Supporting Information

Surfactant-free synthesis of cyclomatrix and linear organosilica phosphazene-based hybrid nanoparticles

Vanessa Poscher, †,‡ Ian Teasdale †,‡ and Yolanda Salinas, †,‡,*

† Institute of Polymer Chemistry (ICP), Johannes Kepler University Linz, Altenberger Strasse 69, 4040 Linz, Austria.
‡ Linz Institute of Technology (LIT), Johannes Kepler University Linz, Altenberger Strasse 69, 4040 Linz, Austria.

Corresponding author:

*E-mail: yolanda.salinas@jku.at
General techniques. Thermogravimetric analysis (TGA), scanning electron microscopy (SEM), transmission electron microscopy (TEM), transmission electron microscopy with energy dispersive X-Ray spectroscopy (TEM-EDS), dynamic light scattering (DLS), nuclear magnetic resonance spectroscopy (NMR), N2 adsorption-desorption analysis, and Fourier Transform Infrared Spectroscopy (FT-IR) were employed to characterize the synthesized materials. TGA analyses were carried out on a Q5000 TA (TA instruments, New Castle, DE, USA) under nitrogen atmosphere (25 mL min⁻¹) in a platinum pan with a heating program from 40-900 °C at 10 °C min⁻¹. SEM images were captured with JEOL 6400. TEM images were obtained with Jeol JEM-2200FS microscope (Jeol, Peabody, MA, USA) and elemental mapping analysis (TEM-EDS) was also performed with Jeol JEM-2200FS microscope. DLS measurements were taken on a Zetasizer nano ZSP, Malvern, in Milli Q water as dispersant (1 mg mL⁻¹) at 25 °C in disposable cuvettes (DTS 0012), previously sonicated (15 min) and filtrated (PTFE syringe filter, 0.45 μm). ¹H, and ³¹P NMR spectra were taken on Bruker Avance III 300. The ¹H NMR spectra were measured at 300 MHz using CDCl₃ or MeOD as an internal reference. The ³¹P NMR measurements were conducted at 121 MHz. N₂ adsorption-desorption isotherms were recorded with a Micromeritics TriStar II 3020 surface area and porosimetry analyzer (Micromeritics, Norcross, GA, USA). The samples were degassed at 60 °C in vacuum for 2 h previous measurement. The measurements were performed at 77.30 K and ca. 100 measurement points were recorded. Specific surface areas were calculated from the adsorption data within the low pressure range using the Brunauer, Emmett and Teller (BET) model. Pore size was determined following the Barret, Joyner and Halenda (BJH) method. FT-IR measurements were performed in the range from 600 – 4000 cm⁻¹ in a Spectrum 100, Perkin Elmer. Solid state NMR measurements (¹³C, ²⁹Si and ³¹P) were performed on a Bruker Avance III 500 MHz spectrometer. The ¹³C NMR experiments were conducted at resonance frequencies of 126 MHz. The ²⁹Si, and ³¹P NMR experiments were measured at resonance frequencies of 99 MHz and 202 MHz.

Experimental

Materials. Anhydrous diethylether (p.a) from VWR, PCl₃, allylamine, 2,2-Dimethoxy-2-phenylacethophenone (DMPA, 99 %) and 3-mercaptopropyltrimethoxysilane (95 %) from Sigma Aldrich, SOCl₂ (99 %, Fluka), anhydrous DCM (99.7 %) and THF (99.8 %) Alfa Aesar, NEt₃ (≥99 %) and Ethanol (p.a) from Merck. Tetraethyl orthosilicate (TEOS, 98 %)
Aldrich, ammonia 28% w/w aq. soln. Alfa Aesar, ethanol (pa) Merck. Lithiumbis(trimethylsilyl)amide (LiN(SiMe₃)₂, 97%), Dichlorotriphenylphosphorane (Ph₃Cl, 95%) and Hexachlorocyclotriphosphazene (99%) from Sigma Aldrich. Deuterated chloroform (CDCl₃) (99.8%, Sigma Aldrich) and methanol (MeOD-d₄) (> 99.8%, Fluorochem) were used for NMR experiments. The chemicals and solvents were purchased and used as received.

**Synthesis of monomer (Cl₃PNTMS) (2).** LiN(SiMe₃)₂ (25.12 g, 150.12 mmol) was filled in a 500 mL two neck round bottom flask under argon atmosphere. LiN(SiMe₃)₂ was dissolved in anhydrous diethylether, until it was completely dissolved (around 500 mL diethylether) and the mixture was cooled to 0°C using an ice bath. PCl₃ (13.13 mL, 150.11 mmol) was added dropwise and the reaction mixture was stirred for one hour at 0°C (Figure S1). A white precipitation can be observed. Subsequently, SOCl₂ (12.13 mL, 167.21 mmol) was added dropwise and the mixture was again stirred for one hour at 0°C. Then the ice bath was removed and the solution was stirred until room temperature was reached. In the next step the insoluble salt was removed via filtration using a funnel filled with celite and filter paper. The solvent was removed under reduced pressure and a yellow, oily substance was obtained.

Purification by distillation using a ball tube oven yielded a transparent liquid Cl₃PNTMS, which was then stored in the glove box at -35 °C (m= 17.85 g, 71.29%).

¹H NMR (300 MHz, CDCl₃, δ / ppm): 0.18 (s, 9H) (see Figure S2).

³¹P NMR (300 MHz, CDCl₃, δ / ppm): -54.5 (see Figure S3).

![Synthesis reaction of monomer 2 (Cl₃PNTMS)](image)

**Figure S1.** Synthesis reaction of monomer 2 (Cl₃PNTMS)
**Figure S2.** $^1$H NMR spectrum of 2 (Cl$_3$PNTMS) in CDCl$_3$.

**Figure S3.** $^{31}$P NMR spectrum of 2 (Cl$_3$PNTMS) in CDCl$_3$. 
Synthesis of linear poly[bis(allylamino)phosphazene] (6) (n~5). \( \text{Ph}_3\text{PCl}_2 \) (0.46 g, 1.37 mmol) was dissolved in 5 ml anhydrous DCM. This mixture was added to the aforementioned monomer (1.5 g, 6.68 mmol) and afterwards, the solution was stirred overnight at room temperature under argon atmosphere. Mixtures of anhydrous THF, \( \text{NEt}_3 \) and the poly(dichloro)phosphazene solution were prepared. First, 20 ml anhydrous THF and \( \text{NEt}_3 \) (3.5 mL, 25.25 mmol, 3 eq) were mixed together in a vial. 15 ml of this solution were injected in a round bottom flask and the poly(dichloro)phosphazene solution was added dropwise. To the mixture in the vial the substitution reagent, allylamine (1.25 mL, 16.64 mmol, 2.5 eq), was added (Figure S4). After addition, the insoluble salt triethylammonium chloride precipitated (white solid). The solution was stirred overnight at 40 °C under argon atmosphere (m= 1.20 g, 79.7 %).

\(^1\text{H NMR (300 MHz, CDCl}_3, \delta / \text{ppm): 7.5 (m, 15H); 5.89 (m, 2H); 5.05 (m, 4H); 3.56 (m, 4H) (see Figure S5).} \)

\(^{31}\text{P NMR (300 MHz, CDCl}_3, \delta / \text{ppm): 17.41; 10.02 (see Figure S6).} \)

![Synthesis reaction of linear poly[bis(allylamino)phosphazene] (n~5) (6)](image_url)
**Figure S5.** $^1$H NMR spectrum of 6 ($n\sim 5$) in CDCl$_3$ (*). 

**Figure S6.** $^{31}$P NMR spectrum of 6 ($n\sim 5$) in CDCl$_3$. 
**Synthesis of silane derived linear polyphosphazene (8), UV Reaction.** Polymer 6 (0.68 g, 4.33 mmol) was dissolved in 35.54 mL degassed ethanol. One equivalent of 3-mercaptopropyltrimethoxysilane per double bond (2 eq in total) (1.61 mL, 8.66 mmol) was added. Subsequently DMPA (0.33 g, 1.29 mmol, 0.3 eq) was added. The solution was transferred to the UV-reactor and the reactor was flushed with argon. Then, the mixture was irradiated with UV light for 15 min while stirring. Afterwards the mixture was cooled with an ice bath for 15 min. The irradiation was repeated 4 times and the cooling 3 times (Figure S7). To avoid crosslinking the solvent was not evaporated, hence the polymer 8 dissolved in EtOH was directly used for silica-based nanoparticle preparation. Quantitative yields were obtained.

\[ ^1H \text{ NMR (300 MHz, CDCl}_3, \text{ ppm): 7.4 (m, 15H); 3.80 (m, 2H); 3.55 (m, 18H); 2.98 (m, 4H); 2.67 (m, 8H); 2.53 (m, 4H); 1.73 (m, 4H); 0.73 (m, 4H).} \]

\[ ^31P \text{ NMR (300 MHz, CDCl}_3, \text{ ppm): 13.72; 10.86.} \]

![Figure S7](image.png)

**Figure S7.** Synthesis reaction of 3-mercaptopropyltrimethoxysilane (7) and poly[bis(allylamino)phosphazene] (6) to obtain the silane derived linear polyphosphazene L-SiPPz (8) (n~5).
Synthesis of silica-based nanoparticles with linear polymer precursor (L-SiPPz NPs). A mixture of 60 mL Milli Q water and 0.44 mL sodium hydroxide solution (2M) was stirred in a beaker and heated up to 80 °C. Then, a mixture of the silica source (polymer precursor from UV reaction (2.32 mL of the previous polymer 8 solution in EtOH)) in 10 mL EtOH was added dropwise and solution was stirred at 80 °C for 2 hours. Subsequently, the stirred mixture was cooled to room temperature. The reaction mixture was centrifuged to collect the solid nanoparticles and the nanoparticles were washed with Milli Q water until reaching pH 7. For the final washing step ethanol was used in order to dry the particles more quickly. The particles were dried overnight under air conditions and characterized using standard techniques (m = 92 mg).

Synthesis of allylamino cyclic phosphazene (10). Hexachlorocyclotriphosphazene (15 g, 43.15 mmol) was dissolved in 60 mL anhydrous THF in the glove box. To this solution NEt3 (36.5 mL, 258.89 mmol, 6 eq) was added. The mixture was transferred out of the glove box. Allylamine (19.44 mL, 263.2 mmol, 6.1 eq) was utilized as substitution reagent. After dropwise addition of allylamine to the aforementioned solution, the mixture was stirred for 48 h at 40 °C under argon atmosphere (Figure S8). After addition, the insoluble salt triethylammonium chloride precipitated (white solid). The mixture was filtrated to remove the insoluble salt, washed with THF and after evaporation of the solvent, the product could be obtained (m = 14.17 g; 71.4 %).

$^1$H NMR (300 MHz, MeOD, δ / ppm): 4.38 (m, 6H); 3.7 - 3.65 (d, J = 15 Hz, 6H); 3.51 – 3.48 (d, J = 9 Hz, 6H); 1.98 (s, 12H) (see Figure S9)

$^{31}$P NMR (300 MHz, MeOD, δ / ppm): 17.02 (see Figure S10)

![Synthesis reaction of hexachlorocyclotriphosphazene (9) and allylamine (5) to obtain the allylamino cyclic phosphazene (10).](image)

Figure S8. Synthesis reaction of hexachlorocyclotriphosphazene (9) and allylamine (5) to obtain the allylamino cyclic phosphazene (10).
Figure S9. $^1$H-NMR spectrum of 10 in MeOD (*).

Figure S10. $^{31}$P-NMR spectrum of 10 in MeOD.
Synthesis of silane derived cyclic phosphazene (11), UV Reaction. Compound 10 (0.50 g, 1.06 mmol) was dissolved in 13.32 mL degassed ethanol. One equivalent of 3-mercaptopropyltrimethoxysilane (7) per each double bond of compound 10, 6 eq in total (1.18 mL, 6.38 mmol) was added. Subsequently DMPA (0.09 g, 0.32 mmol, 0.3 eq) was added. The solution was transferred to the UV-reactor previously flushed with argon. Then, the mixture was irradiated with UV light for 15 min while stirring. Afterwards the mixture was cooled with an ice bath for 15 min. The irradiation was repeated 6 times and the cooling 5 times (Figure S11). To avoid crosslinking the solvent was not evaporated, hence the polymer dissolved in EtOH was directly used for silica-based nanoparticle preparation. Quantitative yields were obtained.

$^1$H NMR (300 MHz, MeOD, $\delta$ / ppm): 3.87 (m, 6H); 3.58 (s, 54H); 3.03 (broad s, 12H); 2.60 (m, 24H); 1.83 (m, 12H); 1.70 (m, 12H); 0.77 (m, 12H) (see Figure S12).

$^{31}$P NMR (300 MHz, MeOD, $\delta$ / ppm): 14.68 (see Figure S13).

Figure S11. UV reaction of 3-mercaptopropyltrimethoxysilane (7) and allylamine substituted hexachlorocyclotriphosphazene (10) to obtain the silane derived cyclic phosphazene C-SiPPz (11).
Figure S12. $^1$H-NMR spectra of 11 in MeOD (*). EtOH peaks (#) visible in spectra because the solvent could not be evaporated due to crosslinking.

Figure S13. $^{31}$P-NMR spectrum of 11 in MeOD.
Synthesis of silica-based nanoparticles with cyclic polymer precursor (C-SiPPz NPs). A mixture of 60 mL Milli Q water and 0.44 mL sodium hydroxide solution (2 M) was stirred in a beaker and heated up to 80 °C. Then, the silica source (3.52 mL of the previous polymer 11 solution in EtOH) in 10 mL EtOH was added dropwise and solution was stirred at 80 °C for 2 hours. Subsequently, the stirred mixture was cooled to room temperature. The reaction mixture was centrifuged to collect the solid nanoparticles and the nanoparticles were washed with Milli Q water until reaching pH 7. For the final washing step ethanol was used in order to dry the particles more quickly. The particles were dried overnight under air conditions and characterized by standard techniques (m = 257 mg).

Synthesis of solid silica nanoparticles (TEOS NPs). Solid and spherical nanoparticles containing only silica were prepared as control following a reported modified Stöber procedure.1-2 A mixture solution of ethanol (22.5 mL), Milli Q water (2.5 mL) and ammonia 28 % w/w (1.5 mL) was stirred for 1 min, and the silica precursor tetraethyl orthosilicate (TEOS) (0.75 mL, 3.86 mmol) was added dropwise. The reaction mixture was stirred for 2 h at room temperature. After that, the precipitated nanoparticles were isolated by centrifugation for 15 min, and washed with ethanol (23 mL). Finally the TEOS NPs were dried overnight in the air to obtain a white fine powder (260 mg). The nanoparticles were characterized by standard techniques.
Particles Characterization.

Particles prepared with linear polymer precursor (L-SiPPz NPs).

N₂ adsorption-desorption isotherms were measured for L-SiPPz NPs (Figure S14).

![Figure S14](image_url)

**Figure S14.** Nitrogen adsorption-desorption isotherms of L-SiPPz NPs. The black squares sign the adsorption curve, the white circles can be assigned to the desorption.

Solid state NMR spectroscopic studies (³¹P, ¹³C and ²⁹Si) were performed to verify the incorporation of the linear polymer precursor in the silica nanoparticles (Figure S15 and S16). ²⁹Si NMR spectrum is shown in manuscript.
Figure S15. Solid state $^{31}$P NMR spectrum of L-SiPPz NPs.

Figure S16. Solid state $^{13}$C NMR spectrum of L-SiPPz NPs.
Dynamic light scattering (DLS) was utilized for the measurement of the intensity size distribution of L-SiPPz NPs (Figure S17).

**Figure S17.** Intensity size distribution of L-SiPPz NPs. Data shown from average values of three measurements with 1 mg mL$^{-1}$ aqueous particles suspension at 25 °C, non-filtered suspension (black) and filtered suspension (red) through 0.45 μm PTFE syringe filter.
Particles prepared with cyclic polymer precursor (C-SiPPz NPs).

N₂ adsorption-desorption isotherms were measured for C-SiPPz NPs (Figure S18).

![N₂ adsorption-desorption isotherms of C-SiPPz NPs. The black squares sign the adsorption curve, the white circles can be assigned to the desorption.](image)

**Figure S18.** Nitrogen adsorption-desorption isotherms of C-SiPPz NPs. The black squares sign the adsorption curve, the white circles can be assigned to the desorption.

Energy dispersive X-ray spectroscopy was used to semi-quantitatively confirm the composition of the final C-SiPPz NPs (Figure S19).

![TEM-EDS elemental mapping analysis (At%) images of C-SiPPz NPs.](image)

**Figure S19.** TEM-EDS elemental mapping analysis (At%) images of C-SiPPz NPs.
Solid state NMR spectroscopic studies ($^{31}$P, $^{13}$C and $^{29}$Si) were performed to verify the incorporation of the cyclic polymer precursor in the silica nanoparticles (Figures S20 and S21). $^{29}$Si NMR is shown in manuscript.

Figure S20. Solid state $^{31}$P NMR spectrum of C-SiPPz NPs.

Figure S21. Solid state $^{13}$C NMR spectrum of C-SiPPz NPs. EtOH peaks (*) visible due to the particles not being completely dried.
Dynamic light scattering (DLS) was used to measure the hydrodynamic diameter of the particles (Figure S22).

**Figure S22.** Intensity size distribution of C-SiPPz NPs. Data shown from average values of three measurements with 1 mg mL\(^{-1}\) aqueous particles suspension at 25 °C, non-filtered suspension (black) and filtered suspension (red) through 0.45 μm PTFE syringe filter.
Comparison studies using solid silica nanoparticles TEOS NPs, as a control.

TGA measurements of all the nanoparticles were performed under nitrogen atmosphere in a platinum pan, from 50-900 °C (Figure S23).

**Figure S23.** Overview of TGA curves of L-SiPPz, C-SiPPz and TEOS NPs.

TEOS NPs were well characterized. N₂ adsorption-desorption isotherms of TEOS NPs were also utilized to compare with the novel PPz-based nanoparticles (Figure S24).

**Figure S24.** Nitrogen adsorption-desorption isotherms of solid silica nanoparticles prepared with TEOS. The black squares were assigned for the adsorption curve, the white circles for desorption.
Size and morphology of the **TEOS NPs** were observed with transmission and scanning electron microscopy (Figure S25).

**Figure S25.** a) SEM image b) TEM images and c) DLS measurement of solid silica nanoparticles (TEOS NPs).

Energy dispersive X-ray spectroscopy was used to semi-quantitatively confirm the composition of the **TEOS NPs** (Figure S26).

**Figure S26.** TEM-EDS elemental mapping analysis images of **TEOS NPs**.
References

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