A R T I C L E

Sulfonic acid anchored on silica, $SiO_2@SO_3H$: A superior solid acid catalyst for quick and solvent-free reductive-deoxygenation of ketones with $NaBH_3CN$

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$NaBH_3CN$ as a modified hydroborate agent and due to a strong withdrawing CN group does not show any reducing ability to reduce functional groups in the absence of acidic media (pH ~ 3–4). In this study, the immobilized sulfonic acid on silica, $SiO_2@SO_3H$, was prepared and applied as a new solid acid catalyst for extremely enhancing the reducing ability of $NaBH_3CN$. The influence of $SiO_2@$-SO_3H was highlighted by performing the quick and green reduction of structurally diverse carbonyl compounds involving aldehydes, ketones, α,β-unsaturated enals and enones, α-diketones, and acyloins to the corresponding alcohols or alkanes with $NaBH_3CN$. By the $NaBH_3CN/SiO_2@SO_3H$ system, aldehydes were reduced to the corresponding alcohols and ketonic compounds to alkanes as reductive-deoxygenation products. All reduction reactions were carried out within 3 min at room temperature and under solvent-free conditions to afford the products in high to excellent yields (90–98%).

KEYWORDS
alcohols, alkanes, $NaBH_3CN$, $SiO_2@SO_3H$

1 | INTRODUCTION

Reduction is one of the most important reactions in organic synthesis and a vast variety of reducing agents have been introduced for this achievement. In this context, considerable attention has been paid to modified hydroborate agents for reduction of organic compounds.[1–4] $NaBH_3CN$ with an electron withdrawing cyano group is a remarkable stable and selective reducing agent and has been found many applications in organic synthesis.[5–16] In addition, it is well known that the reducing capability of $NaBH_3CN$ for reduction of functional groups is greatly modified with pH variations. Thus in basic or neutral media, functional groups such as the carbonyl moiety are practically inert toward $NaBH_3CN$, and the adequate reduction rate is obtained when the reaction medium gets acidic conditions (pH ~ 3–4).[5,17] Although $NaBH_3CN$ has been used in many organic reactions, this reagent suffers from strong acidic conditions, limitation to use acid-sensitive functional groups, and the formation of some side products. Therefore, the development and introduction of new protocols that use green and mild reaction criteria as well easily separable heterogeneous catalysts is a subject of more interest.

In line with the outlined strategies and continuation of our research program directed to modified hydroborate agents in organic synthesis,[18–22] herein, we wish to introduce sulfonic acid anchored on silica, $SiO_2@SO_3H$, as a new and superior solid acid catalyst for dramatically raising the reducing ability of $NaBH_3CN$ toward green and quick reduction of various carbonyl compounds such as aldehydes, ketones, α,β-unsaturated enals and enones, and α-diketones and acyloins to the corresponding alcohols or alkanes at room temperature and under solvent-free conditions (Scheme 1).
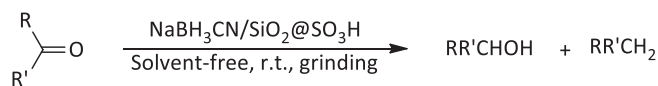
SCHEME 1 Reduction of carbonyl compounds with the NaBH$_3$CN/SiO$_2$@SO$_3$H system
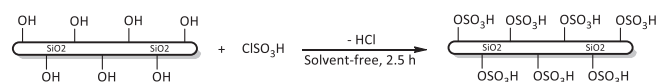
SCHEME 2 Preparation of the immobilized sulfonic acid on SiO$_2$

2 | RESULTS AND DISCUSSION

In recent years, heterogeneous catalysts due to economic concerns have attracted a great deal of attention. They are easily handled, as well as low cost, more reactive and more environmentally benign alternatives than their homogeneous counterparts. As mentioned here, exploring the reducing capability of NaBH$_3$CN due to a strong withdrawing cyano group completely depends on applying vigorous acidic conditions. This situation puts some restrictions to use NaBH$_3$CN for bench-top and practical purposes. To overcome the mentioned drawbacks, we recently introduced wet SiO$_2$ as a solid acid promoter for reduction of carbonyl compounds with NaBH$_3$CN under acid-free and solvent-free conditions.[23] Although the reported method has own merits; however, the requirement for oil bath (70–80°C) conditions (accompanied with the prolonged reaction times) or microwave irradiation as an unconventional energy source are its disadvantages. Therefore, keeping a new strategy in mind encouraged us to investigate the promoter activity of sulfonic acid anchored on silica as a new solid acid catalyst for enhancing the reducing capability of NaBH$_3$CN. According to the reported procedure,[24] the catalyst was prepared by simply mixing and stirring of SiO$_2$ and ClSO$_3$H under solvent-free conditions for 2.5 hr (Scheme 2). It is notable

that the preparation of the catalyst is carried out with the reaction of cheaply available counterparts. After synthesis of SiO$_2$@SO$_3$H, its promoter activity toward reducing potential of NaBH$_3$CN was studied by reduction of carbonyl compounds in the absence of any acidic medium.

2.1 | Catalytic reduction of aldehydes to alcohols

To optimize the reaction conditions, we performed reduction of benzaldehyde as a model compound with NaBH$_3$CN in the presence of SiO$_2$@SO$_3$H under solvent-free conditions. The experiments proved that using 3 mmol NaBH$_3$CN and 0.1 g SiO$_2$@SO$_3$H per 1 mmol of PhCHO at room temperature is the requirement for complete reduction of benzaldehyde to benzyl alcohol (Table 1, entry 2) (Scheme 3).

For highlighting the promoter activity of SiO$_2$@SO$_3$H, we also examined the influence of other solid acids, which were prepared by simple mixing of Amberlyst A-15 and Al$_2$O$_3$ with H$_2$SO$_4$/H$_3$PO$_4$ as well molecular sieve 4 Å with H$_3$PO$_4$, on the reducing potential of NaBH$_3$CN under solvent-free conditions. The summarized results in Table 1 show that in comparison to SiO$_2$@SO$_3$H, the influence of examined solid acids was not satisfactory. In addition, a comparison of the obtained results with the current protocol and reported wet SiO$_2$ shows that the present system exhibits a superior promoter activity toward NaBH$_3$CN (Scheme 4).

The usefulness and generality of the NaBH$_3$CN/SiO$_2$@SO$_3$H system were further studied by performing reduction of structurally diverse aliphatic and aromatic aldehydes under the optimized reaction conditions. The summarized results in Table 2 show that all reduction reactions were carried out at room temperature and under solvent-free conditions to afford the corresponding primary alcohols in high to excellent yields. As seen in Table 2, all reactions were carried out dramatically within 3 min in the absence of any aqueous acidic medium. In addition, because of a dramatic

TABLE 1 Optimization experiments for reduction of benzaldehyde and acetophenone with NaBH$_3$CN in the presence of solid acids

Entry	Reaction components (molar ratio)	Support (g)	Condition	Time (min)	Conversion (%)
1	PhCHO/NaBH$_3$CN (1:2)	SiO$_2$@SO$_3$H (0.1)	Solvent-free/r.t.	120	80
2	PhCHO/NaBH$_3$CN (1:3)	SiO$_2$@SO$_3$H (0.1)	Solvent-free/r.t.	3	100
3	PhCHO/NaBH$_3$CN (1:4)	Amberlyst A-15@H$_3$PO$_4$ (0.1)	Solvent-free/80°C	180	0
4	PhCHO/NaBH$_3$CN (1:4)	Amberlyst A-15@H$_2$SO$_4$ (0.1)	Solvent-free/80°C	180	0
5	PhCHO/NaBH$_3$CN (1:4)	Molecular sieve 4 Å@H$_3$PO$_4$ (0.1)	Solvent-free/80°C	180	0
6	PhCHO/NaBH3CN (1:4)	Al$_2$O$_3$@H$_3$PO$_4$ (0.1)	Solvent-free/80°C	180	0
7	PhCHO/NaBH$_3$CN (1:4)	Al$_2$O$_3$@H$_2$SO$_4$ (0.1)	Solvent-free/80°C	180	30
8	PhCOCH$_3$/NaBH$_3$CN (1:2)	SiO$_2$@SO$_3$H (0.1)	Solvent-free/r.t.	180	60
9	PhCOCH$_3$/NaBH$_3$CN (1:3)	SiO$_2$@SO$_3$H (0.1)	Solvent-free/r.t.	3	100
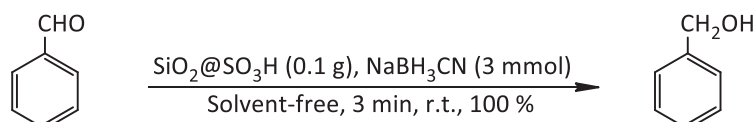
SCHEME 3 Reduction of benzaldehyde with the NaBH$_3$CN/SiO$_2$@SO$_3$H system
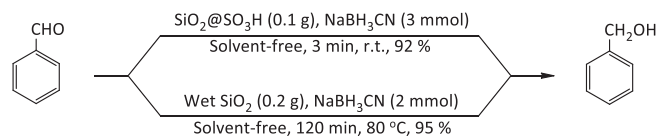
SCHEME 4 Comparing the promoter activity of $SiO_2@SO_3H$ and wet SiO_2 in reduction of benzaldehyde

influence of $SiO_2@SO_3H$, the presence of electron releasing or withdrawing substituents on aromatic rings did not affect the rate of reductions.
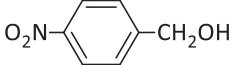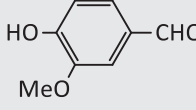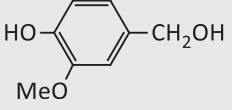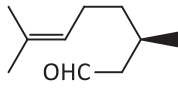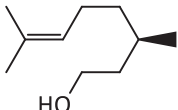
2.2 | Catalytic reduction of ketones to alkanes

Reactivity of ketones toward the $NaBH_3CN/SiO_2@SO_3H$ system was also examined by the reduction of acetophenone under solvent-free conditions. The examinations showed that the optimized reaction conditions for reduction of benzaldehyde by the $NaBH_3CN/SiO_2@SO_3H$ system (Table 1, entry 9) were also suitable for reduction of acetophenone. Thus, using 3 mmol $NaBH_3CN$ and 0.1 g $SiO_2@-SO_3H$ per 1 mmol of acetophenone was sufficient to afford ethylbenzene as a reductive-deoxygenation product at room

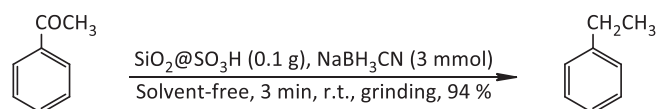**TABLE 2** Solvent-free reduction of aldehydes with the $NaBH_3CN/SiO_2@SO_3H$ system[a]

Entry	Substrate	Product	Molar ratio (subs./NaBH$_3$CN)	SiO$_2$@SO$_3$H (g)	Time (min)	Yield (%)[b]
1			1:3	0.1	3	92
2			1:3	0.1	3	95
3			1:3	0.1	3	91
4			1:3	0.1	3	91
5			1:3	0.1	3	95
6			1:3	0.1	3	94
7			1:3	0.1	3	95
8			1:3	0.1	3	95
9			1:3	0.1	3	94
10			1:3	0.1	3	92

TABLE 2 (Continued)

Entry	Substrate	Product	Molar ratio (subs./NaBH$_3$CN)	SiO$_2$@SO$_3$H (g)	Time (min)	Yield (%)[b]
11	O$_2$N—⟨benzene⟩—CHO	O$_2$N—⟨benzene⟩—CH$_2$OH	1:3	0.1	3	95
12	HO—⟨benzene, MeO⟩—CHO	HO—⟨benzene, MeO⟩—CH$_2$OH	1:3	0.1	3	95
13	⟨OHC structure⟩	⟨HO structure⟩	1:3	0.1	3	93

[a] All reactions were carried out at room temperature.
[b] Isolated yields.

SCHEME 5 Reduction of acetophenone with the NaBH$_3$CN/SiO$_2$@SO$_3$H system

temperature (Scheme 5). This result exhibited that the reducing pathway of the formyl moiety (–CHO) and benzoyl function (ArCO–) with the NaBH$_3$CN/SiO$_2$@SO$_3$H system is entirely different. It means that aldehydes produce primary alcohols; however, the benzoyl function affords a reductive-deoxygenation product without formation of secondary alcohol.

To explore the synthetic utility of the NaBH$_3$CN/SiO$_2$@SO$_3$H system toward reductive-deoxygenation of ketones, structurally diverse aromatic ketones were subjected to 3 mmol NaBH$_3$CN in the presence of 0.1 g SiO$_2$@SO$_3$H under solvent-free conditions. The results of this investigation are summarized in Table 3. The Table exhibited that all reduction reactions without influence of electron releasing or withdrawing substituents on aromatic rings were carried out successfully within 3 min to afford the corresponding alkanes in excellent yields. In addition, an examination for 4-phenylcyclohexanone with the NaBH$_3$CN/SiO$_2$@SO$_3$H system shows that in the case of aliphatic ketones, the current protocol obeys from the same mechanistic pathway of aromatic ketones to afford 4-phenylcyclohexane as a reductive-deoxygenation product (Table 3, entry 7). Comparison of the results for wet SiO$_2$ (previously reported) and SiO$_2$@SO$_3$H as solid acid catalysts for NaBH$_3$CN reduction of ketones shows that both of solid acids promote the reduction reaction through different mechanistic pathways. It means that by the promotion with wet SiO$_2$, reduction of ketones leads to the formation of secondary alcohols; whereas, the promotion

by SiO$_2$@SO$_3$H produces alkanes through the reductive-deoxygenation pathway (Scheme 6).
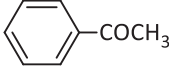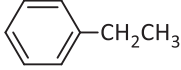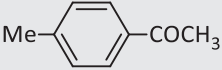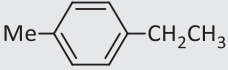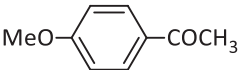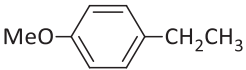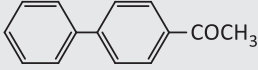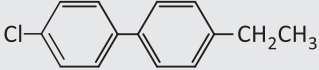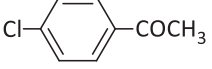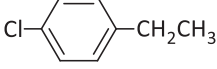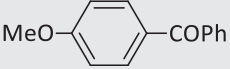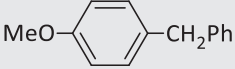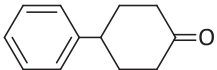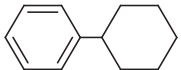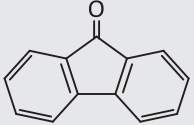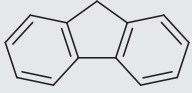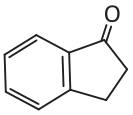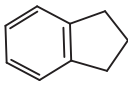
2.3 | Catalytic reduction of α,β-unsaturated aldehydes and ketones

Next, the reducing ability of the NaBH$_3$CN/SiO$_2$@SO$_3$H system toward regioselective reduction of α,β-unsaturated aldehydes and ketones was studied. The results of solvent-free reduction of cinnamaldehyde with 3 mmol NaBH$_3$CN and 0.1 g SiO$_2$@SO$_3$H showed that the reaction was carried out within 3 min to afford a mixture of cinnamyl alcohol (62%) and 3-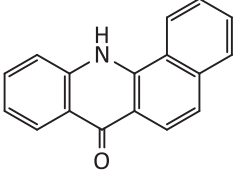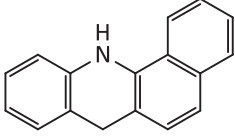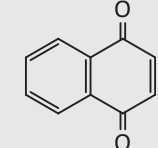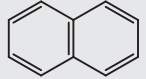phenyl-1-propanol (38%). The examinations for reduction of benzalacetone, benzalacetophenone, and citral with NaBH$_3$CN/SiO$_2$@SO$_3$H and producing the mixture of products showed that the current protocol did not have any regioselectivity toward reduction of conjugated enals and enones. In addition, conjugated aldehydes as the simple aldehydes were reduced to the corresponding alcohols (Table 4, entries 1 and 4), and conjugated ketones as the simple ketones were converted to the conjugated alkanes with this reducing system (Table 4, entries 2 and 4).

2.4 | Catalytic reduction of acyloins and α-diketones

Reactivity of α-diketones and acyloins toward the NaBH$_3$CN/SiO$_2$@SO$_3$H system was further studied through the reduction of benzil (1 mmol) with NaBH$_3$CN (3 mmol) and SiO$_2$@SO$_3$H (0.1 g) under solvent-free conditions. The examination showed that the reaction was completed within 3 min to afford 1,2-diphenylethane as a reductive-deoxygenation product in 92% yield (Table 5, entry 1). Reducing capability of the NaBH$_3$CN (3 mmol)/SiO$_2$@SO$_3$H (0.1 g) system was further examined by the reduction of other α-diketones and acyloins at room temperature and under solvent-free conditions. The results of

TABLE 3 Solvent-free reduction of ketones with the NaBH$_3$CN/SiO$_2$@SO$_3$H system[a]

Entry	Substrate	Product	Molar ratio[b]	SiO$_2$@SO$_3$H (g)	Time (min)	Yield (%)[c]
1	Ph—COCH$_3$	Ph—CH$_2$CH$_3$	1:3	0.1	3	94
2	Me—C$_6$H$_4$—COCH$_3$	Me—C$_6$H$_4$—CH$_2$CH$_3$	1:3	0.1	3	95
3	MeO—C$_6$H$_4$—COCH$_3$	MeO—C$_6$H$_4$—CH$_2$CH$_3$	1:3	0.1	3	95
4	Ph—C$_6$H$_4$—COCH$_3$	Cl—C$_6$H$_4$—C$_6$H$_4$—CH$_2$CH$_3$	1:3	0.1	3	92
5	Cl—C$_6$H$_4$—COCH$_3$	Cl—C$_6$H$_4$—CH$_2$CH$_3$	1:3	0.1	3	96
6	MeO—C$_6$H$_4$—COPh	MeO—C$_6$H$_4$—CH$_2$Ph	1:3	0.1	3	94
7			1:3	0.1	3	98
8			1:3	0.1	3	90
9			1:3	0.1	3	94
10	Ph$_2$C=O	PhCH$_2$Ph	1:3	0.1	3	98
11			1:3	0.1	3	96
12			1:3	0.1	3	96

[a] All reactions were carried out at room temperature.
[b] Molar ratio as: Subs./NaBH$_3$CN.
[c] Isolated yields.
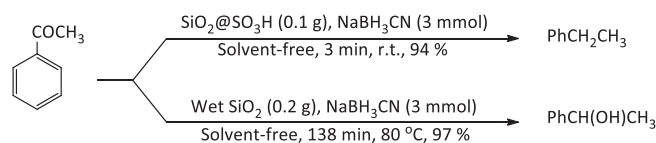
SCHEME 6 Comparing the promoter activity of $SiO_2@SO_3H$ and wet SiO_2 toward the reduction of acetophenone

this investigation are illustrated in Table 5. The obtained results represent that the current reducing system affords reductive-deoxygenation products instead of secondary alcoholic products (Table 5).

3 | EXPERIMENTAL

3.1 | General

All reagents and substrates were purchased from commercial sources with the best quality and they were used without further purification. SiO_2 was used in the form of silica gel 60 (70–230 mesh) and was purchased from Merck company. FT-IR and $^1H/^{13}C$ NMR spectra were recorded on Thermo Nicolet Nexus 670 FT-IR and Bruker Avance 300 MHz spectrometers, respectively. The products were characterized by a comparison with authentic samples (melting or boiling points) and their spectral data. All yields refer to isolated pure products. TLC was applied for the purity determination of substrates, products, and reaction monitoring over the silica gel 60 F254 aluminum sheet.

3.2 | Preparation of sulfonic acid anchored on silica, $SiO_2@SO_3H$

In a round-bottom flask containing silica gel (1 mmol, 60 g, 70–230 mesh) and a magnetic stirrer, $ClSO_3H$ (0.2 mol, 23.3 g) was added within 30 min at room temperature. During the addition of $ClSO_3H$, the mixture was stirred magnetically and the evolution of HCl gas was taken place. Stirring of the reaction mixture was continued for 2 hr to completely release HCl gas. The immobilized silica ($SiO_2@SO_3H$) was obtained as a white and fine granular powder in 76 g and 39% *w/w*.[24]

3.3 | A typical procedure for solvent-free reduction of carbonyl compounds with the $NaBH_3CN/SiO_2@SO_3H$ system

In an agate mortar, a mixture of $SiO_2@SO_3H$ (0.1 g), acetophenone (0.12 g, 1 mmol), and $NaBH_3CN$ (0.187 g, 3 mmol) was ground at room temperature for 3 min. Progress of the reaction was monitored by TLC (eluent; *n*-hexane/EtOAc: 5/2). After completion of the reaction, the mixture was washed with ethyl acetate. Evaporation of the solvent under reduced pressure affords the pure liquid ethylbenzene (0.99 g, 94% yield) (Table 3, entry 1).

4 | CONCLUSIONS

In this study, the immobilized sulfonic acid on silica, $SiO_2@$-SO_3H, was used as a superior solid acid catalyst for extremely raising the reducing ability of $NaBH_3CN$. Structurally diverse

TABLE 4 Solvent-free reduction of conjugated carbonyl compounds with the $NaBH_3CN/SiO_2@SO_3H$ system[a]

			Yield of products (%)[b,c]			
Entry	Substrate	Time (min)	–CH=CH-CHOH–	–CH=CH-CH₂–	–CH₂CH₂CH₂–	–CH₂CH₂CHOH–
1		3	62	—	—	38
2		3	—	64	36	—
3		3	—	60	40	—
4		3	54	—	—	46
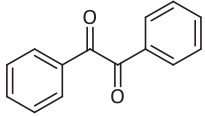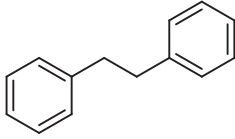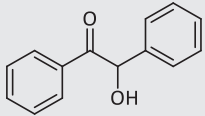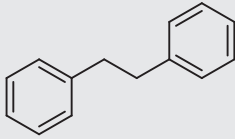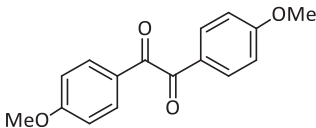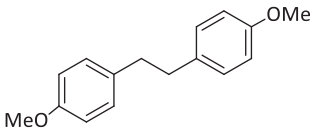
[a] All reactions were carried out in a molar ratio of Subs./$NaBH_3CN$ (1:3) in the presence of 0.1 g $SiO_2@SO_3H$ at room temperature.
[b] Isolated yields.
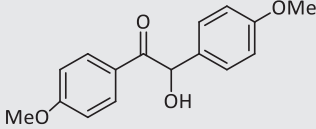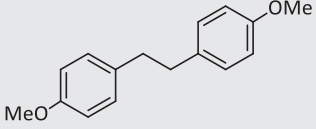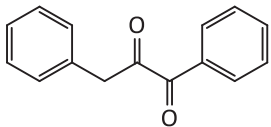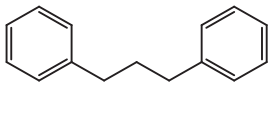[c] The percentage of products was determined by ^1H NMR.

TABLE 5 Solvent-free reductive-deoxygenation of acyloins and α-diketones with the NaBH$_3$CN/SiO$_2$@SO$_3$H system[a]

Entry	Substrate	Product	Molar ratio (subs./NaBH$_3$CN)	SiO$_2$@SO$_3$H (g)	Time (min)	Yield (%)[b]
1			1:4	0.1	3	92
2			1:4	0.1	3	95
3			1:4	0.1	3	95
3			1:4	0.1	3	93
5			1:4	0.1	3	94

[a] All reactions were carried out at room temperature and under solvent-free conditions.
[b] Isolated yields.

carbonyl compounds were reduced by the NaBH$_3$CN (3 mmol)/SiO$_2$@SO$_3$H (0.1 g) system at room temperature and under solvent-free conditions. All reduction reactions were carried out within 3 min to afford the corresponding alcohols or alkanes in high to excellent yields. The obtained results showed that via this reducing system, reduction of aldehydes led to the formation of primary alcohols, and ketones to the corresponding alkanes. Easy preparation of the catalyst, its dramatic influence on reducing potential of NaBH$_3$CN, quick and mild reaction conditions, high to excellent yield of the products, and easy workup procedure as well as the benefits of solvent-free conditions are the advantages that make this protocol a prominent choice for the reduction of carbonyl compounds by NaBH$_3$CN.

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