

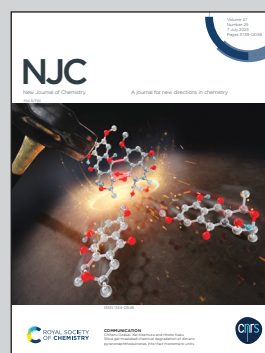


Showcasing research from Professor Hiroshi Nakazawa's laboratory, Department of Chemistry, Osaka Metropolitan University, Osaka, Japan, and significant contribution from Katsuaki Kobayashi (OMU) and Norihisa Fukaya (AIST).

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Catalytic hydrosilylation using an immobilized Co-terpyridine complex activated by inorganic salts and its application in a flow reactor†

Katsuaki Kobayashi, ^a Norihisa Fukaya ^b and Hiroshi Nakazawa ^{*a}

The activation of a dibromo Co-terpyridine complex immobilized on a stationary phase (**Co(tpy)Br₂@SiO₂**) as a hydrosilylation catalyst was investigated. Inorganic salts that are sparingly soluble in an organic solvent were examined as activators, and K₂CO₃ was found to show advantages in activator ability, stability, cost, and ease of handling. Catalytic hydrosilylation using **Co(tpy)Br₂@SiO₂** activated by K₂CO₃ afforded the products in good yield, in both the reactions of styrene with triethoxysilane (92%) and 1-octene with diphenylsilane (88%). Both **Co(tpy)Br₂@SiO₂** and K₂CO₃ were easily separable from the hydrosilylated product, which contributed to achieving a reusable hydrosilylation system in both the catalyst and activator. Moreover, the **Co(tpy)Br₂@SiO₂/K₂CO₃** system was found to be applicable in a continuous flow reactor as a catalyst in the stationary phase.

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Introduction

Organosilane compounds are versatile and indispensable chemicals for the silicone industry. Hydrosilylation is one of the most straightforward means of obtaining organosilane compounds that are not produced in natural systems. Hydrosilylation usually requires precious metal catalysts such as Pt complexes.¹ However, the problem with precious metals is that there are very few reserves on earth. Recent interest in this research field has brought about the development of base metal complex catalysts.^{2–6} There are many examples of hydrosilylation catalysts based on Mn,^{4,7} Fe,^{3,5,8–10} Co,^{2,3,9–13} Ni,^{3,14} or Cu,¹⁵ which show high turnover numbers, as well as good stereoselectivity, and chemoselectivity. Most of them have a pincer type ligand. Our group has reported Fe¹⁶ and Co^{17,18} complexes bearing an iminobipyridine ligand. Fe-iminobipyridine complexes catalyze the hydrosilylation of olefins and ketones with good turnover numbers and frequency.¹⁶ Co-iminobipyridine complexes show chemoselective hydrosilylation between an olefin and a ketone, which is controlled by the reaction solvent.¹⁷ The pincer ligands used in these catalysts have large and complicated substituents. Therefore, the synthesis of these pincer ligands requires considerable effort, time, and cost.

Catalyst reuse is one of the ways to make more effective use of specially synthesized catalysts. The immobilization of a catalyst on a stationary phase is a good method for reusing the catalyst because it can be separated readily from the liquid product or product solution. Pt catalysts immobilized on solid supports have been synthesized and their reuse has been reported.¹⁹ By contrast, base metal complexes for hydrosilylation that are immobilized on a stationary phase are limited.^{20,21} Recently, our group developed a Co complex supported on silica gel (**Co(tpy)(X)₂@SiO₂**, where X = OH, Br) in which a Co complex with terpyridine (tpy), being one of the simplest pincer ligands, was immobilized on the surface of silica gel or glassware.²² **Co(tpy)Br₂@SiO₂** (a rough image of the silica gel surface supporting **Co(tpy)Br₂** is shown in Fig. 1) exhibited good catalytic activity using NaBHET₃ as the activator for the hydrosilylation of 1-octene with diphenylsilane (Ph₂SiH₂). This Co-supported silica gel was reusable as a catalyst, but the activity gradually decreased with each reuse. The cause of this decrease in catalytic activity was considered to be the cleavage of the Si–O bond in **Co(tpy)Br₂@SiO₂** by the highly active NaBHET₃. Next, we searched for a system that activates the Co complex without using NaBHET₃.

Recently, we found that [Co(tpy)Br₂] was activated by inorganic salts which are stable under air.²³ In particular, K₂CO₃ is a good activator for the hydrosilylation reaction in terms of its ability, cost and stability. It was interesting that K₂CO₃ activated [Co(tpy)Br₂] even though the salt is sparingly soluble in the reaction system (a mixture of an olefin and hydrosilane).

This paper describes whether or not unprecedented combinations of a Co-complex immobilized on silica gel and activators,

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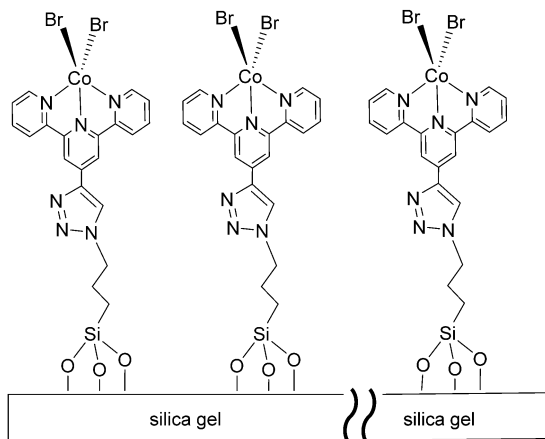


Fig. 1 Schematic of the silica gel surface supporting $\text{Co}(\text{tpy})\text{Br}_2$.

which include extremely sparingly soluble inorganic salts, result in catalytic activity for hydrosilylation; in addition, a flow reactor system is reported in which the hydrosilylation product is eluted simply by passing the reactants (the olefin and hydrosilane) through a column packed with this silica gel and K_2CO_3 powder.

Results and discussion

Catalytic activity of $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$ for hydrosilylation in the presence of an activator

It has been reported that $[\text{Co}(\text{tpy})\text{Br}_2]$ did not show any catalytic activity for hydrosilylation, although it did show activity in the presence of an activator such as KOAc (potassium acetate), KOPv (potassium pivalate), and K_2CO_3 .²³ Thus, we examined the catalytic activity of $[\text{Co}(\text{tpy})\text{Br}_2]$ immobilized on silica gel ($\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$) in the presence of an activator.

KOAc, KOPv, KO^tBu , K_2CO_3 , KF, and K_3PO_4 were selected as the activators, considering our previous report on $[\text{Co}(\text{tpy})\text{Br}_2]$.²³ The hydrosilylation of styrene with $(\text{EtO})_3\text{SiH}$ (eqn (1), Table 1) and that of 1-octene with diphenylsilane (Ph_2SiH_2) (eqn (2)) were used as model reactions. In the absence of an activator, $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$ did not show any catalytic activity for the hydrosilylation of styrene with $(\text{EtO})_3\text{SiH}$ (Table 1, entry 1). The hydrosilylation of 1-octene with Ph_2SiH_2 using $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$ without an activator afforded moderate yields of the products, with the linear one (**2l**) as the major product and the branched one (**2b**) as the minor product (Table 1, entry 2).

The addition of KOAc to the reaction mixture of styrene and $(\text{EtO})_3\text{SiH}$ containing $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$ resulted in a high catalytic activity and the formation of **1** (82%; Table 1, entry 3). Similarly, in the presence of other salts, **1** was produced in high yield. In particular, the addition of KOPv, K_2CO_3 , and KF afforded the corresponding product in more than 90% yield (entries 4, 6, and 7, respectively). The hydrosilylation reaction between 1-octene with Ph_2SiH_2 was also improved in the presence of inorganic salts: the product yields were more than 80% with the addition of activators such as KOPv, KO^tBu , K_2CO_3 , KF, and K_3PO_4 (entries 10–14, respectively). GC-MS and ^1H NMR measurements carried out on the supernatant

Table 1 Hydrosilylation catalyzed by $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$ in the presence of various salts

Ph	5.4 mmol	50 mg $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$	2.5 mol% additive	Ph—CH ₂ —CH ₂ —Si(OEt) ₃ (1)	(1)
$(\text{EtO})_3\text{SiH}$	5.4 mmol	24 h, neat, 100 °C, under N ₂			
C_6H_{13}	5.4 mmol	50 mg $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$	2.5 mol% additive	C_6H_{13} —CH ₂ —CH ₂ —SiHPh ₂ (2l)	(2)
Ph_2SiH_2	5.4 mmol	24 h, neat, 100 °C, under N ₂		+ SiHPh ₂ (2b)	

Entry	Olefin	Hydrosilane	Additive	Yield ^a (%)
1	Styrene	$(\text{EtO})_3\text{SiH}$	None	N.D. ^b
2	1-Octene	Ph_2SiH_2	None	2l : 52 (2b : 0.3)
3	Styrene	$(\text{EtO})_3\text{SiH}$	KOAc	1 : 82
4	Styrene	$(\text{EtO})_3\text{SiH}$	KOPv	1 : 90
5	Styrene	$(\text{EtO})_3\text{SiH}$	KO^tBu	1 : 80
6	Styrene	$(\text{EtO})_3\text{SiH}$	K_2CO_3	1 : 92
7	Styrene	$(\text{EtO})_3\text{SiH}$	KF	1 : 98
8	Styrene	$(\text{EtO})_3\text{SiH}$	K_3PO_4	1 : 89
9	1-Octene	Ph_2SiH_2	KOAc	2l : 68 (2b : 3.0)
10	1-Octene	Ph_2SiH_2	KOPv	2l : 86 (2b : 6.2)
11	1-Octene	Ph_2SiH_2	KO^tBu	2l : 83 (2b : 2.1)
12	1-Octene	Ph_2SiH_2	K_2CO_3	2l : 88 (2b : 2.1)
13	1-Octene	Ph_2SiH_2	KF	2l : 84 (2b : 3.8)
14	1-Octene	Ph_2SiH_2	K_3PO_4	2l : 84 (2b : 2.4)

^a Determined *via* GC. ^b Not detected.

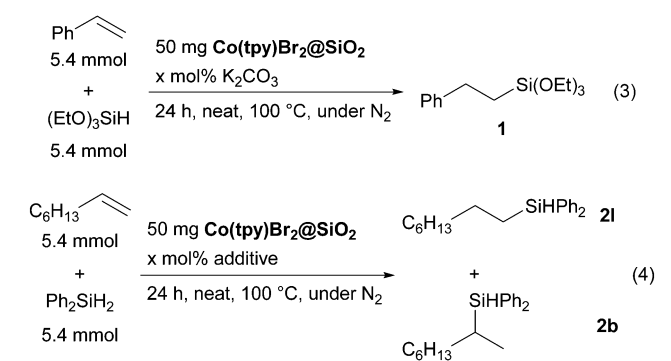
after the reactions in Table 1 revealed that the hydrosilylation products (*i.e.*, **1** for eqn (1), **2l** and **2b** for eqn (2)) and a small amount of the starting materials (olefin and hydrosilane) were detected, although no by-products were detected. These results are quite similar to the effect of the inorganic salts on the hydrosilylation of the catalytic system based on $[\text{Co}(\text{tpy})\text{Br}_2]$.²³

Among the inorganic additives, K_2CO_3 afforded good results for both the hydrosilylation of styrene with $(\text{EtO})_3\text{SiH}$ and that of 1-octene with Ph_2SiH_2 . Both $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$ and K_2CO_3 were barely soluble in organic solvents, showing the high reuse potential of the system. Thus, optimization of the reaction conditions was carried out for the $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2/\text{K}_2\text{CO}_3$ system.

Optimization of reaction conditions catalyzed by $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2/\text{K}_2\text{CO}_3$

Optimization of the amount of $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$ in the presence of 2.5 mol% K_2CO_3 was conducted. When 5.4 mmol of styrene and $(\text{EtO})_3\text{SiH}$ were used as substrates, 10 mg of $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$ was enough to obtain a quantitative amount of the corresponding product (Table S1, ESI†). By contrast, the hydrosilylation of 1-octene with Ph_2SiH_2 (5.4 mmol) required 50 mg $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$ for an 88% yield of the corresponding product (Table S1, ESI†). Thus, 50 mg of $\text{Co}(\text{tpy})\text{Br}_2@ \text{SiO}_2$ was used for the hydrosilylation of 5.4 mmol of the substrates in the subsequent reactions. The amount of K_2CO_3 was changed in the range of 0.5–2.5 mol% (eqn (3) and (4), Table 2). In the case of the hydrosilylation of styrene with $(\text{EtO})_3\text{SiH}$, the product yields were around 90%



Table 2 Hydrosilylation by **Co(tpy)Br₂@SiO₂** in the presence of various amounts of K₂CO₃

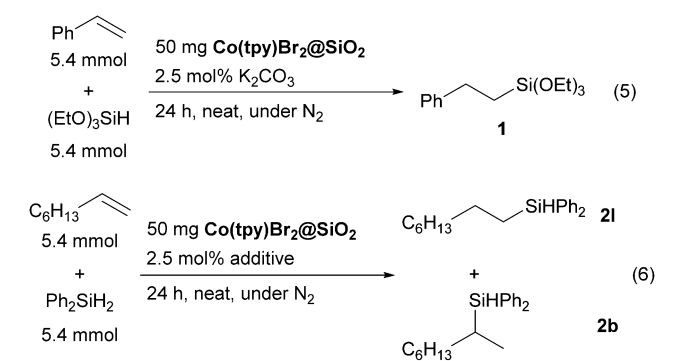
Entry	Amount of K ₂ CO ₃	Olefin	Hydrosilane	Yield ^a (%)
1	0.5	Styrene	(EtO) ₃ SiH	1: 87
2	1.0	Styrene	(EtO) ₃ SiH	1: 88
3	1.5	Styrene	(EtO) ₃ SiH	1: 88
4	2.0	Styrene	(EtO) ₃ SiH	1: 91
5	2.5	Styrene	(EtO) ₃ SiH	1: 92
6	0.5	1-Octene	Ph ₂ SiH ₂	2l: 74 (2b: 1.8)
7	1.0	1-Octene	Ph ₂ SiH ₂	2l: 80 (2b: 2.3)
8	1.5	1-Octene	Ph ₂ SiH ₂	2l: 80 (2b: 2.2)
9	2.0	1-Octene	Ph ₂ SiH ₂	2l: 82 (2b: 2.5)
10	2.5	1-Octene	Ph ₂ SiH ₂	2l: 88 (2b: 2.1)

^a Determined *via* GC.

(Table 2, entries 1–5). When 1-octene and Ph₂SiH₂ were used as the substrates, the addition of 0.5 mol% K₂CO₃ as an activator afforded a 74% yield of **2l** as the main product with a small amount of **2b** as the minor product (Table 2, entry 6). The yield of **2l** increased as the amount of K₂CO₃ was increased, where an 88% yield was achieved with the addition of 2.5 mol% K₂CO₃ (Table 2, entry 10).

Finally, the temperature dependence in the range of 25–100 °C for the hydrosilylation reaction catalyzed by **Co(tpy)Br₂@SiO₂** was investigated in the presence of 2.5 mol% K₂CO₃ (eqn (5) and (6), Table 3). The hydrosilylation of styrene with (EtO)₃SiH afforded a greater than 86% yield of **1** in the temperature range studied (Table 3, entries 1–5). By contrast, the hydrosilylation of 1-octene with Ph₂SiH₂ at 25 °C produced a low yield of **2l** (14%, entry 6). The yield gradually increased as the reaction temperature was increased (entries 6–10), and reached 88% at 100 °C (**2l**: 88% and **2b**: 2.1%; Table 3, entry 10). As reported before, the [Co(tpy)Br₂]/K₂CO₃ system showed catalytic activity at 25 °C for the hydrosilylation of 1-octene with Ph₂SiH₂ (99% conversion).²³ The low yield of the product for the hydrosilylation of 1-octene with Ph₂SiH₂ at 25 °C (entry 6) probably comes from the lack of activation energy for the reaction to proceed, since the unreacted substrates were observed *via* GC analysis without any by-product. Therefore, it seems that a high temperature is required to activate the Co complex supported on silica gel with K₂CO₃.

The hydrosilylation of styrene with (EtO)₃SiH catalysed by **Co(tpy)Br₂@SiO₂/K₂CO₃** (eqn (5), Table 3) was also conducted in air. As a result, the yield of the hydrosilylated product dropped to 45%, which was almost half of that under N₂. This result indicates that the catalytically active Co species produced from **Co(tpy)Br₂@SiO₂** and K₂CO₃ is air-sensitive. The active

Table 3 Temperature dependence of hydrosilylation for the **Co(tpy)Br₂@SiO₂/K₂CO₃** system

Entry	Temperature (°C)	Olefin	Hydrosilane	Yield ^a (%)
1	25	Styrene	(EtO) ₃ SiH	1: 86
2	40	Styrene	(EtO) ₃ SiH	1: 88
3	60	Styrene	(EtO) ₃ SiH	1: 91
4	80	Styrene	(EtO) ₃ SiH	1: 95
5	100	Styrene	(EtO) ₃ SiH	1: 92
6	25	1-Octene	Ph ₂ SiH ₂	2l: 14 (2b: 0.2)
7	40	1-Octene	Ph ₂ SiH ₂	2l: 31 (2b: 0.9)
8	60	1-Octene	Ph ₂ SiH ₂	2l: 76 (2b: 3.5)
9	80	1-Octene	Ph ₂ SiH ₂	2l: 81 (2b: 2.9)
10	100	1-Octene	Ph ₂ SiH ₂	2l: 88 (2b: 2.1)

^a Determined *via* GC.

species has not been identified since it is quite difficult to observe the Co complex on silica gel during the catalytic reaction. By contrast, in our previous report,²³ the activation mechanism in the homogeneous system using [Co(tpy)Br₂] was proposed in which the carbonate anion undergoes nucleophilic attack at the Si atom of hydrosilane causing the release of a hydride ion as a reductant of the Co complex. Considering the previous report, it can be thought, even in an immobilized catalytic system, that **Co(tpy)Br₂@SiO₂** is activated *via* hydrosilane activation by K₂CO₃ to generate the catalytically active Co(I) or Co(0) species.

Turnover frequency (TOF) of the hydrosilylation reaction catalyzed by **Co(tpy)Br₂@SiO₂/K₂CO₃**

To estimate the catalytic activity of the Co complex immobilized on silica gel, it is necessary to determine the amount of the Co complex that is supported on silica gel. Thus, the Co-immobilized silica gel was subjected to energy-dispersive X-ray fluorescence spectrometer (EDXRF) measurements and elemental analysis, and it was found that 1 mg of Co was contained in 1 g of the silica gel (0.1 wt% of Co), and the molar ratio of Co:Br was 1.0:2.0.

A comparison of the catalytic activity for the hydrosilylation reaction derived from discrete [Co(tpy)Br₂] with that from immobilized [Co(tpy)Br₂] is interesting. In the presence of 0.01 mol% [Co(tpy)Br₂] relative to 5.4 mmol of each substrate, and in the presence of 30 mg **Co(tpy)Br₂@SiO₂**, which corresponds to 0.01 mol% immobilized-[Co(tpy)Br₂], a mixture of the olefin and hydrosilane (both 5.4 mmol) to which 2.5 mol% K₂CO₃ had been added was heated at 100 °C for 1 h, and the products were examined. The results are summarized in Table 4.

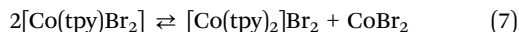


Table 4 TOF of the hydrosilylation by [Co(tpy)Br₂] or **Co(tpy)Br₂@SiO₂** in the presence of 2.5 mol% K₂CO₃ at 100 °C

Entry	Catalyst	Co amount (mol%)	Substrates	Yield ^a (%)	TOF (h ⁻¹) (TOF per 0.01 mol%)
1	[Co(tpy)Br ₂]	0.011	Styrene (EtO) ₃ SiH	76	6910 (6282)
2	Co(tpy)Br₂@SiO₂ (30 mg)	0.0094	Styrene (EtO) ₃ SiH	86	9120 (9702)
3	[Co(tpy)Br ₂]	0.013	1-Octene Ph ₂ SiH ₂	87 ^b	6690 (5146)
4	Co(tpy)Br₂@SiO₂ (30 mg)	0.0094	1-Octene Ph ₂ SiH ₂	34 ^b	3620 (3851)

^a Determined *via* GC. ^b Total yield of **2l** and **2b**.

In the case of the hydrosilylation of styrene with (EtO)₃SiH, the TOF of [Co(tpy)Br₂] was 6910 h⁻¹ (6282 h⁻¹ per 0.01 mol% catalyst) and that of **Co(tpy)Br₂@SiO₂** was 9120 h⁻¹ (9702 h⁻¹ per 0.01 mol% catalyst) (Table 4, entries 1 and 2). It is worth noting that our immobilized catalyst showed a 1.5-fold higher activity than the [Co(tpy)Br₂] catalyst, even though the immobilization of a catalyst often lowers the catalytic activity. There are two possible reasons for this: (i) the tpy ligand was electronically affected due to the connection of an anchor (a triazole substituent) for immobilization, which enhanced the activity of the Co catalyst; and (ii) [Co(tpy)Br₂] is reported to be in equilibrium in solution as shown in eqn (7).²⁴ [Co(tpy)₂]Br₂ and CoBr₂ show no catalytic activity. The immobilization of [Co(tpy)Br₂] inhibits the bimolecular association and inhibits the shifting of the equilibrium to the right, resulting in the high catalytic performance. Although there is no experimental evidence, we tentatively think that (ii) is the main reason for the enhanced catalytic activity.



The TOF for the hydrosilylation of 1-octene with Ph₂SiH₂ using [Co(tpy)Br₂] was 6690 h⁻¹ (5146 h⁻¹ per 0.01 mol% catalyst), whereas the TOF using **Co(tpy)Br₂@SiO₂** was 3620 h⁻¹ (3851 h⁻¹ per 0.01 mol% catalyst), showing that immobilization of the Co complex caused a decrease in the catalytic activity, in contrast to the above case. The reason for this is not clear, but one possibility is shown below. First, a comparison of the steric accessibility of the olefin and hydrosilane to the catalytically active Co center was carried out. The olefin substituent is a planar phenyl group in styrene, whereas it is a hexyl group in 1-octene. Therefore, it is sterically more difficult for 1-octene to approach the Co center than it is for styrene. Concerning the hydrosilane substrate, Ph₂SiH₂ appears to be less able to approach the Co center than (EtO)₃SiH, because the Ph group in the former hydrosilane is considered to make the Si environment more crowded than the OEt group in the latter hydrosilane. Therefore, when Co(tpy)Br₂ is used as the catalyst, the hydrosilylation of 1-octene with Ph₂SiH₂ is considered to be sterically less likely than that for styrene with (EtO)₃SiH, which is consistent with the results of entries 1 vs. 3 in Table 4. This tendency is more pronounced in the catalytic system with Co(tpy)Br₂ immobilized on silica gel. This is because one side of the catalytically active Co species is the silica gel surface, which limits the space that is accessible to the substrates. Therefore, in the **Co(tpy)Br₂@SiO₂** system, the reaction of styrene with (EtO)₃SiH, which is less sterically constrained by the immobilization of the complex, can effectively receive the benefit of (ii) shown above (entries 1 vs. 2 in Table 4), whereas the reaction of 1-octene with Ph₂SiH₂ suffers from more steric constraints due to

immobilization of the complex compared with the benefit of (ii) (entries 3 vs. 4 in Table 4).

Scope of substrates

Several hydrosilylation reactions of olefins containing various functional groups were investigated. The mixtures of 5.4 mmol olefin and hydrosilane were treated with 50 mg **Co(tpy)Br₂@SiO₂** activated using 2.5 mol% K₂CO₃ at 100 °C. Ph₂SiH₂ was used as the hydrosilane substrate (eqn (8), Table 5). Using **Co(tpy)Br₂@SiO₂**/K₂CO₃, styrene and vinyl cyclohexane underwent hydrosilylation with Ph₂SiH₂ in good yields (Table 5, entries 1 and 2, respectively). 1,2-Epoxy-5-hexene was converted to the corresponding product with a moderate yield (67%, entry 3). The hydrosilylation of dimethylallylamine with Ph₂SiH₂ afforded **6** in only 46% yield (entry 4), although [Co(tpy)Br₂] produced the same product in 73% yield.²³ Allyl chloride, vinyl acetate, and methyl acrylate were not suitable substrates for hydrosilylation using **Co(tpy)Br₂@SiO₂**/K₂CO₃ (entries 5–7, respectively). Methyl acrylate was converted by [Co(tpy)Br₂] activated using K₂CO₃ in 41% yield,²³ but **Co(tpy)Br₂@SiO₂**/K₂CO₃ did not afford the product.

Next, the scope of the hydrosilane and siloxane substrates was investigated. Styrene was employed as the olefin substrate

Table 5 Hydrosilylation of olefins bearing various functional groups catalyzed by **Co(tpy)Br₂@SiO₂**/K₂CO₃

$ \begin{array}{c} \text{R}-\text{CH}=\text{CH}_2 \\ 5.4 \text{ mmol} \\ + \\ \text{Ph}_2\text{SiH}_2 \\ 5.4 \text{ mmol} \end{array} \xrightarrow[24 \text{ h, neat, } 100^\circ\text{C, under N}_2]{50 \text{ mg Co}(\text{tpy})\text{Br}_2\text{@SiO}_2, 2.5 \text{ mol\% K}_2\text{CO}_3} \text{R}-\text{CH}_2\text{CH}_2\text{SiHPh}_2 \quad (8) $			
Entry	Olefin	Product	Yield ^a (%)
1			95
2			78
3			67
4			46
5			N.D. ^b
6			N.D. ^b
7			N.D. ^b

^a Determined *via* GC. ^b Not detected.



(eqn (9), Table 6), since hydrosilylation using styrene solely produced the anti-Markovnikov type product (3) with $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2/\text{K}_2\text{CO}_3$ in good yield (Table 5, entry 1). When PhSiH_3 was used as the primary silane, the corresponding product (7) was obtained in 90% yield (Table 6, entry 1). In the case of the tertiary silane, hydrosilylation using $(\text{EtO})_2\text{MeSiH}$ afforded the hydrosilylated product (8) in good yield (84%, entry 2). However, the similar tertiary silane Ph_2MeSiH was not reactive at all (entry 3). These three hydrosilanes were quantitatively converted into the corresponding products by $[\text{Co}(\text{tpy})\text{Br}_2]/\text{K}_2\text{CO}_3$.²³ This indicates that $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2/\text{K}_2\text{CO}_3$ is affected by the steric hindrance around the Si atom of the hydrosilane. This tendency was also observed in the hydrosilylation reaction using siloxane substrates with $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2/\text{K}_2\text{CO}_3$. 1,1,1,3,3-Pentamethyl-disiloxane (PMDS) and 1,1,1,3,5,5,5-heptamethyltrisiloxane (MD'M) were employed as the siloxane substrates. When PMDS and MD'M were used as the substrates the products were obtained in 46% (9) and 36% (10) yield, respectively. Thus, the larger framework of MD'M afforded the hydrosilylation product in a lower yield.

Study on detachment of the Co complex from the silica gel support

It was then examined whether or not the immobilized Co complex moieties detach from the silica gel support during the hydrosilylation reaction in the $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2/\text{K}_2\text{CO}_3$ catalytic system. The hydrosilylation reaction of 5.4 mmol 1-octene and 5.4 mmol Ph_2SiH_2 was carried out at 100 °C for 24 h in the presence of 50 mg $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2$ and 2.5 mol% K_2CO_3 . After that, the reaction solution was centrifuged to separate the solid portion; the supernatant was subjected to inductively coupled plasma mass spectrometry (ICP-MS), and it was found that Co was not detected. Considering that the detection limit of Co per 1 g of sample in the ICP-MS analysis method is 0.5 µg, it can be said that detachment of the immobilized Co portion from the silica gel support is negligible during this reaction, if it occurs at all.

Reusability of $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2/\text{K}_2\text{CO}_3$

Since $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2$ is insoluble and the solubility of K_2CO_3 is extremely low in an organic solvent, the catalyst and activator

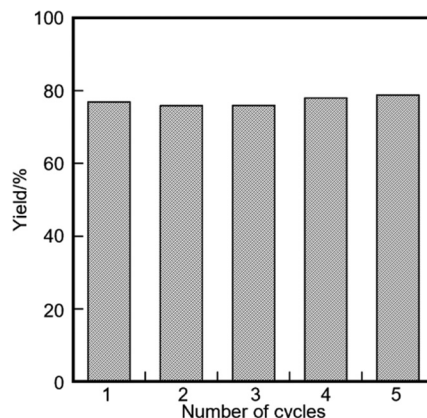
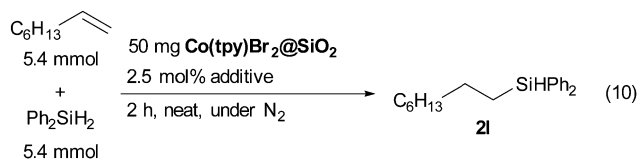


Fig. 2 Repeated hydrosilylation of 1-octene with Ph_2SiH_2 catalyzed using the $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2/\text{K}_2\text{CO}_3$ system.

can be readily separated *via* filtration or centrifugation, indicating the possibility of their reusability.

A mixture of 5.4 mmol each of 1-octene and Ph_2SiH_2 containing 50 mg of $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2$ and 2.5 mol% K_2CO_3 was stirred using a mechanical stirrer (not a magnetic stirrer) to avoid crushing the silica gel ($\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2$). After 2 h of reaction at 100 °C, $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2$ and K_2CO_3 were separated *via* centrifugation, washed with hexane, dried, and used for the second reaction. These sequential operations were repeated five times, and the yield of **2l** was measured for each cycle (the yield of **2b** was lower than 2% in each cycle). From the results shown in Fig. 2, it was found that the $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2/\text{K}_2\text{CO}_3$ system is reusable at least 5 times without any reduction in the catalytic activity.



Application of $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2/\text{K}_2\text{CO}_3$ to a continuous flow reactor

Since it was shown that the $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2/\text{K}_2\text{CO}_3$ system can be reused and that the Co complex does not detach from the silica gel support, we tried applying this system to a continuous flow reactor. A powdered mixture of 500 mg $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2$ and 200 mg K_2CO_3 was packed into a stainless-steel tubular reactor (5 mm internal diameter, 100 mm length). This reactor was positioned in the temperature controller. The liquid substrate mixture of 1-octene and Ph_2SiH_2 was deaerated *via* N_2 bubbling and introduced to the tubular reactor using a pump unit. Shortly after starting, the outflow of the products stopped. Thinking that the reaction tube was clogged due to the high viscosity of the hydrosilylated products (**2l** and **2b**), an organic solvent was added to the substrates and injected into the flow reactor.

When toluene was used as the solvent and the flow was carried out at 100 °C, the flow rate was maintained at 0.03 mL min⁻¹ and

Table 6 Hydrosilylation of styrene with various hydrosilanes or siloxanes catalyzed by $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2/\text{K}_2\text{CO}_3$

Entry	50 mg $\text{Co}(\text{tpy})\text{Br}_2\text{@SiO}_2$ 2.5 mol% K_2CO_3 24 h, neat, 100 °C, under N_2		Product	Yield ^a (%)
	Hydrosilane or siloxane	Ph-CH=CH ₂ +		
1	PhSiH_3	5.4 mmol	$\text{Ph-CH}_2\text{-CH}_2\text{-SiH}_2\text{Ph}$ 7	90
2	$(\text{EtO})_2\text{MeSiH}$	5.4 mmol	$\text{Ph-CH}_2\text{-CH}_2\text{-SiMe}(\text{OEt})_2$ 8	84
3	PhMe_2SiH	5.4 mmol	$\text{Ph-CH}_2\text{-CH}_2\text{-SiMe}_2\text{Ph}$	N.D. ^b
4	$\text{Me}_3\text{SiOSiHMe}_2$ (PMDS)	5.4 mmol	$\text{Ph-CH}_2\text{-CH}_2\text{-SiMe}_2\text{OSiMe}_3$ 9	46
5	$(\text{Me}_3\text{SiO})_2\text{SiHMe}$ (MD'M)	5.4 mmol	$\text{Ph-CH}_2\text{-CH}_2\text{-SiMe}(\text{OSiMe}_3)_2$ 10	36

^a Determined *via* GC. ^b Not detected.



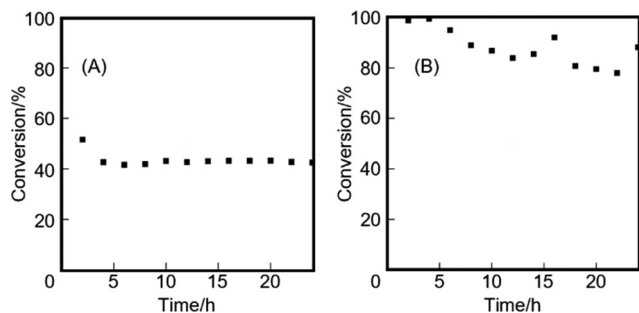


Fig. 3 Time course of the conversion rate of hydrosilylation of 1-octene with Ph_2SiH_2 by continuous flow reaction using $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2/\text{K}_2\text{CO}_3$ in the presence of toluene (A) or THF (B) as a solvent.

the conversion rate was around 45% for 24 h (Fig. 3A). When THF was used and the flow was carried out at 60 °C, the conversion rate improved to more than 95% for the first 4 h, which then settled down to *ca.* 80% after 24 h (Fig. 3B). The real active species is not clear, but it is probably a coordinatively unsaturated Co complex, such as $[\text{Co}(\text{tpy})]$, which is air-sensitive. As THF is known to be a coordinative solvent, whereas toluene is not, it is likely that THF coordinates to the real Co active species and prevents decomposition, resulting in the high catalytic activity. Actually, the batch reaction of $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2/\text{K}_2\text{CO}_3$ in THF was superior to that in toluene (Table S2, ESI[†]). Thus, the continuous flow reaction in the presence of THF in total afforded 21.6 g of the product (**2l**) (88% conversion) with 90% purity after removal of the solvent, in which only small amounts of the starting materials and **2b** (<2%) were found.

These results show that a flow reactor using $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$ and K_2CO_3 can be adapted for hydrosilylation reactions between olefins with hydrosilanes, and the reactor can operate for at least 24 h whilst maintaining a high catalytic activity. Therefore, our reaction system, which combines an air-stable immobilized catalyst and an inorganic salt, is a step towards the practical application of a flow reactor.

Conclusions

The conversion of the dibromo Co-terpyridine complex immobilized on silica gel ($\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$) to a catalytically active species by inorganic salts was demonstrated *via* the hydrosilylation reaction. Among the inorganic salts, K_2CO_3 was the best in terms of the activator ability, stability, cost, and ease of handling. The insolubility of $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$ and the sparing solubility of K_2CO_3 in an organic solvent made separation of the silica gel and K_2CO_3 from the product easy and facilitated the reusability of the $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2/\text{K}_2\text{CO}_3$ catalytic system. Furthermore, this system was shown to be applicable for a continuous flow reaction system.

In many hydrosilylation catalyzed reactions, as the catalytically active species is air-sensitive, it is required to conduct the reaction under an inert atmosphere and to separate the product from the catalyst residues after the reaction has been completed. Since this paper reports that a solid catalyst and a solid

activator are packed in a column under air and the deaerated reaction reagents (olefin and hydrosilane) are simply flowed through the column to continuously generate the hydrosilylation product that contains no catalyst residue, our results can be said to be a step towards the realization of an ideal catalytic system. The present research suggests an environmentally friendly catalytic system for hydrosilylation.

Experimental section

Materials

Terpyridine-modified silica gel ($\text{tpy}@/\text{SiO}_2$) and $[\text{Co}(\text{tpy})\text{Br}_2]$ were prepared according to literature methods.^{13,22} The hydrosilylated products **1**,²⁵ **2l**,¹² and **2b**⁹ were synthesized as authentic samples according to the literature. Silica gel for $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$ preparation was purchased from Nacalai Tesque (Silica Gel 60, spherical, neutral). All other chemicals were purchased from commercial sources and were used as received.

Preparation of $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$

2 g of $\text{tpy}@/\text{SiO}_2$ was dispersed in an aqueous solution of CoBr_2 . The mixture was then stirred at 25 °C for 24 h. The resulting powder ($\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$) was collected *via* centrifugation, washed with water or THF (20 mL), and then dried *in vacuo* to obtain approximately 1.8 g of $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$.

Typical procedure for catalytic hydrosilylation by $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$

$\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$ (50 mg) and K_2CO_3 (19 mg, 2.5 mol%) were placed in a Schlenk tube. The air in the tube was replaced with N_2 . The olefin (5.4 mmol) and hydrosilane (5.4 mmol) substrates were added to the tube. The suspension was heated at 100 °C and stirred for 24 h. After the reaction, the solution was cooled to room temperature. $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$ and K_2CO_3 were separated *via* centrifugation and the supernatant was analyzed using GC.

Author contributions

K. K. and H. N. conceived and designed the experiments. K. K. performed the experiments. N. F. measured EDXRF and elemental analysis of $\text{Co}(\text{tpy})\text{Br}_2@/\text{SiO}_2$. K. K. and H. N. prepared the manuscript.

Conflicts of interest

There are no conflicts to declare.

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