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# Heterogenized Gold Complexes: Recoverable Catalysts for Multicomponent Reactions of Aldehydes, Terminal Alkynes, and Amines

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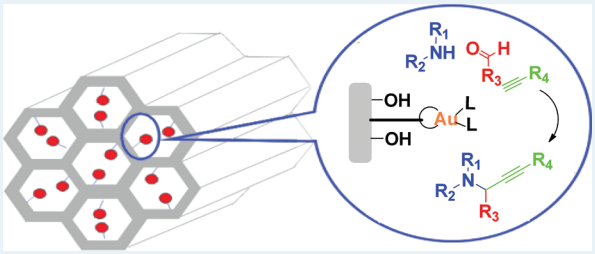
Supporting Information

**ABSTRACT:** A series of gold complexes were tested as catalysts in the synthesis of propargylamines by the three component coupling reaction of amines, aldehydes, and alkynes. These complexes are efficient catalysts for the three-component coupling reaction (yields up to 97%). In homogeneous solution, the conversions to the respective propargylamine were higher than under heterogeneous conditions. Heterogenized complexes were stable and recoverable for at least six cycles. Ligands, gold(I) or gold(III), homogeneous or heterogenized systems have pronounced effects on the catalytic activity of the corresponding gold complexes.




**KEYWORDS:** *Heterogenized catalysts, MCR, gold, propargylamine*

## INTRODUCTION

One of the fundamental aspects in green chemistry is linked to the number of steps in organic synthesis as well as atom economy. Multicomponent reactions (MCRs) are thus becoming an increasingly important class of reactions because they allow several starting materials to be combined, usually to form a single compound and in a one-pot operation.[1−8] They therefore exhibit an economy of steps and often atom economy, most of the incoming atoms being linked together in a single product, and have emerged as a powerful tool in the synthesis of biologically important compounds for reducing operative steps and enhancing synthesis efficiency.[9−11]

Combining these aspects with heterogeneity and catalysis would reinforce the "greenness" of such reactions. To offer solutions to such problems, we are currently applying mesoporous support as MCM-41, modified or unmodified, to organic synthesis.[12−17] Yu et al.[18] recently described a polystyrene-immobilized homogeneous gold(I) complex, which showed remarkable catalytic activities and recyclability in three model transformations: the 3,3-rearrangement and Nazarov reaction of an enynyl acetate, the cyclization of a 1,6-enyne, and the rearrangement of an alkyne furan. In this work, we describe a heterogenized gold-catalyzed synthesis of propargylic amines through a three-component reaction (Scheme 1).

Propargylamines are high-value building blocks in organic synthesis,[19] and their structural motif has been found in various natural products[20,21] and in compounds of pharmaceutical[22−27] or phytoprotective[28] importance. The conventional methods for their synthesis involve the amination of propargylic halides, phosphates, or triflates.[29−31] Another possible way is the reaction of lithium acetylides or Grignard reagents with imines or their derivatives.[32−37] However, these methods require the use of stoichiometric amounts of organometallic reagents and strictly controlled reaction conditions. They can be obtained by the addition of alkynes to imines,[19] but because imines are easily formed from aldehydes and amines, three-component versions of the reaction are known, either as such[38,39] or promoted by various transition metals as copper,[40−48] gold,[49−53] iridium,[54,55] ruthenium,[56] silver,[57−63] and zinc[64] etc. The use of these homogeneous catalysts, however, has some disadvantages, because they are expensive and not recyclable and their separation from the reaction mixture is tedious.

**Scheme 1. Metal-Catalyzed Three-Component Synthesis of Propargylamines**


This has led to the elaboration of different heterogeneous, recyclable catalysts. Lo and co-workers[65] developed a gold-based complex, which was successfully used in aqueous media for the preparation of propargylamines. In addition, a supported gold(III)−metal organic framework catalyst[66] has

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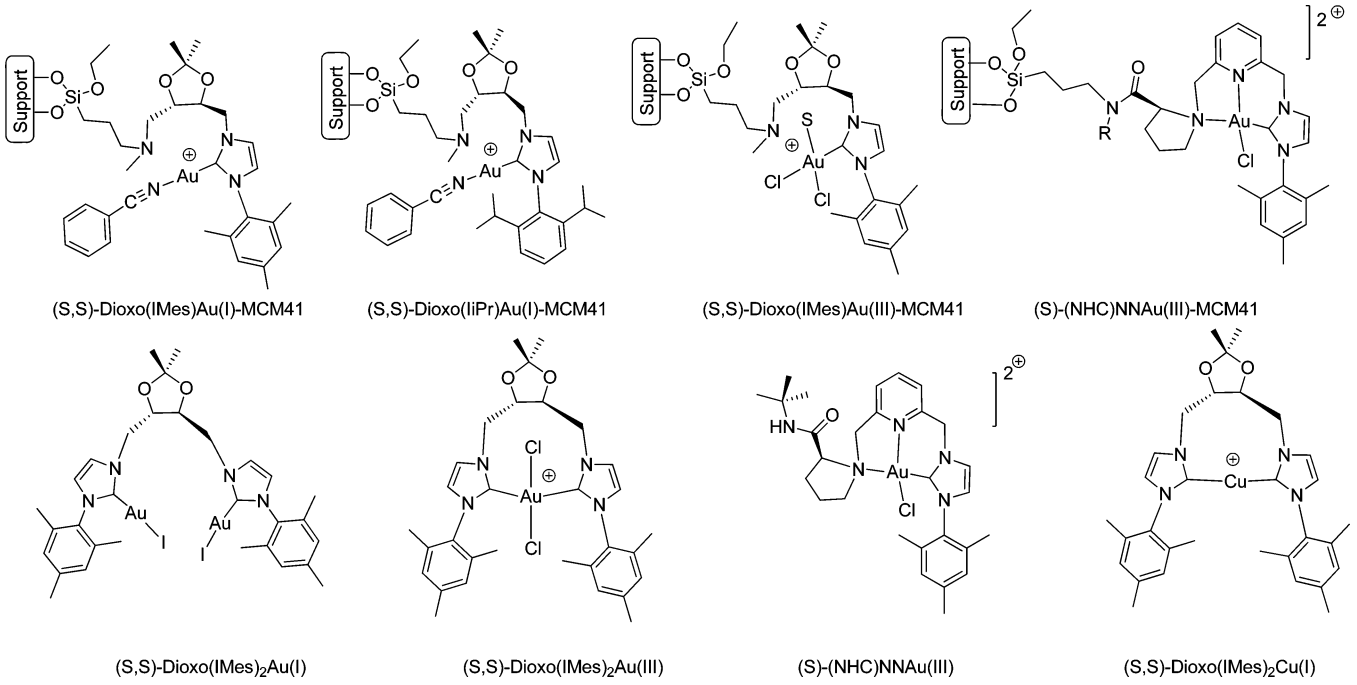
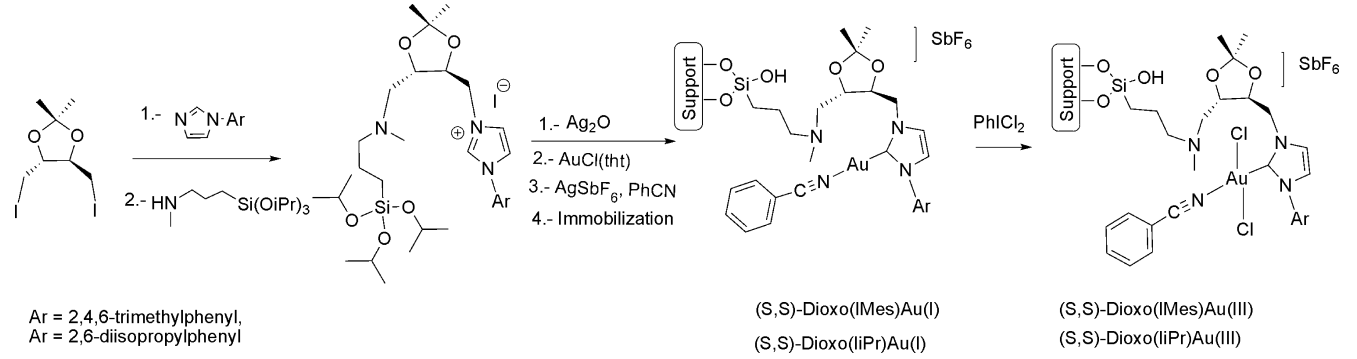
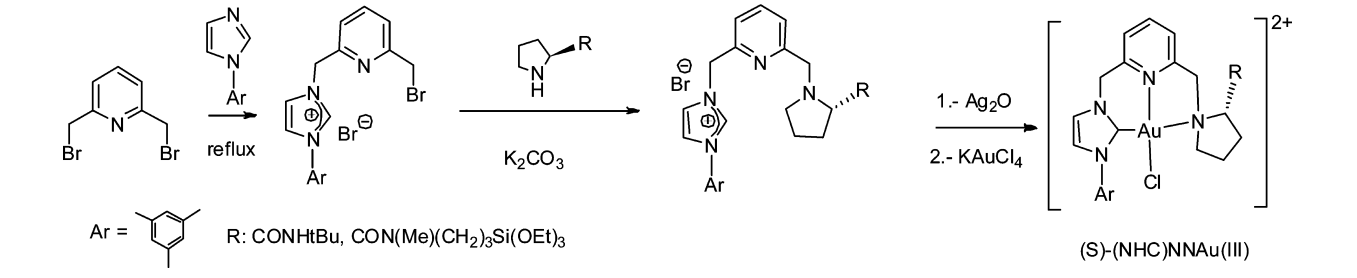



**Figure 1.** Gold and copper catalysts.

**Scheme 2. Synthesis of (NHC)Dioxolane−Gold Catalysts**




**Scheme 3. Synthesis of (NHC)NN-Gold(III) Catalysts**




been reported as highly active and selective for domino coupling and cyclization reactions in liquid phase. Other metal-based heterogeneous catalysts have also been used successfully; for example, in AgI−tungstophosphoric acid,[60] CuI anchored on a silica gel support[67] or on USY-zeolite,[68] $Cu^{II}$ salt on a hydroxyapatite support,[69] or N-heterocyclic carbene−CuI on a silica support.[70,71] Since MCR catalysis with gold salts/complexes indicates that Au(III) and Au(I) could be active species,[49−53] we examine here the possibility of the applicability of heterogenized (NHC) gold catalysts, depicted in Figure 1, in a three-component reaction and show that they are highly active, selective, and recyclable catalysts.

## RESULTS AND DISCUSSION

To search for the optimal catalyst, different transition metal complexes with N-heterocyclic carbene−dioxolane and pincer-type (NHC)NN ligands (Au(I), Au(III)), homogeneous and heterogenized on MCM-41 (Figure 1), were prepared according to a reported procedure.[12,13]

Gold complexes with a triethoxysilyl group ((*S*,*S*)-dioxo-(IMes)Au(I), (*S*,*S*)-dioxo(IiPr)Au(I), (*S*)-(NHC)NNAu(III))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shown in Schemes 2 and 3 were used in the MCM-41 heterogenization studies. Imidazolium salts are precursors to NHC ligands, and their gold complexes were synthesized by Lin's method of transmetalation from intermediate silver(I) complexes (Schemes 2, 3).[72−75] The trialkoxysilyl complexes were supported on MCM-41 by addition of the corresponding solution on a dispersion of MCM-41[76] in toluene and heating for 24 h affording the materials complex−MCM-41 with metal loadings of ∼1.6−2.0 wt % Au, corresponding to $8.1 \times 10^{-2}$ mmol·g$^{-1}$. The resulting solids were characterized by FT-IR, DRUV, and solid state CP MAS $^{13}$C NMR and compared with its counterpart before heterogenization.

Behavior of heterogenized gold complexes compared with similar soluble counterparts in MCRs was screened by using a classical reaction, the synthesis of propargylamines (Scheme 1). To determine the best reaction conditions required affording excellent yields of propargylamines (i.e., solvent, gold species in supported catalyst, and reaction time), a series of three-component reactions were carried out using benzaldehyde, piperidine, and phenylacetylene as model substrates (see Scheme 1).

For solvent-screening studies, a mixture of benzaldehyde (0.19 mmol), piperidine (0.22 mmol), phenyl acetylene (0.28 mmol), and the corresponding Au catalyst was stirred at different temperatures in 2 mL of a suitable solvent until the completion of the reaction (as monitored by GC and TLC). Table 1 shows that chloroform, is the most promising one because excellent yield of the desired 1-(1,3-diphenylprop-2-ynyl) piperidine product was obtained. Interestingly, when polar solvents such as ethanol, or acetonitrile were used as a solvent for this model reaction, only poor to moderate yields for the desired product was obtained. As can be deduced from Table 1, the reaction was more dependent on temperature than on solvent polarity. Indeed, reaction yields were higher at solvent reflux temperature (example: entries 2, 3, 5, 6) than at room temperature (entries 1, 4).

**Table 1. Screening of Catalysts and Reaction Conditions for the Three-Component Reaction[a]**

| entry | catalysts | solvent | $T$ (deg) | yield (%)[b] |
|---|---|---|---|---|
| 1 | dioxo(IMes)Au(I)−MCM-41 | EtOH | r.t | traces |
| 2 | | EtOH | reflux | 41 |
| 3 | | $CHCl_3$ | reflux | 85 |
| 4 | dioxo($I^iPr$)Au(I)−MCM-41 | EtOH | r.t | traces |
| 5 | | EtOH | reflux | traces |
| 6 | dioxo$(IMes)_2$Au(I) | EtOH | reflux | traces |
| 7 | | $CHCl_3$ | reflux | 99 |
| 8 | dioxo(IMes)Au(III)−MCM-41 | EtOH | reflux | traces |
| 9 | | $CHCl_3$ | reflux | 80 |
| 10 | dioxo$(IMes)_2$Au(III) | EtOH | 50 | traces |
| 11 | | EtOH | reflux | 22 |
| 12 | | $CHCl_3$ | reflux | 99 |
| 13 | (NHC)NNAu(III)−MCM-41 | EtOH | 50 | 64 |
| 14 | | $CHCl_3$ | reflux | 65 |
| 15 | (NHC)NNAu(III) | EtOH | 50 | 33 |
| 16 | | $CHCl_3$ | reflux | 94 |
| 17 | dioxo$(IMes)_2$Cu(I) | $CHCl_3$ | 40 | 5[c] |
| 18 | K[$AuCl_4$] | $CHCl_3$ | reflux | 63 |
| 19 | no catalyst | $CHCl_3$ | reflux | 0 |

[a]Reaction conditions: benzaldehyde (0.19 mmol), piperidine (0.22 mmol), phenyl acetylene (0.28 mmol), catalyst (1 mol % based on Au), and solvent (EtOH or $CHCl_3$, 2 mL) stirred at reflux temperature for 24 h. [b]Isolated yields based on benzaldehyde after silica-gel flash column chromatography. [c]Alkyne homocoupling.

On the other hand, Table 1 shows that gold(I) was more effective than copper(I), which behaves mainly as a catalyst for phenylacetylene homocoupling (entry 17). The copper-catalyzed reaction was performed at −20 °C to avoid the homocoupling of the alkyne.

Thus, the optimal catalytic conditions chosen are catalyst (1 mol %); chloroform as solvent (2 mL); at reflux temperature (70 °C); and aldehyde, amine, and alkyne in a 1:1.2:1.5 ratio. Under these conditions, the catalyst nature proved to be critical (homogeneous or supported). As expected for MCRs in which three molecules have to meet within the support pores, the shapes of the MCM-41 have a marked influence on the reaction efficiency. The reaction efficiency seemed directly correlated with the channel pore size (see entries 3 and 7, 9, and 12 or 14 and 16). In this MCR, the three starting reagents have to meet and react within the large pores of the support, which could accommodate three molecules together, and their intermediates gave lower yields than homogeneous systems, taking into account that the structure of reference homogeneous system is not exactly the same as the complex supported. No conversion was found in the absence of catalyst under identical conditions (entry 18), and the $KAuCl_4$-catalyzed reaction yields only 63% of the product. These results clearly emphasize the role of the support itself and the nature of gold.

Using the optimized reaction conditions, the one-pot, three component coupling reactions of various aldehydes, amines, and acetylenes were studied using Au(I)/Au(III) (homogeneous and supported) catalysts in chloroform. As was the case with the model reaction described in Scheme 1, 0.19 mmol of aldehyde, 0.22 mmol of amine, and 0.28 mmol of acetylene along with 1 mol % of Au catalyst, and 2 mL of chloroform was stirred at reflux for 24 h. For these studies, three different strategies were employed to explore the efficiency of homogeneous and heterogeneous Au catalytic systems for the synthesis of diverse propargylamines.

In the first strategy, the aldehyde substrate was kept constant (only benzaldehyde was used) and it was allowed to react with different heterocyclic amines, such as piperidine, morpholine, and pyrrolidine, or diisopropylamine along with acetylenic substrates such as phenylacetylene, tolylacetylene, 1-decyne, or trimethylsilylacetylene for the one-pot construction of propargylamines. The results obtained from these studies are presented in Tables 2−4. As can be seen from Table 2, pyrrolidine reacted easily with benzaldehyde and phenylacetylene and gave good yield for the desired product (Table 2, entries 4−9). Similarly, excellent yield of propargylamine was also obtained when piperidine was engaged to react with benzaldehyde and phenylacetylene under our experimental conditions (Table 2, entries 1−3). To verify whether long-chain aliphatic alkynes can also be catalytically activated, 1-decyne was allowed to react with benzaldehyde and piperidine under our optimized experimental conditions. As can be seen from Table 2, entry 3, this reaction also afforded excellent yield for the corresponding propargylamine product that contains long-chain aliphatic structural unit. This finding opens up immense possibility of synthesizing variety of propargylamine motifs containing long-chain acetylenic subunits in their molecular structures. The more bulky diisopropylamine gave only traces for the expected propargylamine.


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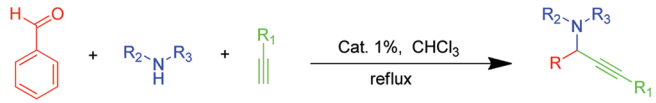
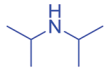
**Table 2. Effect of Alkyne and Amine on the Catalyzed Three-Component Reaction**[a]




| Entry | Catalysts | amine | $R^1$ | Yield (%)[b] |
|---|---|---|---|---|
| 1 | |  | Ph | 85 |
| 2 | Dioxo(IMes)Au(I)-MCM41 | | MePh | 82/48h |
| 3 | | | $C_8H_{17}$ | 97/48h |
| 4 | Dioxo(IMes)Au(I)-MCM41 | | Ph | 40 |
| 5 | Dioxo(IMes)Au(I) | | Ph | 20 |
| 6 | Dioxo(IMes)Au(III) |  | Ph | 48 |
| 7 | (NHC)NNAu(III)-MCM41 | | Ph | 49 |
| 8 | (NHC)NNAu(III) | | Ph | 93 |
| 9 | Dioxo(IMes)$_2$Cu(I) | | Ph | 21[c] |
| 10 | Dioxo(IMes)Au(I)-MCM41 |  | Ph | Traces |
| 11 | Dioxo(IMes)Au(I)-MCM41 |  | Ph | Traces |

[a]Reaction conditions: benzaldehyde (0.19 mmol), amine (0.22 mmol), alkyne (0.28 mmol), catalyst (1 mol %), in $CHCl_3$ (2 mL) at 70 °C for 24 h. [b]Yields of isolated product based on aldehyde. [c]Alkyne homocoupling.

With its electron-withdrawing oxygen atom in $\beta$-position to the nitrogen atom in a cyclohexyl structure, morpholine is less nucleophilic than piperidine. Indeed, when subjected to the above-mentioned conditions, the yield of the corresponding propargylamine was significantly lowered. Interestingly, trimethylsilylacetylene, a heteroatom (silicon) containing acetylene, also reacted with piperidine and benzaldehyde and gave good yields for the corresponding silicon-containing propargylamine product (Table 4). This result is very important because a heteroatom such as silicon can be synthetically manipulated using various organic synthesis techniques and, thus, could enable additional "structural motifs" to be introduced into the molecular structure that already contains propargylamine moiety.

The effect of the alkyne on the Au(I)−MCM-41-catalyzed MCR was also investigated. As already shown above, phenylacetylene was highly reactive, usually giving good to high yields of adducts (Table 2, entries 1−3). Tolylacetylene was less effective than phenylacetylene, giving the expected adduct in high yields after 48 h (entry 2). Aliphatic alkynes reacted as well as aromatic ones, as exemplified with 1-decyne, which gave the expected adduct in a high yield, similar to that obtained with tolylacetylene (entry 3). In these systems, we could also observe the support effect, which showed beneficial behavior for the soluble catalyst in s gold(I) system (Table 2, entries 4 and 5).

In the third strategy, various structurally divergent aldehydes were allowed to react with piperidine and phenylacetylene for the three-component coupling reaction. The results obtained from these studies are presented in Table 3. As can be seen from Table 3, the Au-based catalytic protocol is rather general in nature because it is applicable for a variety of electron-rich and electron-deficient aromatic aldehydes well as aliphatic aldehyde substrates, such as *n*-heptaldehyde, which readily reacts with piperidine and phenylacetylene to form the corresponding propargylamine product in good yields.

Benzaldehyde afforded an excellent yield for the desired propargylamine product (Table 3, entries 1, 2) than those of any other aldehydes employed for the studies. Electron-deficient aromatic aldehydes such as 4-nitrobenzaldehyde displayed marginal reactivities, and only traces of the corresponding propargylamine product were obtained (Table 3, entries 9, 10). To better understand the role of steric effects in our synthesis protocol, a more sterically hindered 2,4,6-trimethoxybenzaldehyde was employed as a substrate for the reaction with piperidine and phenylacetylene, and a moderate yield of the propargylamine product was obtained (Table 3, entries 6, 7). These results demonstrate the fact that a Au-based catalytic system is sensitive to sterically congested substrates employed for the one-pot synthesis of propargylamines.

This finding encouraged us to verify whether even more sensitive substrates, such as aliphatic aldehydes, could also react under our experimental conditions. As can be seen from Table 3, entries 11 and 12, heptanal readily reacted with piperidine and phenylacetylene and gave an excellent yield for the corresponding propargylamine product. This result is another


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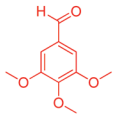
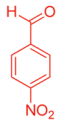
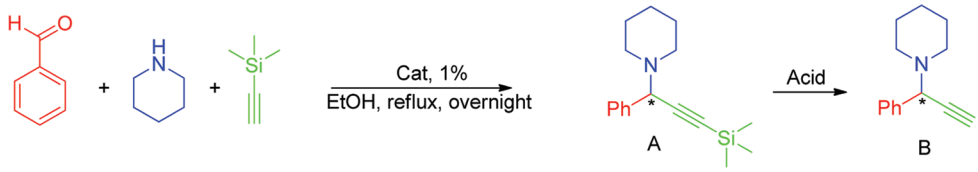
Table 3. $A^3$ Reaction Involving Piperidine, Phenyl Acetylene and Different Aldehydes[ab]

| Entry | Catalysts | aldehyde | Yield (%) |
|---|---|---|---|
| 1 | (NHC)NNAu(III) |  | 94 |
| 2 | (NHC)NNAu(III)-MCM41 | | 65 |
| 3 | (NHC)NNAu(III) |  | 50 |
| 4 | (NHC)NNAu(III)-MCM41 | | 40 |
| 5 | Dioxo(IMes)Au(I) | | 37 |
| 6 | (NHC)NNAu(III) |  | 64 |
| 7 | (NHC)NNAu(III)-MCM41 | | 30 |
| 8 | Dioxo(IMes)Au(I)-MCM41 | | 3 |
| 9 | (NHC)NNAu(III) |  | 5 |
| 10 | (NHC)NNAu(III)-MCM41 | | 0 |
| 11 | (NHC)NNAu(III)-MCM41 |  | 74 |
| 12 | Dioxo(IMes)Au(I)-MCM41 | | 80 |

[a]Conditions: aldehyde (0.19 mmol), piperidine (0.22 mmol), phenyl acetylene (0.28 mmol), catalyst (1 mol %), in $CHCl_3$ (2 mL) at 70 °C for 24 h. [b]Yields of isolated product based on aldehyde.

Table 4. $A^3$ Reaction with Ethynyltrimethylsilane As Substrate[a]




| entry | catalyst | T | product | Yield (%)[b] |
|---|---|---|---|---|
| 1 | (NHC)NNAu(III) | 50 °C | A | 60 |
| 2 | (NHC)NNAu(III)−MCM-41 | 50 °C | A/B 50:50 | 50 |
| 3 | (NHC)NNAu(III) | 80 °C | A/B 95:5 | 63 |
| 4 | (NHC)NNAu(III)/$SO_3$H-Sil | 80 °C | B | 62 |
| 5 | (NHC)NNAu(III)−MCM-41 | 80 °C | A/B 2:98 | 40 |
| 6 | K[$AuCl_4$] | 80 °C | A/B 76:24 | 42 |

[a]Unless otherwise noted, all reactions were performed with aldehyde (0.19 mmol), piperidine (0.22 mmol), ethynyltrimethylsilane (0.28 mmol), catalyst (1 mol %), in EtOH (2 mL) at the corresponding temperature for 24 h. [b]Isolated yield..

significant finding in this work because aliphatic aldehydes have a strong tendency to undergo trimerization reaction in the presence of metal-based catalysts, which we did not observe under our experimental conditions. This result opens up the immense possibility of using long-chain aliphatic aldehydes for construction of propargylamine motifs containing long-chain aliphatic side chains in the molecular structure.

To study the possibility of a subsequent reaction after the multicomponent process, we have studied the $A^3$ reaction with ethynyltrimethylsilane (Table 4). This system offers the opportunity that once the three-component reaction is finished, deprotection of the silyl acetylene may occur as one additional step, resulting in a product that can be a precursor to obtain new compounds through reactions such as a CC coupling reactions or addition of water or alcohols to alkynes.

Table 4 shows the considerable influence of the support (MCM-41) in the selectivity of the process; thus, homogeneous catalyst (NHC)NNAu(III) with high selectivity gives almost exclusively the product A (Table 4, entries 1 and 3). In comparison, K[$AuCl_4$] (Table 4, entry 6) does not confer this selectivity in the process. On the other hand, MCM-41 supported complex (NHC)NNAu(III)−MCM-41 afforded almost exclusively the desilylated product B, due to the slight acidity of the support itself that acts here as an acid catalyst. When soluble complex was reacted in the presence of a supported sulfonic acid, we observed that the reaction yields only the desilylated product B (Table 4, entry 4), so we have a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clear example of how the support modifies the catalytic properties of the heterogenized catalyst. As a result, we can see the heterogenized catalyst acts as a bifunctional solid catalyst.

In such MCRs, the reaction proceeds through the initial formation of an iminium intermediate from the starting amine and aldehyde. This iminium compound then reacts with the alkyne, usually in the presence of a metal as catalyst. However, the iminium formation, which proceeds through an aminal, is equilibrated, and this equilibrium could be influenced by the support. The residual acidity of the MCM-41 could, indeed, favor iminium formation, and interactions of the oxygen or nitrogen atoms with the zeolite frame could also facilitate the reaction. The fact that the heterogenized systems are more active than homogeneous ones tends to support an active role of the MCM-41 in the formation of this intermediate.

Under our conditions, the gold atoms probably act as the catalyst. Upon coordination, the alkyne is probably deprotonated, either by the starting amine or the intermediate aminal. The gold acetylide thus formed could then add concomitantly to the iminium compound produced within the support.

To study the effect of the support on the reaction, we have tried to heterogenize the Au complex on aerosil, but we have found that it decomposes to Au (0) because of the higher acidity for this support. On the other hand, we have carried out a series of experiments to verify if the supported catalyst is active in a reaction series, such as the addition of water to the previously formed alkyne. We have found that for soluble Au (III) catalyst, the addition of sulfuric or a silica-supported sulfonic acid led more quickly to the unprotected product, but only traces of the water addition product.

**Reusability and Heterogeneity Studies of Supported Catalysts.** Heterogenized catalysts offer ease of handling and purification through simple filtration. They also allow catalyst recovery and recycling, another interesting eco-friendly aspect of these catalysts. To examine this possibility, we performed a condensation reaction between piperidine, benzaldehyde, and phenylacetylene several times with the same supported catalyst (Table 5), the latter being filtered and reused after each run, although a reactivation step has to be performed. After the completion of the reaction, the contents were centrifuged to separate the solid catalyst from the reaction mixture. This solid was treated with benzonitrile at 70 °C for 5 h, then it was reused for at least another six reaction cycles. This regeneration process was needed because the recovered solid, probably a gold−alkyne species formed with excess alkyne, is not a catalytically active species, which we have confirmed by adding more reactants (aldehyde and amine) to the reaction that just finished, without separating the mixture. As can be seen, heterogenized complexes with dioxolane backbone ligands (Au(I) and Au(III)) were reused for at least three cycles, but Au(III)-pincer derivatives were used only one time.

**Table 5. Reusability Experiments with Heterogenized Gold Catalysts**[a,b]

| | | cycle | | | | |
|---|---|---|---|---|---|---|
| entry | catalyst | 1 | 2 | 3 | 4 | cycle 5 |
| 1 | dioxo(IMes)Au(I)−MCM-41 | 99 | 78 | 73 | 70 | 70 |
| 2 | dioxo(IMes)Au(III)−MCM-41 | 99 | 83 | 85 | 82 | 80 |
| 3 | (NHC)NNAu(III)−MCM-41 | 65 | | | | |

[a]Reaction conditions: benzaldehyde (0.19 mmol), amine (0.22 mmol), alkyne (0.28 mmol), catalyst (1 mol %), in $CHCl_3$ (2 mL), 70 °C for 24 h. Catalysts were treated with benzonitrile after each run. [b]Isolated yields based on benzaldehyde after silica-gel flash column chromatography.

After five runs, gold reduction was not observed for all heterogenized catalysts, even with gold(I) catalysts. To confirm the absence of gold soluble species, the reaction mixture was filtered after reaction, and the powder XRD patterns of dioxo(IMes)Au(I)−MCM-41 (before reaction) and dioxo-(IMes)Au(I)−MCM-41 (after reaction), and the dried filtered crude have been analyzed in Figure 2. The positions of the peaks of dioxo(IMes)Au(I)−MCM-41 (before reaction) remain almost unchanged, suggesting the retention of the long-range hexagonal symmetry of the host material. The powder patterns also remain unchanged for dioxo(IMes)Au-(I)−MCM-41 (after reaction). A reduction of the peak intensities is observed in this case; this is not interpreted as a loss of crystallinity, but rather, as a reduction in the X-ray scattering contrast between the silica walls and pore-filling material, a situation well described in the literature,[77,78] and also observed for other types of materials.[79] In the case of a reaction mixture and any peaks were observed, this fact suggests that any metal species is in solution in the course of the reaction.

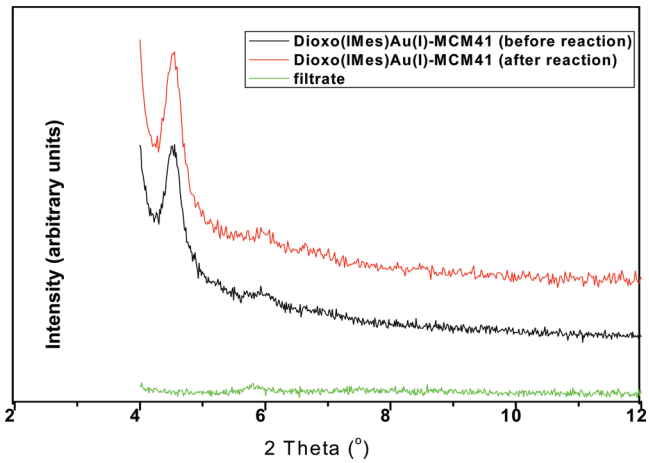


**Figure 2.** XRPD patterns of dioxo(IMes)Au(I)−MCM-41 (before reaction), recovered dioxo(IMes)Au(I)−MCM-41 (after reaction), and liquid solution.

To study the extent of leaching, the catalysts (after four uses) were digested in a minimum volume of "aqua regia" and diluted with double-distilled water to prepare standard volumetric solutions. The gold contents in both of them were analyzed by ICP-MS. There was a loss of ∼10.0% of the initial amount of gold that was originally present in the fresh catalyst. To further verify the heterogeneity of the catalyst, benzaldehyde, piperidine, phenylacetylene, and catalyst were allowed to stir in 2 mL toluene at 100 °C. The reaction was terminated after 7 h, and the conversion was found to be 60%. At this juncture, the catalyst was separated from the reaction mixture at the reaction temperature, and the reaction was continued with the filtrate for an additional 24 h. The conversion remained almost unchanged, thereby proving that the reaction followed a heterogeneous pathway and the leached gold was not active for the reaction.

## CONCLUSION

Heterogenized homogeneous catalysts based on gold have been successfully developed for the one-pot $A^3$ coupling reaction. It


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is demonstrated that such heterogenized gold complexes perform efficiently as a recyclable heterogeneous catalytic system for a one-pot construction of diverse propargylamines involving three-component condensation of aldehydes, amines, and alkynes. The key findings of high significance described in this work are 2-fold. The first one is that a heterogenized Au catalytic system enables compounds such as aliphatic aldehydes to react under our experimental conditions to obtain corresponding propargylamines in good yields. Another key finding in our work is that no external ligands/additives or inert atmosphere is needed to promote the reaction, and a low loading of gold is sufficient to efficiently catalyze our reactions. These key findings make these recyclable heterogeneous catalysts economical; green; and, therefore, environmentally sustainable for a one-pot synthesis of propargylamines.

## EXPERIMENTAL SECTION

Details of the preparation and characterization of the supported gold catalysts are given in the Supporting Information.

**General Procedure for the Three-Component Coupling Reaction.** All commercially available reagents were purchased from Aldrich and used as received. The desired amount of supported gold catalyst was added to a mixture of benzaldehyde (20 mg, 1.88 mmol), piperidine (19.3 mg, 2.26 mmol), and phenylacetylene (28.9 mg, 2.82 mmol) in 2.0 mL of $CHCl_3$ with dodecane as an internal standard. The $A^3$ coupling reaction was performed in a closed Schlenk flask with stirring (1000 rpm) at 70 °C under inert atmosphere. After a given reaction time, the product mixtures were cooled to room temperature and centrifuged. The reaction mixture was analyzed by GC to determine the aldehyde conversion. The pure product was obtained by flash chromatography and identified by GC/MS and $^1H$ NMR spectroscopy (see Supporting Information).

**Recycling Experiments.** At the end of the process, the reaction mixture was filtered, and the catalyst residue was washed to completely remove any remaining products and reactants. The solid was treated with benzonitrile at 70 °C and used in a new reaction, and we have not observed a significant decrease in reactivity. The supernatant liquid is also used in a new reaction, and there is no formation of new products.

## ASSOCIATED CONTENT

### Supporting Information

Compound characterization data, including images of $^{13}C$ NMR spectra, HPLC traces. This material is available free of charge via the Internet at http://pubs.acs.org.

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### Notes

The authors declare no competing financial interest.

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