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HIGHLY EFFICIENT CONDENSATION OF GLYCEROL TO CYCLIC ACETALS CATALYZED BY TITANIUM-EXCHANGED MONTMORILLONITE

Takato Mitsudome,[1] Tsuyoshi Matsuno,[1] Shoichiro Sueoka,[1]
Tomoo Mizugaki,[1] Koichiro Jitsukawa,[1] and Kiyotomi Kaneda,[1,2]*

[1] Department of Materials Engineering Science, Graduate School of Engineering Science, Osaka University, 1-3 Machikaneyama, Toyonaka, Osaka, 560-8531, Japan. [2] Research Center for Solar Energy Chemistry, Osaka University, 1-3 Machikaneyama, Toyonaka, Osaka, 560-8531, Japan.
e-mail: kaneda@cheng.es.osaka-u.ac.jp
Fax: +81 6-6850-6260; Tel: +81 6-6850-6260

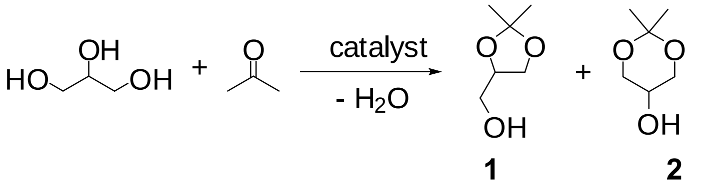
Abstract – Titanium cation-exchanged montmorillonite (Ti^{4+}-mont) showed high catalytic activity for the condensation reaction of glycerol with ketones or aldehydes to provide cyclic acetals under mild conditions. The solid Ti^{4+}-mont catalyst could be easily separated after the reaction and reused without any loss of activity.

The conversion of biomass to valuable chemicals is a significant issue in green and sustainable chemistry. A large amount of glycerol is formed as a by-product during the production of biodiesel by the transesterification of vegetable oils and animal fats.[1] The rapid increase in demand for biodiesel has caused an oversupply of glycerol. Therefore, the development of catalytic processes for transformation of abundant glycerol to value-added molecules has attracted much attention from both academia and industry as a promising solution to this problem. The condensation reaction of glycerol with carbonyl compounds to the corresponding cyclic acetals is one of the most important transformations for the effective utilization of glycerol.[2] The protection of two hydroxyl groups of glycerol allows its use as a platform chemical for the selective synthesis of three-carbon chemicals such as propanediol, acrolein, and dihydroxyacetone. Furthermore, cyclic acetals are valuable additives for diesel fuels, flavor compounds and cosmetic chemicals. The dehydrative condensation has been carried out using conventional acid catalysts such as sulfuric acid, hydrochloric acid or *p*-toluenesulfonic acid, resulting in the production of salt waste from the neutralization of these acids after the reaction. Alternatively, a number of homogeneous transition metal catalysts for the condensation under neutral conditions has been reported such as Pd(II) and Pt(II) complexes,[3] and $[Cp^*IrCl_2]_2$.[4] However, these catalyst systems suffer from several drawbacks including the difficulty of catalyst separation and recycling. To overcome these problems, solid acid catalysts such as MoO_3/SiO_2,[5] phosphomolybdic acid,[6] Amberlyst-36[7] and zeolite Beta[8] have been developed.

Montmorillonites of smectite clays are composed of negatively charged layers and an interlayer containing cationic species. The cationic species can be easily replaced by other metal polycations and these ion-exchanged montmorillonites have great potential as solid acid catalysts for many environmentally friendly reactions because the selection of different polycations enables tuning of their acidity.[9] We have recently succeeded in creating a chain-like titanium oxide species within the interlayers of montmorillonite (Ti^{4+}-mont), which acts as an efficient heterogeneous Brønsted acid catalyst for the acetalization of carbonyl compounds, the deprotection of acetals and the esterification of carboxylic acids.[10] Herein, we report the efficient Ti^{4+}-mont-catalyzed condensation of glycerol with carbonyl compounds to the cyclic acetals. The reaction proceeds at room temperature, and the used Ti^{4+}-mont catalyst is easily separable from the reaction mixture and reusable while maintaining its high efficiency.

The condensation of glycerol with acetone as both reactant and solvent using Ti^{4+}-mont was conducted at room temperature for 6 min.[11] Glycerol was smoothly converted to 1,3-dioxolane (**1**) in 88% yield with the production of small amounts of 1,3-dioxane (**2**) (entry 5). With further stirring of the reaction mixture for a total of 15 min, **1** was exclusively obtained in over 99% yield (entry 1). The product **2** was transformed to **1** during the reaction through the hemiacetal intermediate.[7] Among the solid acid catalysts tested, Ti^{4+}-mont showed the highest catalytic activity. Commercially available acid catalysts of H-ZSM-5 and zeolite Beta gave moderate yields of the cyclic acetals (entries 6 and 7). The use of Nafion NR50 and montmorillonite K-10 resulted in low yields under the present reaction conditions (entries 8 and 9), and H-Y hardly functioned as a catalyst (entry 10). At 50% conversion of glycerol, Ti^{4+}-mont was removed from the reaction mixture, and further treatment of the resulting filtrate under similar reaction conditions did not afford any products, confirming that Ti^{4+}-mont acted as a heterogeneous catalyst in this condensation reaction. An additional advantage of this solid catalytic system was its reusability. The Ti^{4+}-mont catalyst was easily separated from the reaction mixture by simple filtration and was reusable without loss of its high activity (entries 2-4).[12] Ti^{4+}-mont was also applicable to large-scale reactions. For example, 9.2 g of glycerol (100 mmol) with acetone was sufficiently converted to 12.9 g of **1** (98% isolated yield) with excellent selectivity under mild reaction conditions.[13]

Table 1. The condensation of glycerol with acetone using acid catalysts[a]



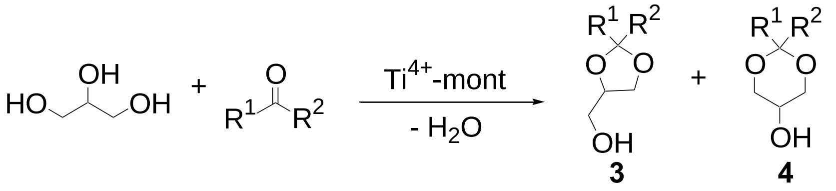
Entry	Catalyst	Time (min.)	Yield of **1** (%)[b]	Yield of **2** (%)[b]
1	Ti^{4+}-mont	15	>99	<1
2	Reuse 1	15	>99	<1
3	Reuse 2	15	>99	<1
4	Reuse 3	15	99	1
5	Ti^{4+}-mont	6	88	5
6	H-ZSM-5	6	17	5
7	H-Beta	6	16	4
8	Nafion NR50	6	7	3
9	K-10	6	5	2
10	H-Y	6	1	0

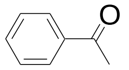
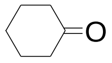
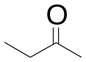
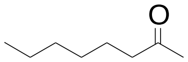
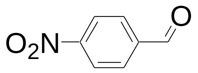
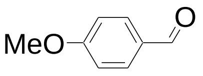
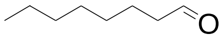
[a] Reaction conditions: catalyst (0.05 g), glycerol (5 mmol), acetone (4 mL), room temperature. [b] Yields were determined by GC based on glycerol.

The substrate scope of Ti^{4+}-mont for the condensation of glycerol with various ketones and aldehydes was investigated using a 1:2 molar ratio of the reactants in the presence of molecular sieves (Table 2). Glycerol was consumed completely at room temperature, giving the corresponding cyclic acetals. Ketones selectively gave the 1,3-dioxolanes in excellent yields (entries 1-4). Aldehydes also reacted sufficiently with glycerol, affording mixtures of 1,3-dioxolanes and 1,3-dioxanes (entries 5-7). *The dehydrative condensation of glycerol using Ti^{4+}-mont proceeded efficiently under milder reaction conditions than those of previously reported catalyst systems that required higher reaction temperature*[5] *or reflux conditions.*[6,8]

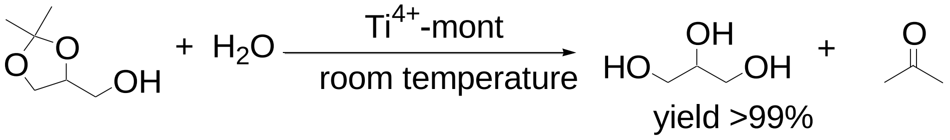
Ti^{4+}-mont was also found to act as an efficient catalyst for the reverse reaction, i.e., the deprotection of glycerol cyclic acetal in water (Scheme 1).[14] This phenomenon demonstrates that Ti^{4+}-mont enables the use of various carbonyl compounds as protective groups of glycerol, which can lead to selective transformations of glycerol by the combination of other oxidation or reduction reactions.

Table 2. The synthesis of cyclic acetals from glycerol using Ti^{4+}-mont[a]



Entry	Carbonyl compound	Time (h)	Yield (**3** + **4**)[b] (%)	Ratio **3:4**
1		15	96	98:2
2		1	99	99:1
3		0.5	99	>99:<1
4		8	95	99:1
5		15	97	66:34
6		8	99	42:58
7		1	94	60:40

[a] Reaction conditions: Ti^{4+}-mont (0.1 g), glycerol (1.0 mmol), carbonyl compound (2 mmol), molecular sieves 4A (0.5 g), 1,4-dioxane (5 mL), room temperature. [b] Yields were determined by GC based on glycerol.



Scheme 1. Deprotection of cyclic glycerol acetal catalyzed by Ti^{4+}-mont

In conclusion, Ti^{4+}-mont acted as a highly efficient heterogeneous acid catalyst for the condensation reaction of glycerol with carbonyl compounds and deprotection of cyclic acetals under mild conditions. Ti^{4+}-mont was also reusable without any loss of activity and applicable to large-scale conditions.

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11. Ti^{4+}-mont was prepared according to our previous report; see reference 10d. A typical condensation reaction of glycerol with acetone was carried out in a Schlenk glass tube. The glass tube was charged with glycerol (5.0 mmol), acetone (4 mL) and Ti^{4+}-mont (0.05 g). The reaction mixture was vigorously stirred at room temperature. The solid catalyst was removed by filtration and the yield was determined by GC analysis using an internal standard technique.
12. The recycling experiments were conducted as follows; after the condensation of glycerol, the mixture of Ti^{4+}-mont and molecular sieves were recovered by filtration, washed with 1,4-dioxane and dried at 110 °C in air for 3 h. Then, another portion of glycerol and carbonyl compounds were added, followed by stirring in the same manner as identical reaction conditions of the first run.
13. Scale-up condensation reaction of glycerol was carried out as follows; Ti^{4+}-mont (0.5 g), glycerol (100 mmol) and acetone (300 mL) were placed in a flask. The reaction mixture was vigorously stirred at room temperature for 3 h. After the addition of magnesium sulfate, the mixture was filtered.

The resulting filtrate was concentrated to afford 12.9 g of **1** (98% isolated yield) which was confirmed by GC.

14. Deprotection of **1** was carried out as follows; Ti^{4+}-mont (0.05 g), water (4 mL) and **1** (5 mmol) were placed in a Schlenk tube. The reaction mixture was vigorously stirred at room temperature for 24 h. The yield of glycerol was determined by GC analysis.