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Multi-component reaction on free nano-SiO_2 catalyst: Excellent reactivity combined with facile catalyst recovery and recyclability

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Abstract. Nano-SiO_2 catalyst was readily prepared from inexpensive starting materials in aqueous media which catalysed the synthesis *a*-aminophosphonates from aldehydes, amines and diethylphosphate under ultrasonication in water. High catalytic activity and ease of recovery from the reaction mixture using filtration, and reuse without significant losses in performance are additional eco-friendly attributes of this catalytic system.

Keywords. Nano-SiO_2; ultrasonication; green catalyst; *a*-aminophosphonates; one-pot synthesis; green chemistry.

1. Introduction

The 'greening' of chemical processes to attain environmental friendliness[1] and sustainability has become a major issue in academia and industry. Greener and environmentally sound synthetic protocols and reaction conditions have played pivotal roles in recent years toward the goal of switching to increasingly efficient and benign processes that avoid the use of volatile organic solvents, toxic reagents, hazardous and harsh reaction conditions, as well as challenging and time-consuming wasteful separations.[2] Designing organic reactions in aqueous media is another attractive area in green chemistry.[3] Water is an abundant and environmentally benign solvent. As a reaction medium, it offers several benefits including control over exothermic reactions, salting in and salting out and variation of pH. Work-up and purification can be carried out by simple phase separation techniques. Also, organic reactions in water exhibit unique reactivity and selectivity that are different from reactions in organic solvents. In particular, reactions with negative activation volume are reported to occur faster in water than in organic solvents.[4] Green catalysis is a subchapter of green chemistry but probably the most important one. In most cases of organocatalysed reactions a large amount of the organocatalyst (typically, 10–30 mol%) is needed, which presents a challenge for organic chemists to utilize organocatalysts more efficiently and economically. In this context, and in view of the environmental and economical reasons, here an ongoing effort to replace such classical method with a newer method using multi-component reactions using a nano catalyst is reported.[5] In general, nano catalysts offer higher surface area and lower coordinating sites, which are responsible for the higher catalytic activity.[6] Furthermore, nano catalysis has the advantage of high atom efficiency, easy product purification, and reusability of the catalyst.[7] Clearly, the development of 'free' nanoparticles with tunable catalytic activity is of great significance for both academia and industry.[8] Among the nanoparticle, SiO_2 has been a focus of extensive research due to its chemical stability, large surface area, non-toxicity, cheap, environmentally friendly and abundant. Nano-SiO_2 showed their potential in many fields, such as a catalyst or catalyst support.

a-Aminophosphonates have attracted much attention owing to their biological activities. Their utilities as enzyme inhibitors, antibiotics, peptide mimics, herbicides, pharmacological agents and many other applications are well-documented.[9] Thus, a number of synthetic methods including enantioselective hydrophosphonylation reactions[10] have been developed during the last decades. In continuation of our work on the synthesis of biologically important compounds using simple, efficient, non-toxic, and readily available catalysts,[11–13] we have used of nano-SiO_2 for the

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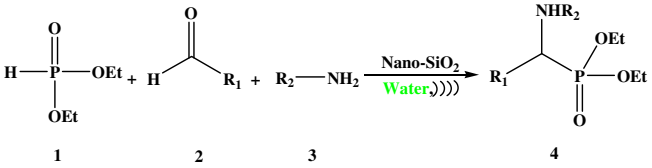


Scheme 1. Synthesis of *a*-aminophosphonates from aldehydes, amines and diethylphosphate in the presence of nano-SiO_2.

synthesis of *a*-aminophosphonates from aldehydes, amines and diethylphosphate under ultrasonication in water with good to excellent yield (scheme 1).

2. Experimental

2.1 *General procedure*

Chemicals were purchased from Fluka and Merck in high purity. Melting points were determined in open capillaries using an Electrothermal 9100 apparatus and are uncorrected. FTIR spectra were recorded on a VERTEX 70 spectrometer (Bruker) in the transmission modein spectroscopic grade KBr pellets for all the powders. The particle size and structure of nano-SiO_2 were observed by using a Philips CM10 transmission electron microscope operating at 100 KV. Scanning electron microscopy (SEM) studies were conducted on a Philips XL 30 scanning electron microscope. Powder X-ray diffraction data were obtained using Bruker D8 Advance model with Cu kα radiation. NMR spectra were recorded in $CDCl_3$ on a Bruker Avance DRX-400 MHz instrument spectrometer using TMS as internal standard. The purity determination of the products and reaction monitoring were accomplished by TLC on silica gel polygram SILG/UV 254 plates.

2.2 *Synthesis of nano-SiO_2*

The synthesis of nano-SiO_2 was achieved by the ammonia-catalysed hydrolysis of tetraethyl orthosilicate (TEOS) in a mixed solvent of deionized water and ethanol using PEG as the surfactant agent in the process at room temperature. In a typical procedure, 100 mL ethanol and 20 mL deionized water were mixed together in a beaker, and then 1.0 g of PEG (MW 6000) was dispersed into the mixture by ultrasonication. After adding ammonia water (2.5 mL), tetraethyl orthosilicate (TEOS, 2 mL) was added to the reaction solution. The resulting dispersion was under mechanically stirred continuously for 20 h at room temperature. The resultant products were collected and washed with ethanol and deionized water in sequence, and then dried under vacuum at 60°C for 2 h for further use.

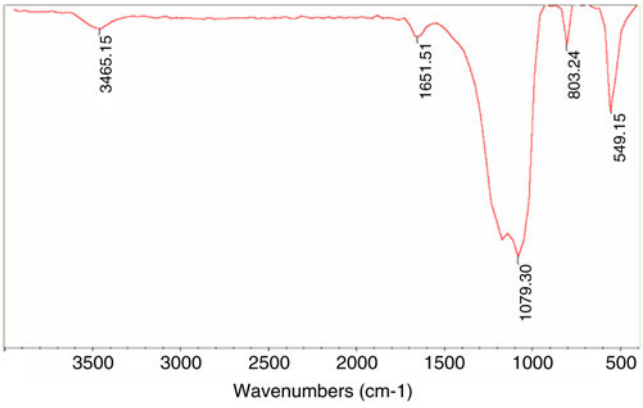


Figure 1. FT-IR spectrum of precipitated nano-SiO_2.

2.3 *FT-IR spectroscopy*

Figure 1 shows the FT-IR spectrum of nano-SiO_2. The IR band at 3465 cm^{-1} could be assigned to the stretching vibrations of Si–OH groups in the structure of amorphous SiO_2. Correspondingly, the IR band at 1651 cm^{-1} is due to the bending vibration of H_2O molecules. The very strong and broad IR band at 1079 cm^{-1} with a shoulder at 1178 cm^{-1} is usually assigned to the TO and LO modes of the Si–O–Si asymmetric stretching vibrations. The IR band at 803 cm^{-1} can be assigned to Si–O–Si symmetric stretching vibrations, whereas the IR band at 549 cm^{-1} is due to O–Si–O bending vibrations.

2.4 *X-ray diffraction (XRD) analysis*

Figure 2 shows the broadened XRD peak for amorphous silica centred at a $2\theta = 23°$ value to our measurement.[14]

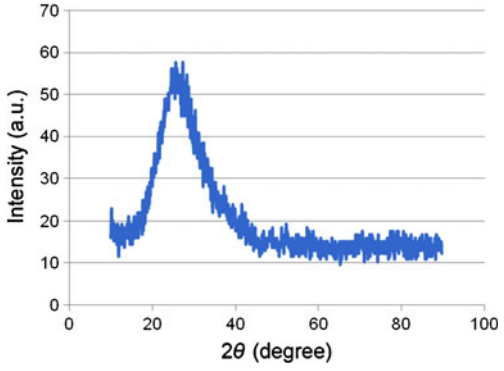


Figure 2. XRD analysis of nano-SiO_2.

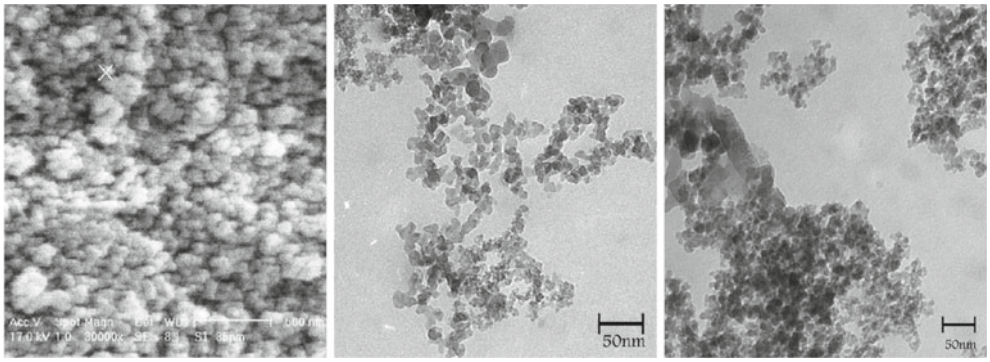


Figure 3. SEM image of nano-SiO_2. (**a**) TEM images of nano-SiO_2 before use (**b**) and after reuse ten times. Agglomeration of silica can be seen (**c**).

2.5 *SEM and TEM*

The size and structure of the nano-SiO_2 were also evaluated using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). According to the SEM (figure 3a) and TEM (figure 3b), it was observed that the synthesized nano-SiO_2 has nano dimension ranging from ∼20 to 25 nm. The results indicate that the product consists of spherical nanoparticles with smooth surfaces.

2.6 *General procedure for the synthesis of a-aminophosphonates*

A mixture of aldehydes (1 mmol), amines (1 mmol), diethylphosphate (1 mmol) and nano-SiO_2 (0.0007 g) in water (5 ml), at room-temperature was irradiated by ultrasound for 10–20 min (the progress of the reaction was monitored by TLC). After completion, the catalyst was filtered and washed with H_2O (5 ml) and EtOH (5 ml). The reaction mixture was cooled to ambient temperature and extracted with ethyl acetate (2 × 10 mL). The combined organic layers were dried over Na_2SO_4, filtered and the solvent removed under reduced pressure.

2.7 *Data for compounds*

4a. ^{1}H NMR; δ, ppm: 1.15 (t, J = 6.8 Hz, 3H), 1.32 (t, J = 6.8 Hz, 3H), 3.64–3.72 (m, 1H), 3.90–4.01 (m, 1H), 4.04–4.19 (m, 2H), 4.77 (d, J = 24.4 Hz, 1H), 4.85 (br, s, 1H), 6.59 (d, J = 8.4 Hz, 2H), 6.72 (t, J = 6.8 Hz, 1H), 7.09 (t, J = 7.6 Hz, 2H), 7.25–7.37 (m, 3H), 7.48 (d, J = 7.6 Hz, 2H); ^{13}C NMR; δ, ppm: 146.41, 146.23, 135.93, 129.19, 128.61, 128.59, 127.92, 127.86, 118.42, 113.89, 63.34, 63.29, 63.26, 63.22, 56.82, 55.35, 16.45, 16.39, 16.19, 16.14.

4b. ^{1}H NMR; δ, ppm: 1.10 (t, J = 7.2 Hz, 3H), 1.21 (t, J = 7.2 Hz, 3H), 3.68–3.79 (m, 1H), 3.89–3.97 (m, 1H), 3.99–4.11 (m, 2H), 4.77 (dd, J = 7.6 Hz, J = 24.4 Hz, 1H), 5.40–5.48 (m, 1H), 6.41 (d, J = 8 Hz, 1H), 6.55 (t, J = 7.6 Hz, 1H), 6.69 (t, J = 8 Hz, 1H), 7.18–7.27 (m, 4H), 7.40 (d, J = 7.6 Hz, 2H); ^{13}C NMR; δ, ppm: 142.39, 142.25, 135.34, 135.31, 128.59, 128.00, 127.69, 127.61, 119.93, 118.44, 112.66, 63.42, 63.38, 63.31, 63.24, 56.53, 55.15, 16.40, 16.33, 16.21, 16.15.

4c. ^{1}H NMR; δ, ppm: 1.08 (t, J = 7.2 Hz, 3H), 1.27 (t, J = 7.2 Hz, 3H), 3.60–3.68 (m, 1H), 3.88–3.96 (m, 1H), 4.05–4.21 (m, 2H), 4.75 (dd, J = 8.0 Hz, J = 24.4 Hz, 1H), 5.37 (br, s, 1H), 6.45 (dd, J = 2.0 Hz, J = 8.4 Hz, 1H), 6.60–6.64 (m, 2H), 6.97 (t, J = 8 Hz, 1H), 7.26–7.34 (m, 3H), 7.48 (d, J = 7.2 Hz, 2H); ^{13}C NMR; δ, ppm: 147.88, 147.72, 135.59, 134.82, 130.13, 128.69, 128.58, 128.11, 128.06, 127.92, 127.86, 118.09, 113.80, 111.82, 63.82, 63.40, 63.29, 63.23, 56.58, 55.06, 16.49, 16.43, 16.22, 16.18.

4d. ^{1}H NMR; δ, ppm: 1.12 (t, J = 6.8 Hz, 3H), 1.28 (t, J = 6.8 Hz, 3H), 3.63–3.74 (m, 1H), 3.87–3.96 (m, 1H), 4.09–4.22 (m, 2H), 4.73 (d, J = 24 Hz, 1H), 5.22 (br, s, 1H), 6.57 (d, J = 8.8 Hz, 1H), 7.04 (d, J = 9.2 Hz, 2H), 7.27–7.34 (m, 3H), 7.49 (d, J = 7.6 Hz, 2H); ^{13}C NMR; δ, ppm: 147.88, 147.70, 135.55, 134.82, 130.13, 128.65, 128.57, 128.11, 128.06, 127.92, 127.86, 118.09, 113.83, 111.81, 63.49, 63.40, 63.30, 63.23, 56.56, 55.08, 16.51, 16.45, 16.23, 16.18.

4e. ^{1}H NMR; δ, ppm: 1.09 (t, J = 6.8 Hz, 3H), 1.27 (t, J = 6.8 Hz, 3H), 3.62–3.72 (m, 1H), 3.87–3.97 (m, 1H), 4.05–4.19 (m, 2H), 4.71 (d, J = 24.4 Hz, 1H), 4.99 (br, s, 1H), 6.53–6.56 (m, 2H), 6.78 (t, J = 8.8 Hz, 2H), 7.22–7.33 (m, 3H), 7.48 (d, J = 7.2 Hz, 2H); ^{13}C NMR; δ, ppm: 146.01, 144.87, 135.43, 129.00, 128.10, 128.07, 127.85, 127.82, 127.79, 123.02, 115.00, 63.48, 63.41, 63.36, 63.29, 56.90, 55.40, 16.46, 16.40, 16.21, 16.15.

4f. ^{1}H NMR; δ, ppm: 1.13 (t, J = 7.2 Hz, 3H), 1.34 (t, J = 7.2 Hz, 3H), 3.59–3.71 (m, 1H), 3.87–3.98 (m, 1H), 4.12–4.23 (m, 2H), 4.43 (dd, J = 7.6 Hz, J = 24 Hz, 1H), 6.35 (br s, 1H), 6.44 (d, J = 9.2 Hz, 1H), 7.28–7.36 (m, 3H), 7.51 (d, J = 7.2 Hz, 2H), 8.00 (d, J = 9.2 Hz, 2H); ^{13}C NMR; δ, ppm: 152.25, 138.83, 134.44, 128.89, 128.58, 128.52, 128.49, 127.86, 127.81, 126.05, 112.42, 63.92, 63.85, 63.40, 63.33, 56.24, 54.73, 16.48, 16.40, 16.22, 16.14.

4g. ^{1}H NMR; δ, ppm: 1.15 (t, J = 7.2 Hz, 3H), 1.35 (t, J = 7.2 Hz, 3H), 2.23 (s, 3H), 3.68–3.76 (m, 1H), 3.94–4.03 (m, 1H), 4.09–4.21 (m, 2H), 4.79 (d, J = 24 Hz, 1H), 6.59 (d, J = 8 Hz, 2H), 6.96 (d, J = 8 Hz, 2H), 7.29–7.32 (m, 1H), 7.39 (t, J = 7.4 Hz, 2H), 7.52 (d, J = 7.2 Hz, 2H); ^{13}C NMR; δ, ppm: 136.06, 129.66, 128.67, 128.57, 127.88, 127.82, 127.60, 113.98, 63.32, 63.27, 63.24, 63.19, 57.13, 55.63, 20.39, 16.49, 16.43, 16.24, 16.18.

4h. ^{1}H NMR; δ, ppm: 1.15 (t, J = 6.8 Hz, 3H), 1.30 (t, J = 6.8 Hz, 3H), 3.67 (s, 3H), 3.69–3.78 (m, 1H), 3.87–3.99 (m, 1H), 4.09–4.21 (m, 2H), 4.74 (d, J = 24 Hz, 1H), 6.59 (d, J = 8.8 Hz, 2H), 6.70 (d, J = 8.8 Hz, 2H), 7.24–7.29 (m,1H), 7.34 (t, J = 7.4 Hz, 2H), 7.45 (d, J = 7.2 Hz, 2H); ^{13}C NMR; δ, ppm: 152.66, 140.46, 140.32, 136.08, 128.58, 127.93, 127.88, 115.24, 114.70, 63.35, 63.28, 63.24, 63.18, 57.71, 56.22, 55.60, 29.68, 16.44, 16.38, 16.20, 16.14.

4i. ^{1}H NMR; δ, ppm: 1.17 (t, J = 7.2 Hz, 3H), 1.32 (t, J = 7.2 Hz, 3H), 3.60–3.75 (m, 1H), 3.78 (s, 3H), 3.91–3.99 (m, 1H), 4.05–4.23 (m, 2H) 4.82 (dd, J = 7.6 Hz, J = 23.2 Hz, 1H), 6.38 (br, s, 1H), 6.63 (d, J = 9.2 Hz, 2H), 6.87 (d, J = 8.4 Hz, 2H), 7.42 (d, 2H), 7.98 (d, J = 9.2 Hz, 2H); ^{13}C NMR; δ, ppm: 159.68, 152.65, 152.31, 152.19, 138.72, 129.05, 129.00, 126.42, 126.00, 114.29, 112.38, 63.85, 63.78, 63.31, 63.25, 55.15, 54.56, 22.63, 16.44, 16.40, 16.28, 16.22, 14.10.

4j. ^{1}H NMR; δ, ppm: 1.12 (t, J = 7.09 Hz, 3H), 1.35 (t, J = 7.09 Hz, 3H), 3.76–3.89 (m, 1H), 3.93–4.03 (m, 1H), 4.14–4.27 (m, 2H), 5.05 (br, s, 1H), 6.21 (dd, J = 3.8 Hz, J = 22.8 Hz, 1H), 6.70 (d, J = 8 Hz, 2H), 6.77 (t, J = 7.2 Hz, 1H), 7.17–7.20 (m, 2H), 7.43–7.47 (m, 1H), 7.58 (t, J = 8 Hz, 1H), 7.78–7.80 (m, 1H), 8.01 (d, J = 8 Hz, 2H); ^{13}C NMR; δ, ppm: 149.49, 149.42, 145.48, 145.31, 133.52, 133.50, 131.96, 129.42, 128.92, 128.77, 128.56, 128.53, 125.28, 118.86, 113.61, 63.94, 63.87, 63.42, 63.35, 50.68, 49.20, 16.41, 16.35, 15.99, 15.91.

4k. ^{1}H NMR; δ, ppm: 1.23 (t, J = 6.8 Hz, 3H), 1.34 (t, J = 6.8 Hz, 3H), 3.86–3.97 (m, 1H), 4.03–4.11 (m, 1H), 4.13–4.26 (m, 2H), 4.86 (d, J = 25.2 Hz, 1H), 6.55 (d, J = 7.6 Hz, 2H), 6.70–6.79 (m, 1H), 7.10–7.15 (m, 2H), 7.69–7.72 (m, 2H), 8.20–8.24 (m, 2H); ^{13}C NMR; δ, ppm: 147.64, 146.82, 146.68, 144.15, 129.38, 128.72, 123.76, 119.10, 113.84, 63.80, 63.70, 63.47, 63.40, 56.42, 54.50, 16.45, 16.41, 16.27, 16.21.

4l. ^{1}H NMR; δ, ppm: 1.22 (t, J = 7.2 Hz, 3H), 1.34 (t, J = 7.2 Hz, 3H), 3.86–3.95 (m, 1H), 4.01–4.10 (m, 1H), 4.11–4.27 (m, 2H), 4.81 (d, J = 24.8 Hz, 1H), 5.15 (br, s, 1H), 6.64 (d, J = 8 Hz, 2H), 6.70 (t, J = 7.6 Hz, 1H), 7.10 (t, J = 7.8 Hz, 2H), 7.30 (d, J = 8 Hz, 2H), 7.43–7.46 (m, 2H); ^{13}C NMR; δ, ppm: 146.19, 146.05, 134.65, 133.71, 129.25, 129.20, 128.82, 128.78, 118.63, 113.88, 63.51, 63.45, 63.40, 63.31, 56.25, 54.92, 16.46, 16.41, 16.31, 16.24.

4m. ^{1}H NMR; δ, ppm: 1.18 (t, J = 6.8 Hz, 3H), 1.32 (t, J = 6.8 Hz, 3H), 2.33 (s, 3H), 3.68–3.79 (m, 1H), 3.93–4.04 (m, 1H), 4.10–4.20 (m, 2H), 4.75–4.86 (m, 2H), 6.64 (d, J = 7.7 Hz, 2H), 6.74 (t, J = 7.2 Hz, 1H), 7.11–7.19 (m, 4H), 7.38–7.41 (m, 2H); ^{13}C NMR; δ, ppm: 146.51, 146.37, 137.63, 137.58, 132.78, 129.38, 129.34, 129.32, 129.24, 129.17, 127.79, 127.71, 118.32, 113.85, 63.32, 63.24, 63.20, 63.17, 56.54, 55.00, 21.18, 16.50, 16.42, 16.26, 16.20.

4n. ^{1}H NMR; δ, ppm: 1.15 (t, J = 7.2 Hz, 3H), 1.26 (t, J = 7.2 Hz, H), 3.76 (s, 3H), 3.90–3.99 (m, 1H), 4.06–4.22 (m, 2H), 4.78 (dd, J = 5.6 Hz, J = 24 Hz, 1H), 4.96 (br, s, 1H), 6.65 (d, J = 7.6 Hz, 2H), 6.69 (t, J = 7.2 Hz, 1H), 6.88 (d, J = 8.4 Hz, 2H), 7.11 (t, J = 8 Hz, 2H), 7.40–7.43 (m, 2H); ^{13}C NMR; δ, ppm: 159.32, 159.27, 146.53, 146.39, 129.10, 129.03, 128.95, 118.24, 114.01, 113.87, 63.25, 63.15, 56.05, 55.12, 46.53, 16.45, 16.38, 16.28, 16.22.

3. Results and discussion

The reaction was carried out in various solvents under similar conditions. In this study, it was found that water is a more efficient (table 1, entry 1) over other organic solvents (table 1, entries 2–13) with respect to reaction time and yield of the desired *a*-aminophosphonates. The reaction proceeded perfectly in polar solvents (table 1, entries 1, 2, 3, 7, 10, 11), but the yields decreased when the reaction was carried out in nonpolar solvents (table 1, entries 8, 9, 12).

At this stage, We have studied the catalyst concentration on model reaction. The catalyst plays a crucial role in the success of the reaction in terms of the rate and the yields. For example, diethylphosphate reacts with benzaldehyde and benzenamine in the presence of 0.0003 g nano-SiO_2 in water giving the product of 78% yield. Increasing the percentage of catalyst to 0.0005 g and 0.0007 g resulted in the yields 91% and 97%, respectively. Higher amounts of the catalyst did not improve the results to a greater extent. Thus, 0.0007 g nano-SiO_2 was chosen as the maximum quantity of catalyst used for these reactions (figure 4).

The activity of the recycled catalyst was also examined under the optimized conditions. After the completion of reaction, nano-SiO_2 was removed by filtration, washed with ethanol and dried at the pump. The recovered catalyst was reused for ten consecutive cycles without any significant loss in catalytic activity, proving its robustness (TEM; figure 5). The characterization of the nano-SiO_2 before and after reuse ten times showed the same particle size by transmission electron microscopy (TEM; figure 3).

Table 1. Solvent screening for the reaction between benzaldehyde, benzenamine and diethylphosphate.[a]

Entry	Solvent	Yield (%)[b]
1	H_2O	97
2	EtOH	69
3	CH_3CN	64
4	THF	52
5	CH_2Cl_2	46
6	Toluene	20
7	EtOAC	75
8	*n*-Hexane	Trace
9	$CHCl_3$	Trace
10	DMSO	70
11	MeOH	72
12	Dioxane	Trace
13	DMF	64
14	Solvent-free	76

[a]Reaction conditions: benzaldehyde (1 mmol), benzenamine (1 mmol), diethylphosphate (1 mmol), solvent (10 ml), nanosilica (0.001 g) at room-temperature under ultrasonication for 30 min

[b]Isolated yields

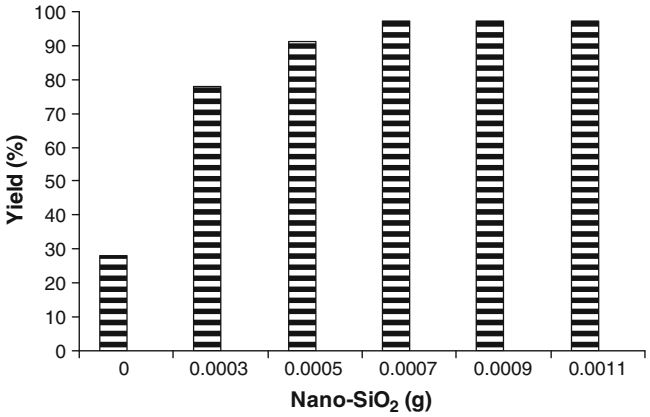


Figure 4. Effect of increasing amount of nano-SiO_2 on the preparation of *a*-aminophosphonates. Reaction of diethylphosphate, benzaldehyde and benzenamine in the presence of nano-SiO_2 at room temperature under ultrasonication in water.

The reaction of benzaldehyde, aniline and diethylphosphite in the presence of different catalyst was considered as the model reaction. In our present study we screened different catalyst and conditions. Surprisingly, the best was result obtained in using 1.1 mol% nano-SiO_2 at room temperature under ultrasonication in 15 min. A careful analysis of table 2 reveals the fact that, the reaction afforded 26–96% yield in the presence 5–20 mol% of different catalysts. Promising results were obtained with nano-SiO_2 in lesser time with better yield and reduced amount of catalyst. The increased catalytic activity of nano-SiO_2 over the another catalysts may be attributed to the higher surface area of SiO_2.

The catalytic activity of the nano-SiO_2 particles was compared with that of the bulk-SiO_2. For this purpose, the reactions were carried out separately under

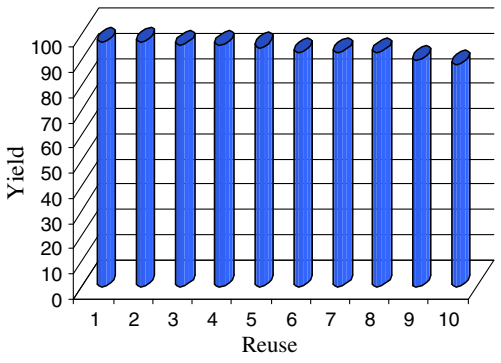


Figure 5. Reuses performance of the catalysts.

Table 2. Effect of various catalysts and solvent condition on the synthesis of α-aminophosphonates.

Entry	Catalyst	Amount of catalyst (mol%)	Solvent	Temp (°C)	Time (min)	Yield[a] (%)
1	$AlCl_3$	20	EtOH	r. t.	60	30[15]
2	$ZnCl_2$	20	EtOH	r. t.	60	26[15]
3	$YbCl_3$	10	EtOH	r. t.	60	68[15]
4	$Yb(OTf)_3$	5	EtOH	r. t.	60	84[15]
5	$Yb(PFO)_3$	5	Neat	r. t.	60	92[16]
6	MoO2Cl2	5	Neat	80	15	87[17]
7	$Cd(ClO_4)_2{\cdot}xH_2O$	5	Neat	40	45	92[18]
8	ChCl_2$ZnCl_2$	15	Neat	r. t.	60	96[19]
10	$FeCl_3$	5	THF	60	45	95[20]
11	Nano-SiO_2	1.1	H_2O	r.t.	15	97

[a]Isolated yields

Table 3. Comparative catalytic activity of nano-SiO_2 with bulk-SiO_2.

Entry	Reaction time (min)	Yield (%)[a]	
		Nano-SiO_2	Bulk-SiO_2
1	5	76	33
2	10	85	39
3	15	97	48
4	20	97	52
5	25	97	52

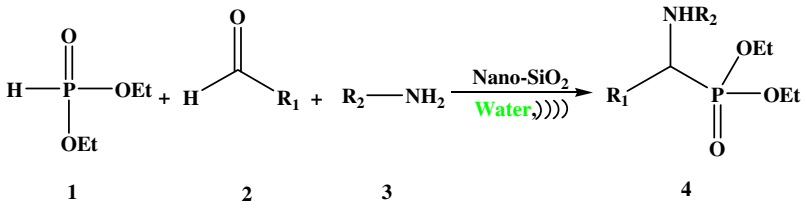
[a]Isolated yields

ultrasonication in water with both the catalysts for the appropriate time (table 3). The aliquots of the reaction mixture were collected periodically at an interval of 5 min. Table 3 shows the variation of the percentage preparation of *a*-aminophosphonates with time, when nano-SiO_2 (0.0007 g) and bulk-SiO_2 (0.0007 g) were employed as catalysts. It is evident that, the catalytic activity of the nano-SiO_2 is much greater than that of the bulk-SiO_2. After 15 min, nano-SiO_2 showed 97% preparation of *a*-aminophosphonates as compared to 48% with bulk-SiO_2. The increased catalytic activity of nano-SiO_2 over the bulk-SiO_2 may be attributed to the higher surface area of SiO_2.

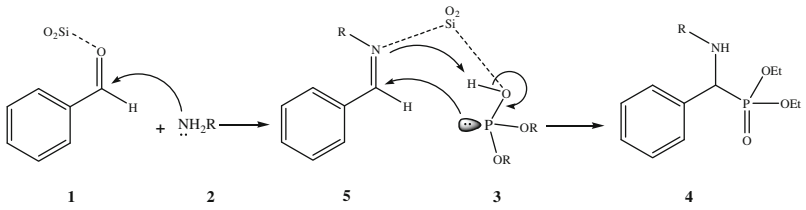
Table 4. Synthesis of *a*-aminophosphonates derivatives catalysed by nano-SiO_2.

Entry	Aldehyde	Amine	Product	Time (min)	Yield (%)[a,b]	Obs. mp (°C)	Lit. mp (°C)
1	C_6H_5CHO	$C_6H_5NH_2$	**4a**	15	97	88–90	91–93[21]
2	C_6H_5CHO	2-$ClC_6H_4NH_2$	**4b**	15	95	84–86	85–86[22]
3	C_6H_5CHO	3-$ClC_6H_4NH_2$	**4c**	10	93	119–121	122–123[23]
4	C_6H_5CHO	4-$ClC_6H_4NH_2$	**4d**	15	96	114–116	111–113[24]
5	C_6H_5CHO	4-$FC_6H_4NH_2$	**4e**	20	94	109–111	111–112[26]
6	C_6H_5CHO	4-$NO_2C_6H_4NH_2$	**4f**	15	97	148–150	145–146[22]
7	C_6H_5CHO	4-$CH_3C_6H_4NH_2$	**4g**	15	93	115–116	117–118[22]
8	C_6H_5CHO	4-$OCH_3C_6H_4NH_2$	**4h**	20	92	80–82	78–80[25]
9	4-$OCH_3C_6H_4CHO$	4-$NO_2C_6H_4NH_2$	**4i**	20	94	103–105	107–108[26]
10	2-$NO_2C_6H_4CHO$	$C_6H_5NH_2$	**4j**	20	92	158–159	155–156[27]
11	4-$NO_2C_6H_4CHO$	$C_6H_5NH_2$	**4k**	15	91	122–124	125–126[21]
12	4-ClC_6H_4CHO	$C_6H_5NH_2$	**4l**	10	95	77–78	75–76[28]
13	4-$CH_3C_6H_4CHO$	$C_6H_5NH_2$	**4m**	20	93	64–66	66–67[21]
14	4-$OCH_3C_6H_4CHO$	$C_6H_5NH_2$	**4n**	10	96	104–106	101–102[25]

[a]Reaction condition: benzaldehyde derivatives (1 mmol), diethylphosphate (1 mmol), amine derivatives (1 mmol), nano-SiO_2 (0.0007 g) at room temperature in water under ultrasonication
[b]Yield refers to isolated product



Scheme 2. Synthesis of derivatives 4 in the presence of nano–SiO_2.



Scheme 3. Suggested mechanism for the preparation of *a*-aminophosphonates.

After optimization of the reaction conditions, to delineate this approach, particularly in regard to library construction, this methodology was evaluated by using different amines, variety of different substituted benzaldehydes and of diethylphosphate in the presence of nano-SiO_2 under similar conditions. As can be seen from table 4, electronic effects and the nature of substituents on the aromatic ring did not show obvious effects in terms of yields under the reaction conditions. The three-component reaction proceeded smoothly and was completed in 10–20 min. Benzaldehyde and other aromatic aldehydes containing electron-withdrawing groups or electron-donating were employed and reacted well to give the desired products in excellent yields with high purity (scheme 2).

The proposed mechanism for the role of nano-SiO_2 as a catalyst is shown in scheme 2. In this mechanism the formation of *a*-aminophosphonates **4** from the three-component reaction of benzaldehyde, amine, and dialkyl phosphite was proposed to involve two steps: Knoevenagel condensation of the benzaldehyde with amine takes place with elimination of the hydroxide anion and formation of product **5** followed by phospha-Michael addition of dialkyl phosphate **3** to electron deficient Knoevenagel adduct **5** leading to the corresponding *a*-aminophosphonates product **4** (scheme 3).

4. Conclusions

In conclusion, the obtained results describe a novel, and simple method for the synthesis of *a*-aminophosphonates via one-pot, three-component reaction using nano-SiO_2 as catalyst at room-temperature in water under ultrasonication with high product yields. This nanoparticles catalyst provides a new way for continuous processes, because of its simple recyclability. From a scientific point, our results expand the application of 'free' nanoparticles. This catalyst would be helpful to understand the advantageous combination of the properties of heterogeneous catalysis and the development of new catalytic systems.

References

1. Anastas P T and Williamson T 1998 *Green chemistry: Frontier in benign chemical synthesis and process* (Oxford, UK: Oxford University Press)
2. Polshettiwar V, Luque R, Fihri A, Zhu H, Bouhrara M and Basset J 2011 *Chem. Rev.* **111** 3036
3. Herrerias C I, Yao X, Li Z and Li C 2007 *Chem. Rev.* **107** 2546
4. Kljin J E and Engberts J B 2005 *N. Nature* **435** 746
5. Pacchioni G 2000 *Surf. Rev. Lett.* **7** 277
6. Kalor A, Cox D and Zakin M R 1988 *Adv. Chem. Phys.* **70** 211
7. Hosseini-Sarvari M 2011 *Catal. Lett.* **141** 347
8. Koukabi N, Kolvari E, Khazaei A, Zolfigol M A, Shirmardi-Shaghasemi B and Khavasi H R 2011 *Chem. Commun.* **47** 9230
9. Allen M C, Fuhrer W, Tuck B, Wade R and Wood J M 1989 *J. Med. Chem.* **32** 1652
10. Nakamura S, Hayashi M, Hiramatsu Y, Shibata N, Funahashi Y and Toru T 2009 *J. Am. Chem. Soc.* **131** 18240
11. Sharghi H, Nasseri M A and Hassani Nejad A 2003 *J. Mol. Catal. A: Chem.* **206** 53
12. Sharghi H, Hassani Nejad A R and Nasseri M A 2004 *New J. Chem.* **28** 946

13. Nasseri M A, Kazemi F and Sharghi H 2004 *Synthesis* **2** 205
14. (a) Yu M, Lin J and Fang J 2005 *Chem. Mater.* **17** 1783; (b) Musi S, Filipovi-Vincekovi N and Sekovani L 2011 *Brazil. J. Chem. Eng.* **28** 89; (c) Wei-Jie Y, Zhen-Feng Z and Chun-Lei G 2008 *Key Eng. Mater.* **368** 787
15. Tang J, Wang L, Wang W, Zhang L, Wu S and Mao D 2011 *J. Fluorine Chem.* **132** 102
16. Noronha R G, Romão C C and Fernandes A C 2011 *Catal. Commun.* **12** 337
17. Dindulkar S D, Reddy M V and Jeong Y T 2012 *Catal. Commun.* **17** 114
18. Disale S T, Kale S R, Kahandal S S, Srinivasan T G and Jayaram R V 2012 *Tetrahedron Lett.* **53** 2277
19. Sheykhan M, Mohammadnejad H, Akbari J and Heydari A 2012 *Tetrahedron Lett.* **53** 2959
20. Rezaei Z, Firouzabadi H, Iranpoor N, Ghaderi A, Jafari M R, Jafari A A and Zare H R 2009 *Eur. J. Med. Chem.* **44** 4266
21. Qian C T and Huang T 1998 *J. Org. Chem.* **63** 4125
22. Firouzabadi H, Iranpoor N and Sobhani S 2004 *Synthesis* 2692
23. Bhanushali M J, Nandurkar N S, Jagtap S R and Bhanage B M 2009 *Synth. Commun.* **39** 845
24. Sobhani S and Vafaee A 2009 *Synthesis* 1909
25. Wu J, Sun W, Xia H G and Sun X Y 2006 *Org. Biomol. Chem.* **9** 1663
26. Srikant B and Asit K C 2007 *J. Org. Chem.* **72** 1263
27. Vinu A, Kalita P, Balasubramanian V V, Oveisi H, Selvan T, Mano A, Chari M A and Subba Reddy B V 2009 *Tetrahedron Lett.* **50** 7132
28. Manabe K and Kobayashi S 2000 *Chem. Commun.* 669