonylation, but we found that in the presence of triphenylphosphine could increase the yield of *N*-acylamino acid (Entry 1 in Table 2 compared with Entry 3 in Table 1). The reason is under investigation. Therefore, triphenylphosphine was added into the system for 10 wt % Pd/HZSM-5 catalyzed amidocarbonylation of other aldehydes. The results are given in Table 2.

Table 1. Screening Different Solvent in the Amidocarbonylation Catalyzed by Pd/HZSM-5[a)]

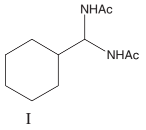
Entry	Solvent[b)] (V/V)	Yield[c)]/%
1	NMP	47.0
2	NMP/Tol = 2	46.9
3	NMP/Tol = 3	56.0
4	NMP/Tol = 4	40.4
5	DMI/THN = 3	43.7
6	NMP/THN = 3	43.1

a) Reaction conditions: 30 mmol isovaleraldehyde and amide, 60 mL solvent, 1.0 mol % Pd/HZSM-5, 6 mol % H_2SO_4, and 35 mol % LiBr were treated with 6.0 MPa CO at 90 °C for 16 h without addition of PPh_3. b) Tol: toluene; DMI: 1,3-dimethyl-2-imidazolidinone; THN: 1,2,3,4-tetrahydronaphthalene. c) Product yield: based on the purity determined by HPLC and isolated yield.

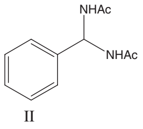
Table 2. Amidocarbonylation Catalyzed by 10 wt % Pd/HZSM-5 Catalyst[a)]

Entry	Staring compound	*N*-acylamino acid[b)]	Yield/%[c)]
1			62.3
2			39.2
3			88.4[d)]
4			40.0[e)]

a) Reaction conditions: 30 mmol aldehyde and amide, 45 mL NMP, 15 mL toluene, 1.0 mol % Pd/HZSM-5, 1.0 mol % PPh_3, 6 mol % H_2SO_4, and 35 mol % LiBr were treated with 6.0 MPa CO at 90 °C for 16 h. b) The products in Entries 1 and 2 were confirmed by HPLC analysis. The products in Entries 3 and 4 were confirmed by direct insertion ESI-MS (esquire 3000 plus), $M + Na^+ = 222$ in Entry 3 and $M + Na^+ = 216$ in Entry 4. c) Product yield: based on the purity determined by HPLC and isolated product. d) The byproduct I was isolated and confirmed by direct insertion ESI-MS ($M + Na^+ = 235$). e) The byproduct II was isolated and confirmed by direct insertion ESI-MS ($M + Na^+ = 229$).



I



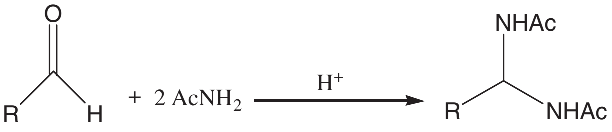
II

In these reactions, Pd/HZSM-5 catalyst gave moderate (Entries 1, 2, and 4) to excellent yields (Entry 3). It indicated that the HZSM-5-supported palladium catalyst demonstrated efficient catalytic activities in the amidocarbonylation reactions.

By-products **I** and **II** were isolated and identified by direct insertion ESI-MS (Esquire 3000 plus). The bisamides were formed in a side reaction (Scheme 2) by condensation of aldehyde with two equivalents of acetamide catalyzed by H_2SO_4.[8,9]

In order to examine the catalyst recycling of the heterogeneous palladium catalysts, amidocarbonylation of isovaleraldehyde and cyclohexanecarboxaldehyde catalyzed by recovered Pd/HZSM-5 and Pd/C was performed. The results are presented in Table 3.

It can be seen from Table 3 that the Pd/HZSM-5 catalyst can be reused at least four times without loss of catalytic activity (Entries 2 and 4), while Pd/C catalyst gave unsatisfactory results. The fresh Pd/C catalyst gave the target product yields of 64.4% (Entry 1) and 94.3% (Entry 3). However, in the catalyst recycling, the yields dramatically declined, and then almost remained at the same level for the remaining runs (≈30% yields in Entry 1 and ≈60% yields in Entry 3). Nevertheless, after reaction no palladium leaching of Pd/HZSM-5 or Pd/C catalysts to the organic solvent was detected in all runs. To explain these results, the images of transmission electron micrographs of Pd/HZSM-5 and Pd/C catalysts were taken and are presented in Figs. 2 and 3, respectively. It can be seen from Figs. 2a and 3a that before reaction the dispersion status of palladium particles was quite uniform over both Pd/HZSM-5 and Pd/C catalysts. After reaction, however, the palladium particles over Pd/C catalyst agglomerated and formed a network (Fig. 2b), which led to loss of the active sites of the palladium species and a decrease in its catalytic activity. However, the dispersion of the palladium particles of Pd/HZSM-5

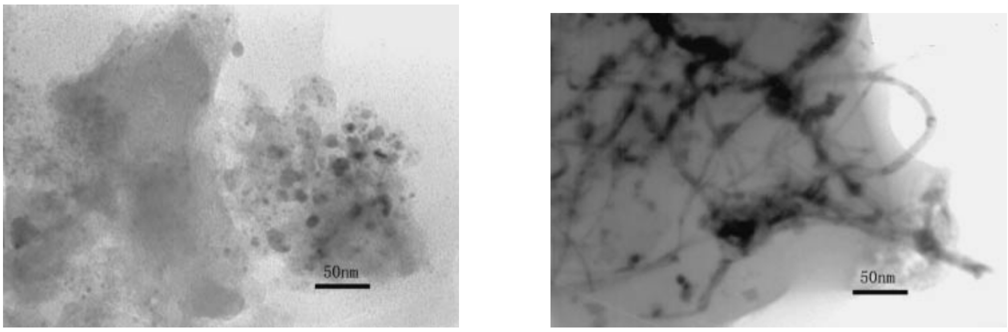


Scheme 2.

Table 3. A Comparison of the Catalyst Recycling of Pd/HZSM-5 and Pd/C Catalysts in Amidocarbonylation[a)]

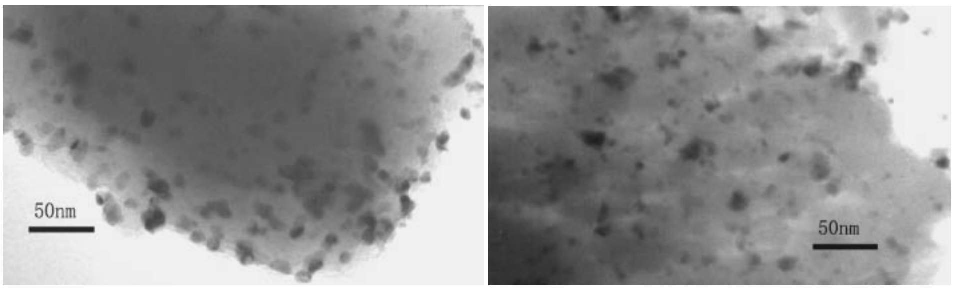
Entry	Catalyst	Product[b)]	Yield/%[c)]				
			1st run	2nd run	3rd run	4th run	5th run
1	Pd/C	**A**	64.4	30.8	30.5	30.6	—
2	Pd/HZSM-5	**A**	62.3	61.6	61.2	60.2	59.9
3	Pd/C	**B**	94.3	61.0	60.2	59.8	—
4	Pd/HZSM-5	**B**	88.4	88.4	88.2	88.0	87.5

a) Reaction conditions: 30 mmol aldehyde and amide, 45 mL NMP, 15 mL toluene, 1.0 mol % Pd/HZSM-5, 1.0 mol % PPh_3, 6 mol % H_2SO_4, and 35 mol % LiBr were treated with 6.0 MPa CO at 90 °C for 16 h. b) **A**: *N*-acylleucine, **B**: *N*-acylcyclohexylglycine. c) Product yield: based on the purity determined by HPLC and isolated yield.



(a) (b)

Fig. 2. (a) TEM image of Pd/C before reaction. (b) TEM image of Pd/C after reaction.



(a) (b)

Fig. 3. (a) TEM image of Pd/HZSM-5 before reaction. (b) TEM image of Pd/HZSM-5 after reaction.

catalyst almost remains the same uniform dispersion status (Fig. 3b). Agglomeration of the palladium species of Pd/HZSM-5 catalyst is avoided during reaction by using HZSM-5 as the support.

This observation may be attributed to palladium species incorporation into the cages of HZSM-5 zeolite, which is a similar situation to that reported in the literature.[10–12] Therefore, the successful recycling of Pd/HZSM-5, for the first time, has been achieved in amidocarbonylation reactions. This is an attractive finding for the promising industrial application for amidocarbonylation.

Conclusion

The heterogeneous palladium catalyst, Pd/HZSM-5, was successfully utilized in amidocarbonylation reactions. Particularly, the reuse of this catalyst for at least four run times without loss of catalytic activity was achieved; while Pd/C catalyst demonstrated unsatisfactory recycling owing to agglomeration of palladium particles after reaction. The TEM images revealed that no agglomeration took place over Pd/HZSM-5 catalyst after reactions. It was attributed to palladium species incorporation into the cages of HZSM-5 support.

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