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Imidazolium-based polymer supported gadolinium triflate as a heterogeneous recyclable Lewis acid catalyst for Michael additions

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Abstract

A heterogeneous Lewis acid catalytic system has been developed by incorporating gadolinium triflate on to poly[styrene-*co*-(1-((4-vinylphenyl)methyl)-3-methylimidazolium) tetrafluoroborate] (**1**-Gd(OTf)$_3$), and the catalytic activity of this system has been examined for Michael additions of amines and thiols to α,β-unsaturated esters and acrylonitrile. The reactions proceed in moderate to excellent yields in the presence of catalytic system **1**-Gd(OTf)$_3$. The catalytic system could be efficiently recycled and reused.

Keywords: Gadolinium triflate; Michael additions; Heterogeneous catalysis; Acrylonitrile; Methyl acrylate

1. Introduction

One of the main themes of contemporary synthetic organic chemistry is the development of atom-economic and environmentally benign catalytic systems.[1] In this context, the development of heterogeneous catalysis is of prime importance not only from the economic point of view, but also due to the easy workup procedures involved in the separation of products from catalyst. Imidazolium-based supported catalysis is receiving increasing attention due to the inherent advantages of the recyclability of the catalyst system from the reaction mixture.[2] Aluminum chloride complexes of supported ionic liquids based on silica support have been used in Friedel–Crafts alkylation and acylation reactions.[3] Recently, imidazolium salts covalently attached to polystyrene supports have been shown to be efficient catalysts for the nucleophilic fluorination reactions.[4] Kobayashi and Nagayama reported a polystyrene supported Lewis acid catalyst which was useful for various organic transformations.[5] They also have reported Gd(OTf)$_3$ as a water-tolerant Lewis acid catalyst for aldol reactions of silyl enol ethers with aldehydes in aqueous media.[6] We have recently shown that Gd(OTf)$_3$ can be used as a mild and recyclable reagent for acylation of alcohols and amines.[7] As part of our ongoing research on Lewis acid catalyzed reactions, we now report a novel heterogeneous catalytic system which involves incorporation of Gd(OTf)$_3$ onto poly[styrene-*co*-(1-((4-vinylphenyl)methyl)-3-methylimidazolium) tetrafluoroborate] (**1**-Gd- (OTf)$_3$) as an active catalyst for the Michael additions of various aliphatic and aromatic amines, and thiols to α,β-unsaturated esters and acrylonitrile.

2. Results and discussion

We have initially explored the catalytic system **1**-Gd(OTf)$_3$ for Michael additions of amines to methyl acrylate and acrylonitrile, and compared it to that of the polystyrene-based catalytic system, PS-Gd(OTf)$_3$. The Michael addition products of methyl acrylate are potentially useful

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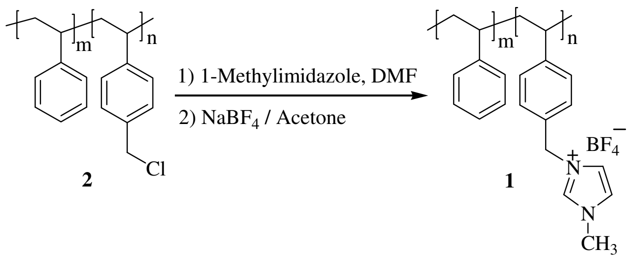
intermediates for the preparation of β-amino esters, which show biologically important properties and can be used as precursors for the preparation of β-lactams.[8] There are several reported examples of the preparation of β-amino esters by Lewis acid mediated Michael additions of amines to α,β-unsaturated esters. However, some of these procedures suffer from poor yields and are limited to aliphatic amines.[9] Further, Michael addition of thiols to α,β-unsaturated esters leads to β-thio esters which have important biological applications.[10]

Our control experiments revealed that under solvent-free conditions, PS-Gd(OTf)$_3$ and **1**-Gd(OTf)$_3$ gave similar yields of the products for the Michael addition of *N*-methylaniline to methyl acrylate. However, whereas the former catalytic system involves a homogeneous reaction medium, the latter provided a heterogeneous medium resulting in relative ease in product separation from the catalytic system. The workup of the reaction mixture using the latter catalytic system is greatly simplified as it involves addition of the solvent ethyl acetate, followed by filtration and solvent evaporation. The catalyst system could thus be recycled conveniently. Because of the ease of separation of products from the catalyst system, and the ready recyclability of the catalyst system, we have extended this reaction to the Michael additions of a variety of secondary amines and thiols to methyl(ethyl) acrylate, methyl methacrylate, and acrylonitrile.

Poly[styrene-*co*-4-chloromethylstyrene] (**2**),[11] prepared by AIBN initiated polymerization of styrene with 4-vinylbenzyl chloride in chlorobenzene as the solvent, was reacted with 1-methylimidazole in dimethylformamide to obtain the poly[styrene-*co*-(1-((4-vinylphenyl)methyl)-3-methylimidazolium) chloride]. Anion exchange[4] of the latter polymer using NaBF$_4$ furnished polymer **1**, which was immobilized with catalytic amounts of Gd(OTf)$_3$ (Scheme 1).

The **1**-Gd(OTf)$_3$ catalytic system was found to be convenient for the Michael additions of a variety of amines and thiols to α,β-unsaturated esters and acrylonitrile. The reactions proceeding under mild conditions and high yields of the adducts were obtained by simple workup procedures, which involve separation of the catalyst system by filtration and solvent evaporation. Most of the reactions were complete in about 1 h at room temperature, using as low as 0.5 mol % of the catalyst based on Gd(OTf)$_3$. Relatively longer reaction times and larger amounts of catalyst (up to 3 mol %) were required for the reactions of *N*-methylaniline and *p*-methoxyaniline (Table 1, entries 4, 10, and 13). A relatively more nucleophilic primary aliphatic amine, benzylamine, on the other hand, gave exclusively the bis-addition product, *N*,*N*-bis[2-(methoxycarbonyl)-ethyl]-benzylamine, as shown by GC/MS analysis.[9c] These reactions are not synthetically useful for sterically crowded β-substituted Michael acceptors, as reaction of methyl 3-methyl-2-butenoate with *N*-methyl benzylamine gave only 19% of the Michael addition product, as shown by GC/MS analysis.



Scheme 1. Preparation of poly[styrene-*co*-(1-((4-vinylphenyl)methyl)-3-methylimidazolium) tetrafluoroborate].

The catalytic system, **1**-(Gd(OTf)$_3$), could be recycled and re-used for subsequent runs. Catalytic activity of the catalyst is maintained for at least 3 cycles (Table 1, entries 1, 3, and 5). However, this catalytic system failed to give Michael adducts with the weakly nucleophilic benzyl carbamate, in accordance with earlier observations for the related catalytic systems.[12]

In order to confirm the true heterogeneity of the catalytic system (i.e., the absence of leaching of the Gd(OTf)$_3$ into the reaction mixture), we have removed the catalyst by decantation at 9% completion of the reaction, and let the reaction proceed in the absence of the catalyst for 24 h, for the reaction shown in Table 1, entry 4. Analysis of the reaction mixture after 24 h by GC/MS showed 12% completion of the reaction, indicating that there was no leaching of the Gd(OTf)$_3$ into the reaction mixture.

Further, we confirmed the absence of leaching of the catalytic system by ICP-MS analysis for the Michael reaction of morpholine with methyl acrylate (Table 1, entry 1), We observed less than 0.1 ppm (corresponds to 1.513×10^{-6} wt %) of the catalyst leaching for this reaction. However, we have observed relatively more leaching for the reactions using acetonitrile as solvent (<600 ppm corresponds to 5.68×10^{-2} wt %), comparable with those of the reported (polymer-micelle)-incarcerated catalytic systems.[13] Based on these data, solvent-free reaction conditions are more ideally suited for our polymer supported catalytic system. It is worth noting, however, that some of the polymer-adsorbed Lewis acids involving AlCl$_3$ show significant leaching of the catalyst during the reaction.[14]

In summary, we have developed a novel heterogeneous catalytic system by incorporating the Lewis acid catalyst Gd(OTf)$_3$ onto the imidazolium-based polymer **1**, and showed that it can be used as a convenient catalyst for Michael additions of a variety of secondary amines to α,β-unsaturated esters and acrylonitrile. The catalytic system could be efficiently recycled and reused. Surface study of the catalytic system using scanning electron-microscopy (SEM) coupled with compositional mapping indicates that Gd(OTf)$_3$ is uniformly distributed on the polymer. Further applications of the catalytic system for Lewis acid-catalyzed organic reactions are currently under progress in our laboratory.

Table 1
Solvent-free **1**-(Gd(OTf)3)-catalyzed Michael addition of amines and thiols to α,β-unsaturated esters and acrylonitrile

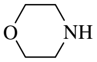
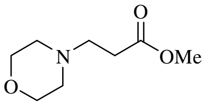
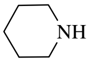
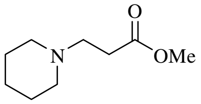
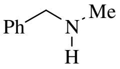
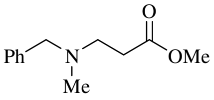
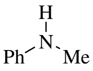
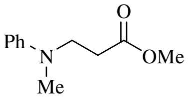
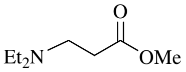
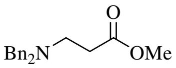
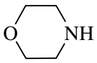
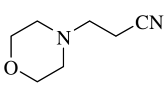
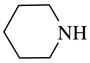
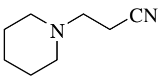
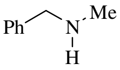
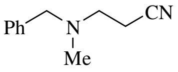
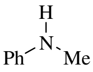
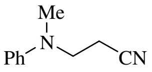
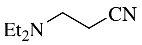
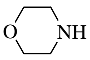
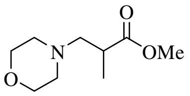
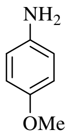
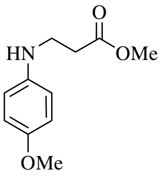
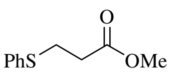
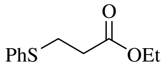
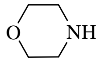
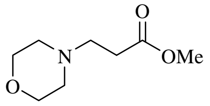
Entry	Amine/thiol	Substrate[d]	Product	Yield[a] (%)
1		**3a**		98 (92, 96)[c]
2		**3a**		95
3		**3a**		94 (96, 91)[c]
4		**3a**		63[b]
5	Et_2NH	**3a**		86 (91, 89)[c]
6	Bn_2NH	**3a**		82[b]
7		**3d**		90
8		**3d**		90
9		**3d**		92
10		**3d**		32[b]
11	Et_2NH	**3d**		83
12		**3c**		99[b]
13		**3a**		71[b]
14	PhSH	**3a**		99[b]

Table 1 (*continued*)

Entry	Amine/thiol	Substrate[d]	Product	Yield[a] (%)
15	PhSH	**3b**		98[b]
16		**3a**		98[b,e]

[a] Isolated yields (0.5 mol % of the catalyst was used); reactions were carried out at room temperature for 1 h, with the exception for entries 4, 10, and 13 (24 h and 3 mol % of the catalyst).

[b] Yields based on GC/MS.

[c] Yields for 2nd and 3rd cycles.

[d] **3a** = methyl acrylate; **3b** = ethyl acrylate; **3c** = methyl methacrylate; **3d** = acrylonitrile.

[e] Reaction was carried out in acetonitrile as solvent.

3. Experimental

3.1. Procedure for the incorporation of Gd(OTf)$_3$ onto polymer **1**

Acetone (40 mL) was added to polymer **1** (1.0 g), followed by Gd(OTf)$_3$ (200 mg), and stirred at room temperature for 24 h. Acetone was evaporated and the polymer dried under vacuum for 4 h to give **1**-Gd(OTf)$_3$ as a powdery material.

3.2. General procedure for michael additions

To a mixture of the secondary amine (5.7 mmol) and methyl acrylate (or acrylonitrile) (11.4 mmol), **1**-Gd(OTf)$_3$ (0.5 mol % based on gadolinium triflate) was added at room temperature under solvent-free conditions and stirred for 1 h (for reactions involving *N*-methylaniline reaction times of over 24 h are required). After completion of the reaction, ethyl acetate (10 mL) was added, filtered, and the solvent evaporated under vacuum to obtain the products, essentially pure by NMR (98%). ^{1}H and ^{13}C NMR, and GC/MS of the products are in agreement with the literature data.[15] The catalytic system was dried for 3 h under vacuum and recycled for subsequent runs. Relatively high conversions could be achieved in the second and third cycles (Table 1, entries 1, 3, and 5). In a controlled experiment in the absence of the catalyst, for the reaction shown in Table 1, entry 4, no product was detected even after 24 h at room temperature.

Acknowledgments

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