

ZnCl₂, ZnI₂ and TiCl₄ supported on silica gel as catalysts for the Diels–Alder reactions of furan

J.M. Fraile, J.I. García, J. Massam, J.A. Mayoral^{*}, E. Pires

Departamento de Química Orgánica, Instituto de Ciencia de Materiales de Aragón, C.S.I.C.-Universidad de Zaragoza, Facultad de Ciencias, E-50009 Zaragoza, Spain

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Abstract

ZnCl₂, ZnI₂ and TiCl₄ supported on silica gel are compared with their non-supported counterparts in the reactions of furan with acrylonitrile, 2-chloroacrylonitrile and methyl acrylate. The results obtained depend on the nature of both the dienophile and the catalyst. Whereas ZnCl₂ and ZnI₂ supported on silica gel lead to very good results with both nitriles and TiCl₄ supported on silica gel cannot be used with these dienophiles, ZnCl₂ and TiCl₄ supported on silica gel are better catalysts when methyl acrylate is used as a dienophile. ZnCl₂ and ZnI₂ supported on silica gel can be recovered and reused in the reactions with nitriles, but only the first catalyst is recoverable in the reactions of methyl acrylate. ZnCl₂ supported on silica gel is the catalyst with a wider applicability in these reactions with furan.

Keywords: Diels–Alder; Heterogeneous catalysis; ZnCl₂/silica; ZnI₂/silica; TiCl₄/silica; Furan; α , β -Unsaturated dienophiles

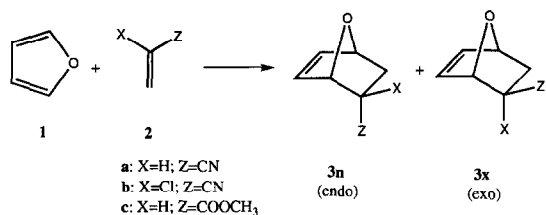
1. Introduction

Several Lewis acids supported on silica gel have shown to be efficient catalysts in Lewis acid catalyzed organic reactions [1]. For instance, ZnCl₂ supported on silica gel has shown to be a very efficient catalyst in the Friedel–Crafts alkylation of benzene with alkyl chlorides, and it has been shown that this catalyst is similar to clayzic (ZnCl₂ supported on K10 montmorillonite) [2,3]. ZnCl₂ [4], TiCl₄ and AlEt₂Cl [5,6] supported on silica gel catalyze Diels–Alder reactions with different dienophiles.

In all these reactions there is a close relationship between the nature of the reagents and the catalytic performance of these solids. So, clayzic has shown rather disappointing activities in the alkylation of anisole [7] and in Friedel–Crafts acylations [8]. ZnCl₂ and AlEt₂Cl supported on silica gel have been compared as catalysts in Diels–Alder reactions with different dienophiles and the catalyst of choice depends on the nature of the dienophile. So, whereas the aluminium catalyst is more efficient in reactions of acrylates, the reverse is true when the dienophile is acrylonitrile.

ZnCl₂ and TiCl₄ supported on silica gel have shown to be efficient catalysts in Diels–Alder reactions of some acid-sensitive reagents and,

^{*} Corresponding author. E-mail: gas@qorg.unizar.es.



Scheme 1.

used in the absence of a solvent, they improve the selectivity with regard to side reactions. For instance, they promote Diels–Alder reactions of non-chiral [9] and chiral [10] (*E*)-2-phenyl-5(4*H*)-oxazolones without causing *E/Z* isomerization.

In view of this we decided to try to increase the scope of applicability of these catalysts by using them in Diels–Alder reactions of an acid-sensitive diene, as furan, with three different dienophiles (Scheme 1). Given that ZnI₂ is one of the best catalysts described to date for these reactions, ZnI₂ supported on silica was also studied.

We decided to use furan for several reasons. First of all furan is an inexpensive compound obtained from agricultural left-overs [11]. Furthermore, its Diels–Alder cycloadducts are powerful intermediates in the preparation of rare carbohydrates and other biologically active compounds (for a review see [12]). Finally, furan is an acid-sensitive reagent, and its cycloadducts are thermally unstable, so that neither the most common Lewis acids nor heating can be used to promote its Diels–Alder reactions. A lot of alternatives have been developed, including for instance, very long reaction times [13], high pressure [14,15] or the use of cupric fluoroborate coupled with long reaction times [16]. The best results have been obtained using ZnI₂ and a reaction temperature of 40°C, which, given the boiling point of furan, requires the reactions to be carried out in a sealed tube and, as a consequence, under an autogenerated pressure. Under these conditions high yields are obtained after 48 h, but without any endo/exo

selectivity [17]. The only precedents about the use of heterogeneous catalysts in Diels–Alder reactions of furan are the use of cation exchanged K10-montmorillonite [18] and Y zeolite [19].

It is well known that supported catalysts can have different activities than their homogeneous counterparts, and that they can lead to different selectivities. When possible, this effect was also considered by comparison of the supported and non-supported catalysts used in exactly the same conditions.

2. Experimental

ZnCl₂ and ZnI₂ were supported on silica gel EP11 from Crossfield as previously described for ZnCl₂ [2,3] and activated by heating at 150°C for 1 h under a flow of dry air prior to use. TiCl₄ was supported on Merck silica gel 60 by means of the previously described method [5,6] and activated by heating at 140°C overnight under vacuum.

2.1. Reaction procedure

Under argon, 1 mmol of the dienophile (2a–2c) and 6 mmol of freshly distilled furan were added on the catalyst (1 g of supported catalyst or 2 mmol of ZnX₂). The mixture was shaken for the corresponding time (Table 1) and after this time CDCl₃ was added. In most of cases the catalyst was removed by filtration (microfiltration with the non-supported catalysts), washed with CDCl₃, and the results of the reactions determined by ¹H-NMR. In the reactions of methyl acrylate (2c) promoted by ZnI₂ or ZnI₂/SiO₂ the solutions obtained after the separation of the catalyst were shaken with Na₂CO₃ · 10H₂O which was separated by filtration and the solution analyzed by ¹H-NMR. The products (3) were recovered by eliminating the CDCl₃ and the remaining reagents by distillation under reduced pressure. The NMR spectra

Table 1
Results obtained in the reaction of furan (1) with acrylonitrile (2a), 2-chloroacrylonitrile (2b) and methyl acrylate (2c) at room temperature

| Entry | Dienophile | Catalyst | Time (h) | Yield (%) ^a | 3n:3x ^a |
|-------|------------|--|----------|------------------------|--------------------|
| 1 | 2a | ZnCl ₂ | 3 | 48 | 55:45 |
| 2 | 2a | ZnCl ₂ /SiO ₂ (1.5) ^b | 3 | 78 | 67:33 |
| 3 | | | 6 | 84 | 66:34 |
| 4 | | | 9 | 95 | 63:37 |
| 5 | 2a | ZnCl ₂ /SiO ₂ (1.5) ^c | 3 | 78 | 67:33 |
| 6 | | | 6 | 83 | 66:34 |
| 7 | 2a | ZnCl ₂ /SiO ₂ (2.0) ^d | 3 | 90 | 65:35 |
| 8 | 2a | ZnCl ₂ /SiO ₂ (2.0) ^c | 3 | 84 | 66:34 |
| 9 | 2a | ZnI ₂ | 3 | 85 | 58:42 |
| 10 | 2a | ZnI ₂ /SiO ₂ (2.0) | 3 | 76 | 78:22 |
| 11 | 2a | ZnI ₂ /SiO ₂ (2.0) ^c | 3 | 70 | 78:22 |
| 12 | 2a | TiCl ₄ /SiO ₂ | 24 | 0 | — |
| 13 | 2b | ZnCl ₂ | 3 | 30 ^e | 67:33 |
| 14 | 2b | ZnCl ₂ /SiO ₂ (1.5) | 3 | 60 ^f | 72:28 |
| 15 | 2b | ZnCl ₂ /SiO ₂ (2.0) | 1 | 73 ^f | 60:40 |
| 16 | | | 3 | 55 ^f | 38:62 |
| 17 | 2b | ZnCl ₂ /SiO ₂ (2.0) ^c | 3 | 59 ^f | 50:50 |
| 18 | 2b | ZnI ₂ | 3 | 45 ^f | 78:22 |
| 19 | 2b | ZnI ₂ /SiO ₂ (2.0) | 3 | 55 ^f | 70:30 |
| 20 | 2b | ZnI ₂ /SiO ₂ (2.0) ^c | 3 | 57 ^f | 70:30 |
| 21 | 2c | TiCl ₄ /SiO ₂ | 3 | 46 | 88:12 |
| 22 | | | 24 | 71 | 73:27 |
| 23 | 2c | ZnCl ₂ | 3 | 5 | 83:17 |
| 24 | | | 24 | 47 | 78:22 |
| 25 | 2c | ZnCl ₂ /SiO ₂ (2.0) | 3 | 41 | 86:14 |
| 26 | | | 24 | 75 | 81:19 |
| 27 | 2c | ZnCl ₂ /SiO ₂ (2.0) ^c | 24 | 50 | 74:26 |
| 28 | 2c | ZnI ₂ | 3 | 32 | 70:30 |
| 29 | | | 24 | 90 | 67:33 |
| 30 | 2c | ZnI ₂ /SiO ₂ (2.0) | 3 | 11 | 63:37 |
| 31 | | | 24 | 58 | 50:50 |

^a Determined by NMR; for 2b the endo and exo isomers were assigned by the chemical shift of the nitrile carbon in ¹³C-NMR (3nb = 114.16 ppm, 3xb = 114.30 ppm) and for 2c on the basis of previously described spectra [13].

^b 1.5 mmol ZnCl₂ per gram of catalyst.

^c Recovered catalyst.

^d 2.0 mmol of ZnX₂ per gram of catalyst.

^e CH₃CHClCN is formed in less than 1%.

^f 5% CH₃CHClCN is formed.

were in agreement with those previously described.

2.2. Recovering of the catalyst

After the reaction, the supported ZnCl₂ or ZnI₂ was separated by filtration, thoroughly washed with CH₂Cl₂, and activated by heating

at 150°C for 1 h under a flow of dry air. TiCl₄ supported on silica gel loses most of its catalytic activity after recovering [5,6].

3. Results and discussion

The results obtained in the reactions of furan (1) with acrylonitrile (2a), 2-chloroacrylonitrile (2b) and methyl acrylate (2c) are gathered in Table 1. There is a close relationship between the nature of the dienophile and the performance of the catalyst. When acrylonitrile (2a) is used as a dienophile, TiCl₄/SiO₂ cannot be used as a catalyst because the reagents are destroyed without leading to the cycloadducts (entry 12). The highest chemical yields are obtained with ZnCl₂/SiO₂ and ZnI₂ (entries 4, 7 and 9), whereas the highest endo/exo selectivities are obtained with the supported catalysts. It is known that in Diels–Alder reactions of furan the endo/exo selectivity can be modified with the time due to the reversibility which leads to an increase of the amount of the more stable exo cycloadduct. It may be speculated that the increase in endo/exo selectivity obtained with the supported catalysts is due to a more difficult retro-Diels–Alder reaction. Whereas ZnCl₂/SiO₂ is a much better catalyst than ZnCl₂ (entries 1 and 7), the behavior of ZnI₂/SiO₂ and ZnI₂ is not very different (entries 9 and 10). The influence of the amount of supported Lewis acid has been studied with ZnCl₂/SiO₂ and it has been shown that slightly better results are obtained when this amount increases (entries 2 and 7). The supported catalysts can be recovered and reused without modification of the results (entries 5, 6, 8 and 11), this result was not easily predictable because the use of coordinating reagents could cause the leaching of the supported Lewis acid.

When 2-chloroacrylonitrile (2b) is used as a dienophile ZnI₂ and ZnI₂/SiO₂ lead to similar results (entries 18 and 19) whereas ZnCl₂/SiO₂ is more efficient than ZnCl₂ (entries 13 and 15).

The influence of the reversibility on the endo/exo selectivity is clearly shown with $\text{ZnCl}_2/\text{SiO}_2(2.0)$; in this case the endo or exo cycloadducts are preferably obtained as a function of the time (entries 15 and 16), furthermore the exo preference after 3 h is not observed when the solid contains only 1.5 mmol ZnCl_2/g (entry 14). The supported catalysts can be again recovered and reused (entries 17 and 20).

We have finally tested a different type of dienophile, methyl acrylate (**2c**) and have obtained very different results. Whereas TiCl_4 cannot be used in this reaction, silica gel treated with TiCl_4 is a good catalyst (entries 21 and 22). If this behavior is compared with the reaction of furan with acrylonitrile (entry 12) it can be concluded that it is the dienophile and not the diene that is responsible for these differences. Unluckily this catalyst loses most of its catalytic activity when recovered [5,6]. As it happens with the other dienophiles $\text{ZnCl}_2/\text{SiO}_2$ leads to better results (entries 25 and 26) than ZnCl_2 (entries 23 and 24), and the supported catalyst can be recovered and reused (entry 27) but it loses some of its catalytic activity; elemental analysis indicates that there is not leaching of ZnCl_2 but some organic products, probably polymers, remain and poison the catalyst. ZnI_2 leads to better results (entries 28 and 29) than $\text{ZnI}_2/\text{SiO}_2$ (entries 30 and 31) and in both cases the reduction of the selectivity with the time is observed. The cycloadducts form strong complexes with ZnI_2 which difficults the work-up and, in the case of the supported catalyst, produces the leaching of ZnI_2 and the catalyst cannot be recovered.

4. Conclusions

It can be concluded that, in general, supporting on silica gel improves the applicability of ZnCl_2 , ZnI_2 and TiCl_4 in Diels–Alder reactions of furan. There is a close relationship between the nature of the dienophile and the performance of the catalyst. So, whereas TiCl_4

supported on silica gel cannot be used in reactions with nitriles, it leads to very good results in the reaction of furan with methyl acrylate. The reversal is true with ZnI_2 supported on silica gel which cannot be used with methyl acrylate because of the leaching of the ZnI_2 . ZnCl_2 supported on silica gel is probably the best and more general catalyst described for these reactions. Furthermore it can be recovered and reused with the three dienophiles. The amount of supported catalyst and the reaction time have a noticeable influence on the chemical yield and the endo/exo selectivity.

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