European Polymer Journal 73 (2015) 391–401

Contents lists available at ScienceDirect

European Polymer Journal

journal homepage: www.elsevier.com/locate/europolj

Novel cross-linked polystyrenes with large space network as tailor-made catalyst supports for sustainable media

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ARTICLE INFO

Article history:
Received 14 July 2015
Received in revised form 25 September 2015
Accepted 1 October 2015
Available online 9 October 2015

Keywords:
Polystyrenes
Gel-type resins
Polymer supports
Heterogeneous catalyst
Green chemistry

ABSTRACT

A novel class of polystyrene-based gel-type resins (SPACeR, SP), containing the large 1,4-bis (4-vinylphenoxy)benzene cross-linker, is introduced; SP-immobilized 1,5,7-triazabicyclo [4.4.0]dec-5-ene (TBD) and triethylamine (TEA) bases are synthesized and characterized in terms of their structural, thermal and morphological features, and their catalytic efficiency in a series of fundamental chemical transformations under solvent-free conditions is investigated.

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1. Introduction

Chemical methodologies scaling up requirements, along with the need of creating clean synthetic processes, lead to an ever increasing interest in the area of catalysts' immobilization technologies [1].

The simple properties of supported heterogeneous catalysts make separation of these materials from the reaction media much easier compared to their non-supported counterparts. Next, the repeated use of solid catalysts substantially reduces the production costs and chemical waste [1].

Merrifield firstly introduced the concept of solid phase peptide synthesis by using heterogeneous chloromethylated polystyrene that was slightly cross-linked by divinylbenzene [2].

Merrifield resins and their derivatives are still the most commonly employed resins in the solid phase synthesis of both peptides and small organic molecules, due to their easy handling and availability, as well as their high-loading capability. However, since catalysis with these supports requires solvent swelling for reactants access to internal active sites, in cases where sufficient swelling cannot be attained (e.g. by using polar reaction media) the use of these resins may meet with problems [3].

The identification of novel polymeric supports that enable the minimization of such major drawback, and, ultimately, the access to significantly more reactive catalytic systems, that are more suitable for a wide range of solid phase organic

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http://dx.doi.org/10.1016/j.eurpolymj.2015.10.002
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transformations, is therefore of great interest. Among these polymers, one important class are the gel-type resins, which are swollen gels which collapse to an essential non-porous state when dry [4]. For instance, a new gel-type polystyrene resin was introduced by Itsuno et al. [5], Burchardt and Meldal [6], Kurth et al. [7] and Kumar and Pillai [8] among others, in which polystyrene was slightly cross-linked by hydrophilic flexible polyethyleneglycol (PEG) derivatives. The concept behind this choice was that "likes dissolve likes" and since polar solvents are good solvents for many organic reaction, incorporating PEG into a polystyrene resin was expected to increase polymer swelling in such solvents. Indeed, improved swelling and mechanical properties have been observed with these resins compared to divinylbenzene/polystyrene (DVB/PS) polymers. However, one significant drawback is that PEG has a strong tendency to form helical structure able to bind metal cations, thereby limiting the use of the catalytic systems in organometallic and anionic reactions. There are also potential problems with the presence of chemically labile benzylic ether linkages.

More recently, Janda and co-workers investigated the use of flexible polytetrahydrofuran cross-linkers in gel-type polystyrene resins (so-called *JandaJel* resins), which revealed to be chemically more stable and easier to prepare than polystyrenes with PEG-based cross-linkers, and have been successfully used as supports in a variety of synthetic transformations [9].

For many years we have been developing waste-minimized synthetic protocols employing eco-compatible reaction procedures, including the use of water, solvent free conditions (SolFC), and supported organocatalysts [10]. In this context, here we introduce a novel class of polystyrene-based gel-type resins to be employed as heterogeneous catalyst supports, containing the 1,4-bis(4-vinylphenoxy)benzene cross-linker (Fig. 1), which is a novel large spacer more polar but less flexible than Janda's cross-linker. According to the cross-linker used these polymers are therefore more "SPACed" and "Rigid" and we named them SPACeR (SP).

This cross-linker was designed to impart the resin increased compatibility with respect to sustainable reaction media, including SolFC [11], in solid-phase organic synthesis, as well as to gain insights into the structural flexibility–physical properties relationship.

Thus, we report on the synthesis and characterization, in terms of its structural, thermal and morphological features, of the first member of this series, namely SP-Cl resin (**1**) (Fig. 1). Resin functionalization with 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD) and diethylamine to access catalytic systems **2** and **3**, respectively (Fig. 1), featuring different strength of the basic sites, along with their characterization is also reported.

Finally, our results demonstrated the efficiency of such catalysts in a variety of organic transformations, i.e. 1,2-epoxide ring-opening, aldol-type condensation, and Michael addition.

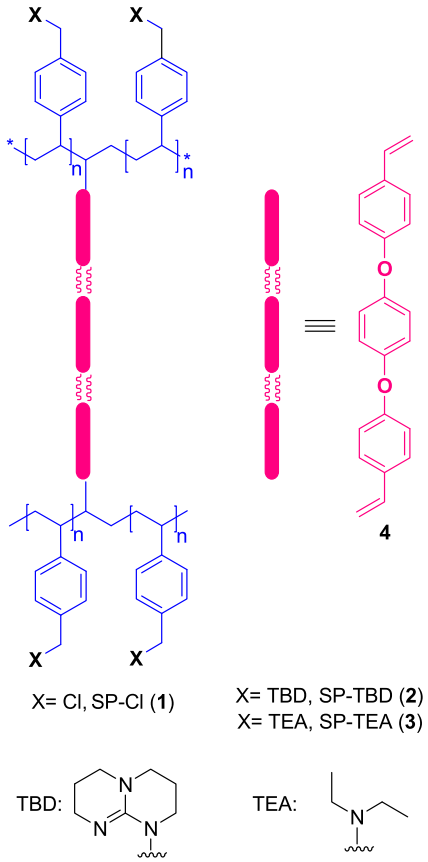


Fig. 1. Schematic of SPACeR (SP) resin **1** and SP-supported catalysts **2** and **3**. Chemical structure of 1,4-bis(4-vinylphenoxy)benzene cross-linker **4**.

2. Experimental

2.1. General remarks

All chemicals were purchased and used without any further purification unless otherwise noted. 4-Vinylbenzylchloride (80% grade) was extracted three times with a 5% w/w NaOH solution to remove the polymerization inhibitor (tert-butyl catechol). Dibenzoylperoxide was recrystallized from methanol. Commercial polystyrene-bound TBD (PS-TBD) was purchased at Sigma–Aldrich Co. (2.6 mmol TBD/g).

Suspension polymerizations were run using a three-neck cylinder-shaped glass vessel, equipped with a mechanical stirrer, condenser, and nitrogen inlet. A silicon oil bath was used as heating source.

Elemental microanalyses were performed using a Fison's EA1106CHN analyzer using atropine, 2,5-bis-2-(5-tert-butylbenzoxazol-yl)-thiophene (BBOT) and phenanthrene as reference standard, with an accuracy of ca. 2 μmol/g.

GLC analyses were performed by using Hewlett–Packard HP 5890A equipped with a capillary column DB-35MS (30 m, 0.53 mm), a FID detector and hydrogen as gas carrier. GLC-EIMS analyses were carried out by using a Hewlett–Packard HP 6890 N Network GC system/5975 Mass Selective Detector equipped with an electron impact ionizer at 70 eV.

All ^{1}H NMR and ^{13}C NMR spectra were recorded at 400 MHz and 100.6 MHz, respectively, using $CDCl_3$ as deuterated solvent and TMS as internal standard.

Compounds **10** [12], **13**, [13] and **16** [14] are known and their spectroscopic data are in agreement with those reported in literature.

2.2. Synthesis of 1,4-bis(4-vinylphenoxy)benzene *4*

In a round bottomed flask equipped with a condenser and a magnetic stirrer, 4-fluorobenzaldehyde **5** (3.18 g, 25.6 mmol), hydroquinone **6** (1.54 g, 14.0 mmol) were dissolved in dimethylacetamide (20.0 mL), and potassium carbonate (4.84 g, 35.0 mmol) was added. The reaction mixture was left under stirring at 160 °C for 6 h, then poured into cold water (20 mL) and filtered to afford 4,4′-[1,4-phenylen-bis-(oxy)]dibenzaldehyde **7** (4.0 g, 12.6 mmol, 90% yield) as brown solid, which was pure according to NMR analysis and was used without further purification. H NMR ($CDCl_3$) δ 7.04–7.16 (m, 8H), 7.84–7.93 (m, 4H), 9.99 (s, 2H); ^{13}C NMR ($CDCl_3$) δ 117.9, 118.5, 129.8, 131.3, 150.1, 162.7, 190.6.

In a three-neck round bottom flask, equipped with a magnetic stirrer and a nitrogen inlet/outlet, methyltriphenylphosphonium bromide (13.40 g, 37.5 mmol) was dissolved in dry THF (150 mL) at 0 °C. A solution of nBuLi (3.8 mL, 1.6 M in *n*-hexane, 95.3 mmol) was then added dropwise, and the reaction mixture was left under stirring at 0 °C for 3 h, then allowed to warm at room temperature. Next, a solution of 4,4′-[1,4-phenylenebis(oxy)]dibenzaldehyde **7** (4.0 g, 12.6 mmol) in dry THF (30.0 mL) was added, and this mixture was stirred at room temperature for an additional 24 h. After this time, THF was removed under vacuum, and the residue was recrystallized from methanol, affording 1,4-bis(4-vinylphenoxy) benzene **4** (3.17 g, 80% yield) as a white solid (m.p. 146–146.5 °C); ^{1}H NMR ($CDCl_3$) δ 5.18–5.21 (d, 1H, J = 11.08 Hz), 5.64–5.68 (d, 1H, J = 17.52 Hz), 6.65–6.72 (dd, 1H, J = 11.08, 6.6 Hz), 6.95–6.97 (d, 2H, J = 8.66 Hz), 7.00 (s, 2H), 7.36–7.39 (d, 2H, J = 8.66); ^{13}C NMR ($CDCl_3$) δ 112.79, 118.25, 120.43, 127.54, 132.65, 135.95, 152.62, 157.40. An. Calcd. for $C_{22}H_{18}O_2$: C, 84.05; H, 5.77%. Found: C, 84.11; H, 5.76%.

2.3. Synthesis of SP-Cl support *1*

A three-neck cylinder-shaped glass vessel, equipped with a mechanical stirrer, a condenser, and a nitrogen inlet was charged with an aqueous NaCl (2 wt%) solution containing acacia gum (4 wt%) (120 mL). After deoxygenation by purging with nitrogen, a mixture of styrene (5.61 g, 53.95 mmol), vinylbenzylchloride (1.48 g, 9.75 mmol), 1,4-bis (4-vinylphenoxy)benzene **4** (0.409 g, 1.3 mmol), chlorobenzene (8 mL), and dibenzoylperoxide (150 mg, 0.62 mmol, 2% wt/wt) was rapidly added to the solution. Next, this reaction mixture was kept under stirring at room temperature for an additional 30 min, then heated at 85 °C for 24 h. Subsequently, the reaction mixture was cooled at room temperature, and the polymer beads were isolated by filtration, washed with water (50 mL), extracted by using water (100 mL), THF (100 mL), and n-hexane (100 mL) in a Soxhlet apparatus. Finally, the resin **1** was then dried under vacuum for 15 h at room temperature (6.18 g, 1.96 mmol Cl/g – theoretical, 80% yield).

2.4. Preparation of catalyst SP-TBD *2*

In a round bottomed flask equipped with a nitrogen inlet, a condenser and a magnetic stirrer, TBD (0.2 g, 1.44 mmol) was dissolved in dry THF (2 mL) and SP-Cl **1** (0.612 g, 1.96 mmol Cl/g, 1.2 mmol) was added. The mixture was left under stirring at 85 °C for 24 h, then allowed to cool at room temperature. The polymer beads were isolated by filtration, washed with THF and then dried under vacuum for 15 h at room temperature. The degree of functionalization was determined to be 0.68 mmol TBD/g (85% yield) by elemental analysis: C 81.92, H 7.82, N 2.96.

2.5. Preparation of catalyst SP-TEA *3*

In a round bottomed flask equipped with a nitrogen inlet, a condenser and a magnetic stirrer, diethylamine (0.182 g, 2.5 mmol) was dissolved in dry DMF (2 mL) and SP-Cl **1** (0.612 g, 1.96 mmol Cl/g, 1.2 mmol) was added. The mixture was

left under stirring at 70 °C for 24 h, then allowed to cool at room temperature. The polymer beads were isolated by filtration, washed with DMF and extracted by using methanol (100 mL), dichloromethane (100 mL), and acetone (100 mL) in a Soxhlet apparatus. Subsequently, the resin was dried under vacuum for 15 h at room temperature. The degree of functionalization was determined to be 0.90 mmol TEA/g (78% yield) by elemental analysis: C 80.29, H 8.25, N 1.20.

2.6. Representative experimental procedure for the thiolysis of epoxides: reaction of 2,3-epoxypropyl-phenyl ether (**8**) by thiophenol **9** catalyzed by SP-supported TBD **2** under solvent free conditions

In a screw capped vial equipped with a magnetic stirrer SP-TBD **2** (0.05 mmol, 0.68 mmol TBD/g), 2,3-epoxypropyl-phenyl ether (**8**) (0.15 g, 1 mmol) and thiophenol **9** (0.11 g, 1 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C. After 100 min, ethyl acetate was added, the catalyst recovered by filtration and the organic solvent evaporated under vacuum to give ⩾98% pure 1-phenoxy-3-(phenylthio)propan-2-ol (**10**) as a colouless oil.

2.7. Representative experimental procedure for the Knoevenagel condensation: reaction of benzaldehyde **11** with ethyl cyanoacetate (**12**) catalyzed by SP-supported TBD **2** under solvent free conditions

In a screw capped vial equipped with a magnetic stirrer SP-TBD **2** (0.1 mmol, 0.68 mmol TBD/g), benzaldehyde **11** (0.10 g, 1 mmol) and ethylcyanoacetate **12** (0.11 g, 1 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C. After 1 h, ethyl acetate was added, the catalyst recovered by filtration and the organic solvent evaporated under vacuum to give ⩾98% pure product **13**.

2.8. Representative experimental procedure for the Michael addition: reaction of 1-butanethiol (**15**) to (E)-benzylideneacetone (**14**) catalyzed by SP-supported-TBD **2** under solvent-free conditions

In a screw capped vial equipped with a magnetic stirrer SP-TBD **2** (0.05 mmol, 0.68 mmol TBD/g), (E)-benzylidene acetone **14** (1 mmol) and 1-butanethiol **15** (1 mmol) were consecutively added and the resulting mixture was left under stirring at 30 °C. After 40 min, ethyl acetate was added, the catalyst recovered by filtration and the organic solvent evaporated under vacuum to give ⩾98% pure 4-(butylthio)-4-phenylbutan-2-one **16** as a yellowish oil.

FTIR spectra were recorded using a Bruker Optics Vertex 70 spectrometer. Bulk polymer samples were analyzed via ATR-FTIR using a Harrick Scientific MVP Star accessory equipped with a diamond internal reflection element (IRE); a standard deuterated L-alanine doped triglycine sulfate (DLaTGS) detector was used. A background spectrum was collected as the average of 64 scans of the clean ATR crystal while spectra were collected as the average of 64 scans with 4 cm^{-1} resolution and subsequently baseline corrected.

TGA analyses were performed on a TA HIRes TGA 2950 instrument. The sample was heated from room temperature to 600 °C at 20 °C/min under a nitrogen flow rate of 70 cm^3/min. At 600 °C a switch to oxygen atmosphere was performed with subsequent heating at 20 °C/min up to 950 °C. Glass transition temperature (T_g) was determined by differential scanning calorimetry (MDSC Q2000 TA instruments) using a heating rate of 20 °C/min. For SP-Cl **1** and SP-TBD **2** two heating/cool/heat cycle were run between −70 °C and 250 °C. For SP-TEA **3** two heating/cool/heat cycle were run between −70 °C and 160 °C.

Scanning Electron Microscopy (SEM) was performed with a Zeiss Merlin at a voltage less than 2 kV. Transmission Electron Microscopy (TEM) samples were embedded in a low viscosity resin (Ted Pella) before microtoming into ~75-nm-thick slices and examined with a Zeiss Libra 120 at 120 kV.

3. Results and discussion

3.1. Synthesis of 1,4-bis(4-vinylphenoxy)benzene **4**

1,4-Bis(4-vinylphenoxy)benzene cross-linker **4** was synthesized as outlined in Scheme 1.

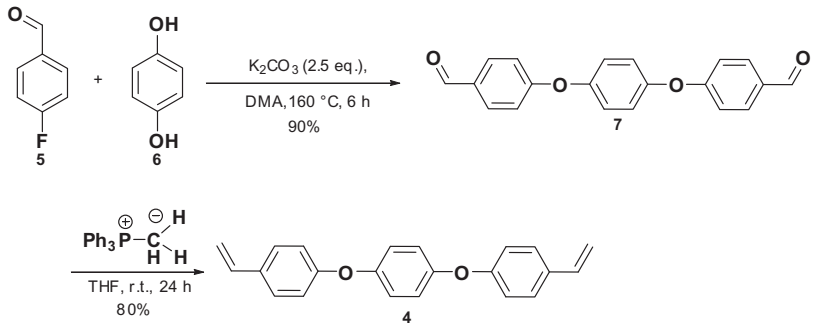
The synthesis begins by reacting 4-fluorobenzaldehyde with hydroquinone in the presence of K_2CO_3 [15]. The resulting ether-linked dialdehyde 4,4′-[1,4-phenylenebis(oxy)]dibenzaldehyde **7** is subjected to subsequent reaction with methyltriphenyl phosphonium bromide under Wittig conditions to afford the target product in good overall yield (72%).

Notably, a major advantage of the proposed cross-linker is that it can be readily synthesized from easily accessible precursors, does not require rare materials, reducing risks regarding materials supply or costs; and, finally, the compound can easily be isolated by re-crystallization.

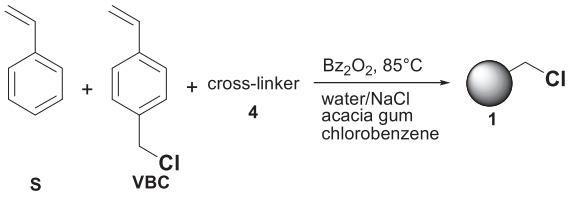
3.2. Resin syntheses

With the cross-linker in hand, SP-resin **1** was prepared in high yield (80%) by suspension copolymerization of styrene (S, 83 mol%), and 4-vinyl-benzylchloride (VBC, 15 mol%) in the presence of 2 mol% 1,4-bis(4-vinylphenoxy)benzene **4** (Scheme 2).

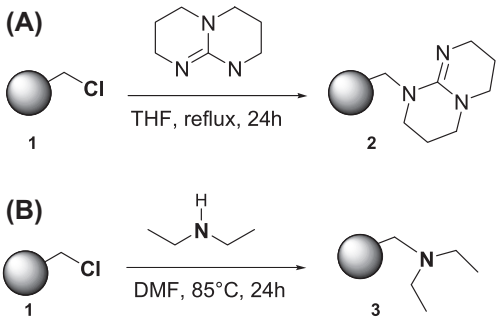
The co-polymerization reactions were performed according to a previously reported procedure [10a] using a reaction vessel equipped with a mechanical stirrer. Nucleophilic substitution of the chlorines atoms by TBD in THF at reflux



Scheme 1. Synthetic route for 1,4-bis(4-vinylphenoxy)benzene **4**.



Scheme 2. Synthesis of chloromethylated resin **1**.



Scheme 3. Synthesis of catalysts **2** (A) and **3** (B).

Table 1
Nitrogen content and loading (*L*) of catalysts **2** and **3**.

Catalyst	*N* (%)	*L*
6	2.96	0.68 mmol TBD/g
7	1.20	0.90 mmol TEA/g

temperature (Scheme 3A) successfully furnished base catalyst **2**. Similarly, SP-TEA catalyst **3** was easily prepared by reacting the corresponding SP-Cl resins **1** with diethylamine excess (2.5 eq) in DMF at 85 °C (Scheme 3B). The micro analytical data (C, H, N) obtained from elemental analysis were used to find out the degree of substitution of **2** and **3** (see Table 1 and Section 2).

3.3. Resin structural properties

FTIR spectroscopy demonstrates the successful synthesis of SP-Cl support **1** and its derivatives SP-TBD **2** and SP-TEA **3** (Fig. 2).

The characteristic peaks of polystyrene at 1493, 1452 and 700 cm^{-1} are clearly visible for SP-Cl **1**, as observed in Figs. 2 and SI1. The TBD derivative of SP-Cl **1**, i.e. SP-TBD **2** was successfully obtained and easily characterized and identified by the IR stretching absorption at 1600 (C=N) and 1362 cm^{-1} (C—N) (Figs. 2 and SI1, respectively). The principal evidence for SP-bound triethylamine SP-TEA **3** was the appearance of a peak at 1277 cm^{-1} relative to the C—N stretching (Fig SI1).

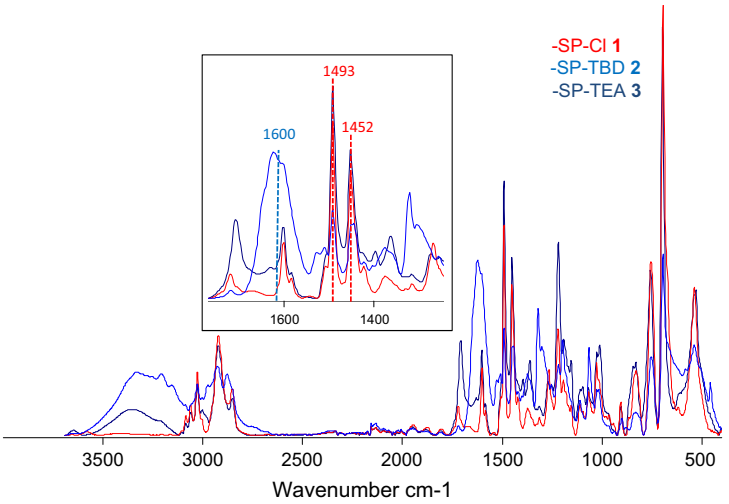


Fig. 2. Full FTIR spectra of SP-Cl **1**, SP-TBD **2** and SP-TEA **3**.

3.4. Thermal properties

The SP-Cl support **1** and its derivatives **2** and **3** showed good thermal stability as evaluated by thermogravimetric analyses (TGA). All systems featured an initial steep loss of weight (0–8%) being attributed to the loss of trapped moisture which is difficult to be removed by vacuum drying (Figs. 3, SI2 and SI3). The degradation of the SP-Cl **1** polymeric chains starts at 300 °C and reaches a maximum at 432 °C. Polymer degradation is coinciding with a carbonization process in which carbonaceous matter (fused aromatic rings such as polycyclic aromatic hydrocarbons – PAHs) is formed. Indeed, during the cracking process, the —CH_2Cl group of VBC initiates radical degradation processes resulting in the formation of fused aromatic ring structures. Since the VBC comonomer concentration is therefore related to the formation of PAHs, this SP-Cl resin **1** specimen, which is characterized by only a small amount of VBC comonomer, showed a limited amount of carbonization. At 600 °C the formed carbonaceous matter, corresponding to only 3% of the initial weight, is quickly combusted with release of carbon dioxide. TGA plot for SP-TEA **3** (Fig. SI3) shows the removal of TEA which starts around 175 °C with a maximum

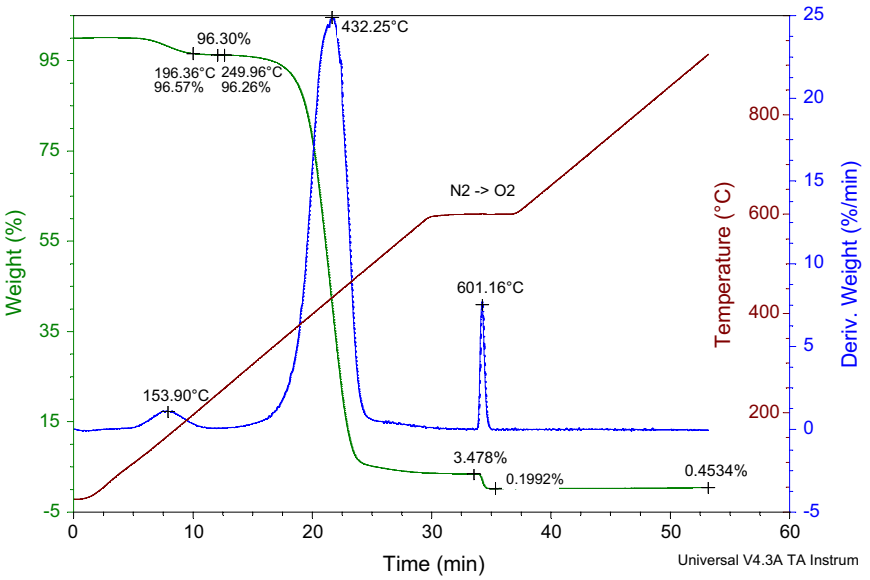


Fig. 3. TGA analysis of SP-Cl resin **1**.

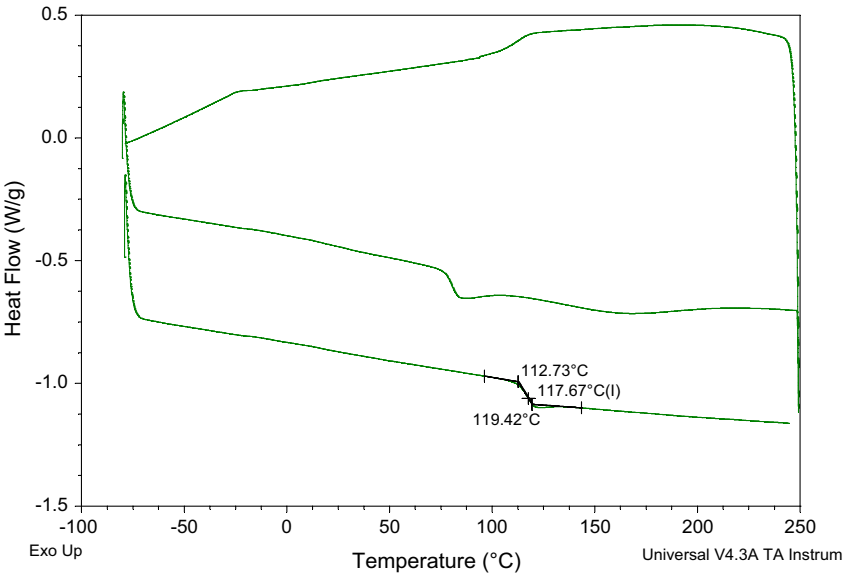


Fig. 4. DSC analysis of SP-Cl resin **1**.

at 192 °C, followed by the polymer degradation which starts approximately at 250 °C and reaches a maximum at 432 °C. At 600 °C the formed carbonaceous matter corresponding to the 6% of the initial weight is combusted (Fig. SI3).

The TGA plot of SP-TBD **2** (Fig. SI2) indicates that the removal of TBD occurs at higher temperature as compared to the TEA. In particular the TBD degradation occurs along with the polymer degradation which starts approximately at 300 °C and reaches a maximum at 442 °C. At 600 °C the formed carbonaceous matter, corresponding to the 9% of the initial weight, is combusted (Fig. SI2). The larger residue for SP-TBD as compared to SP-TEA is related to the structural differences. Upon heating in an inert atmosphere, fused heterocyclic rings are more easily formed from TBD as from TEA for which volatile degradation products are more promoted.

Fig. 4 shows DSC curves of SP-Cl resin **1**. The glass transition temperature (T_g) measured during the first run was decreased by the moisture trapped between the polymeric chains and which is acting as a plasticizer. Therefore, the intrinsic T_g of the polymer was revealed in a second run at a higher temperature of 117 °C. DSC curves for catalyst **2** and **3**, along with the indication of the corresponding T_g are reported in Figs. SI4 and SI5. It was established that the T_g of SP-TBD **2** corresponds to 132 °C (Fig. SI4) and of SP-TEA **3** to 129 °C (Fig. SI5).

3.5. Surface morphology

Scanning and transmission electron microscopy reveal that systems **1**–**3** are spheres with high porosity (Figs. 5 and SI6–8). Scanning electron microscopy (SEM) images in Fig. 5 shows representative surface morphology of the resultant spheres, while additional higher magnification SEM images are available in Fig. SI6.

Detailed microstructures of the copolymers are made available by examining embedded and microtomed sample thin films with transmission electron microscopy (TEM). Representative lower magnification TEM images are presented in Figs. SI7 and SI8.

Higher magnification TEM images in Fig. 6 demonstrate that SP-Cl **1** has an alternating layered structure with spacing values of 8–28 nm based on line scan intensity profiles (Figs. 7, SI9 and SI10).

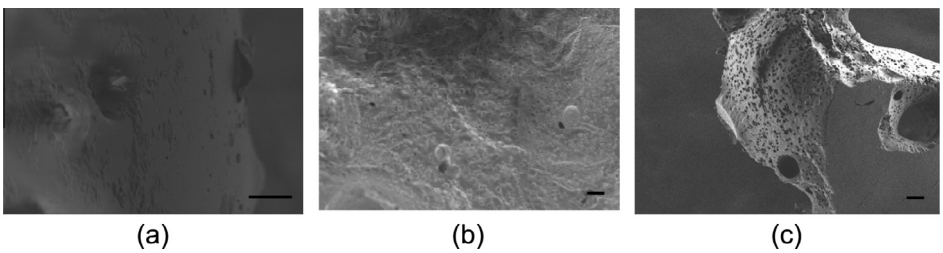


Fig. 5. SEM Images of (a) SP-Cl **1**; (b) SP-TBD **2**; (c) SP-TEA **3** (all scale bars are 20 μm).

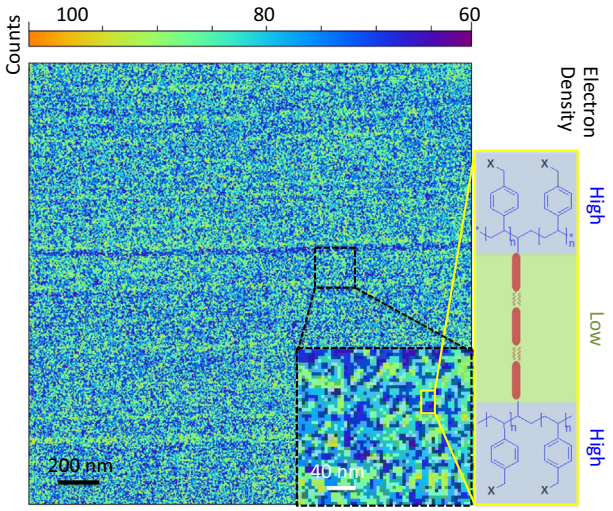


Fig. 6. Leveled and color-scaled TEM image of SP-Cl **1**. The matrix is darker in TEM image (lower counts in line scans), and the spacer is lighter in color (higher counts in line scans). The color scale represents the intensity (counts) distribution of transmitted electrons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

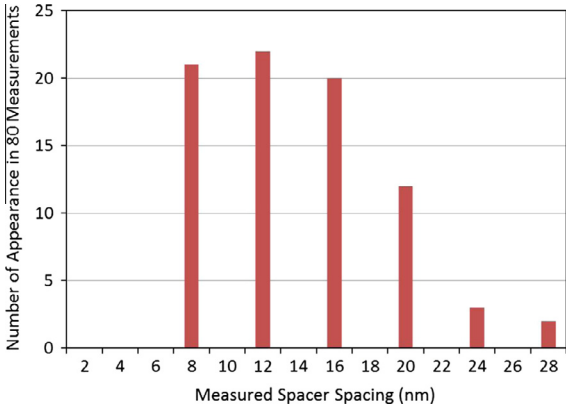


Fig. 7. Measured SP-Cl **1** spacer spacing as a function of their numbers of appearance out of 80 line scan measurements (details methods available in Figs. S4 and S5). A spacer spacing of 8 nm, 12 nm, or 16 nm shows up most frequently, while higher values of 20–28 nm also exist occasionally.

Since TEM images reflect the local electron density variations of the corresponding components, this observed ordered structure may be attributed to the different packing density of spacer component and polymer backbone. TBD functionalization largely obscures such alternating structure, while this ordered structure is essentially diminished in copolymer system after TEA functionalization (Fig. SI11).

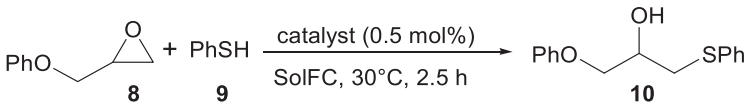
3.6. Catalytic activity

To demonstrate our idea, we investigated the catalytic activity of the systems **2** and **3** in a series of fundamental chemical transformations, i.e. nucleophilic ring opening of 1,2-epoxides, Knoevenagel condensation and Michael addition. Their efficiency have been compared also to commercially available PS-TBD (divinylbenzene (DVB)-cross-linked). Notably, we found the SP polymers highly promising when used in solvent-free conditions (SolFC).

The result of nucleophilic ring opening of styrene oxide **8** by thiophenol **9** using 0.5% mol of catalyst under SolFC are illustrated in Table 2. In the case of SP-TBD, a substantially greater catalytic efficiency was observed compared to commercial PS-supported counterpart (Table 2, entries 1 and 4, respectively).

Indeed, the shorter spacing between the linear polymeric chains in this latter may limit the reactants in accessing the active sites under such reaction conditions. The reaction performed in the presence of an organic medium (CH_3CN, dichloromethane) gave completely unsatisfactory results (Table 2, entries 2 and 3) compared to SolFC. Notably, the use of homogeneous TBD under SolFC (Table 2, entry 5) gave results comparable to that in the presence of SP-TBD, thereby

Table 2
Thiolysis of 2,3-epoxypropyl-phenyl ether (**8**) by thiophenol **9**.[a]



8 **9** **10**

Entry	Catalyst	Conversion[b] (%)
1	SP-TBD	>99[c]
2[d]	SP-TBD	19
3[e]	SP-TBD	–
4	PS-TBD	34
5	TBD	>99
6[f]	SP-TEA	65

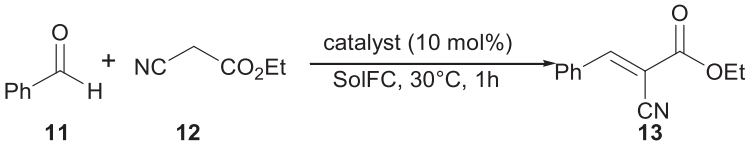
[a] Reaction conditions: 2,3-epoxypropyl-phenyl ether (**8**) (1.0 mmol), thiol (1.0 mmol), catalyst (0.5% mmol, referred to the amount of immobilized basic moiety used), 30 °C, 2.5 h.
[b] Determined by GLC analyses using 1,4-dimethoxy benzene as internal standard; the remaining materials were the unreacted **8** and **9**.
[c] 98% of isolated yield of the pure product **10**.
[d] Reaction conducted in CH_3CN (2 mL).
[e] Reaction conducted in CH_2Cl_2 (2 mL).
[f] Complete conversion of **8**–**10** was achieved after 5 h.

highlighting that the anchoring of the base catalyst does not lead to a marked reduction of its activity, as it happens in organic media. Also, the ring-opening of **8** with thiol **9** gave in all cases a complete C-3 selectivity, thereby indicating that the mechanism of the reaction is not influenced and SP-supported TBD allows to achieve the same regiochemical outcome than the non-supported counterpart.

Not unexpectedly, the reaction mediated by SP-TEA was slower compared to SP-TBD, this latter featuring a higher strength of the basic sites, and the complete conversion was reached after 5 h (Table 2, entry 6). However, SP-supported TEA gave better results (>2× conversion) than PS-TBD, for which the complete conversion into **10** was not reached after long reaction times (10 h). Further, a total regioselectivity in the SP-TEA mediated thiolysis of **8** and **9** was observed.

In a previous report we demonstrated that benzaldehyde **11** reacted with ethyl cyanoacetate **12** at 30 °C and in the presence of 10% mol of PS-TBD to give the corresponding Knoevenagel condensation product **13** in 93% conversion (1 h, Table 3, entry 4) [12]. In the presence of SP-TBD, after the same reaction time a >99% conversion was achieved. Again, solvent-free conditions revealed to be the most efficient. Indeed, in CH_3CN 5 h were needed to achieve a comparable conversion (Table 3, entry 2), whereas a poor 12% **13** was formed when CH_2Cl_2 was used (Table 3, entry 3). Notably, the same reaction performed

Table 3
Polymer-supported base catalyzed Knoevenagel condensation of benzaldehyde (**11**).[a]

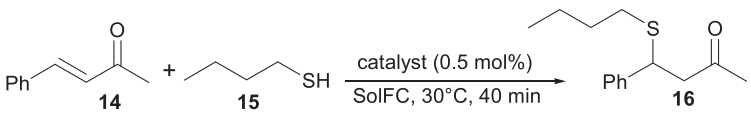


11 **12** **13**

Entry	Catalyst	Conversion[b] (%)
1	SP-TBD	>99[c]
2[d]	SP-TBD	98
3[e]	SP-TBD	12
4	PS-TBD	93[f]
5	TBD	>99[g]
6	SP-TEA	64[h]

[a] Reaction conditions: benzaldehyde (1.0 mmol), ethyl cyanoacetate (1.0 mmol), catalyst (10% mmol, referred to the amount of immobilized basic moiety used), 30 °C.
[b] Determined by GLC analyses using 1,4-dimethoxy benzene as internal standard; the remaining materials were the unreacted **11** and **12**.
[c] 98% isolated yield of the pure product **13**.
[d] Reaction conducted in CH_3CN (2 mL); reaction time: 5 h.
[e] Reaction conducted in CH_2Cl_2 (2 mL).
[f] Yield of the isolated pure product.
[g] Reaction time: 50 min.
[h] Complete conversion of **11**–**13** was achieved in 4.5 h.

Table 4
Michael addition of butanethiol (**15**) on (E)-benzylydene acetone **14**.[a]



Entry	Catalyst	Conversion[b] (%)
1	SP-TBD	>99[c]
2[d]	SP-TBD	–
3[e]	SP-TBD	–
4	TBD	>99
5	PS-TBD	2
6	SP-TEA	64[f]

[a] Reaction conditions: (E)-benzylydene acetone (1.0 mmol), thiol (1.0 mmol), catalyst (0.5% mmol, referred to the amount of immobilized basic moiety used), 30 °C.
[b] Determined by GLC analyses using 1,4-dimethoxy benzene as internal standard; the remaining materials were the unreacted **14** and **15**.
[c] 98% isolated yield of the pure product **16**.
[d] Reaction conducted in CH_3CN (2 mL).
[e] Reaction conducted in CH_2Cl_2 (2 mL).
[f] Complete conversion of **14**–**16** was achieved after 5 h.

under SolFC by using non-supported TBD (Table 3, entry 5) gave results closely comparable to that in the presence of SP-TBD (see above). Finally, SP-TEA catalyst allowed a 64% conversion into **13** (Table 3, entry 6).

As a further example of their versatility, SP-supported catalysts **2** and **3** were also tested in the Michael reaction of (E)-benzylidene acetone (**14**) with sulfur nucleophile **15**. Good-to-excellent conversions into **16** were obtained after 40 min under SolFC when using 0.5% mol SP-supported TBD (or TEA) at 30 °C (Table 4, entries 1 and 6, respectively). Notably, the reaction mediated by commercial PS-TBD (Table 4, entry 5) was extremely slow. By using 0.5 mol% of catalyst SP-TBD in the presence of an organic medium a dramatic drop of the catalytic efficiency was observed (Table 4, entries 2 and 3). Again, under SolFC and with SP-immobilized TBD, the catalyst showed closely comparable efficiency relative to the homogeneous counterpart (Table 4, entry 4).

Finally, we have evaluated the recovery and reuse of the catalytic systems **2** and **3**. After the reactions completion, the catalysts used were recovered by filtration (see Section 2). The recovered catalysts were then washed, dried, and subsequently re-used. In the ring-opening of epoxide **8**, in the Knoevenagel condensation of benzaldehyde (**11**), as well as in the Michael addition of butanethiol (**15**) to (E)-benzylydene acetone (**14**), we have not observed substantial catalytic efficiency decrease after three consecutive runs.

4. Conclusions

A novel class of polystyrene-based gel-type resins, namely SPACeR (SP), containing the 1,4-bis(4-vinylphenoxy)benzene cross-linker, has been introduced for applications in heterogeneous catalysis. The concept behind this idea was to identify supports for efficient catalytic systems tailor made for sustainable reaction media. SP-bound TBD and triethylamine (TEA) have been synthesized and characterized in terms of their structural, thermal and morphological features, and their catalytic efficiency tested in a series of representative fundamental chemical transformations, i.e. nucleophilic ring opening of 1,2-epoxides, Knoevenagel condensation and Michael addition, under SolFC. The investigated SP-supported bases were found to ensure a catalytic efficiency which overcome that of PS-supported TBD catalyst, commercially available, thereby revealing themselves highly promising tools. These findings point out that the spacing between the linear polymeric chains is large enough to enable the reactants to access the active sites easily, without the help of a swelling medium. Further studies to achieve efficient SP-supported catalysts with higher loading value, which is strategic for use under SolFC, are currently in progress.

Acknowledgements

This research has been developed and partially financed within the National project “BIT3G“ – Italian Green Chemistry Cluster.

We gratefully acknowledge the Università degli Studi di Perugia for financial support.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eurpolymj.2015.10.002.

References

[1] For representative examples see: (a) S. Sabater, J.A. Mata, E. Peris, ACS Catal. (2014) 2038–2047;
(b) A. Puglisi, M. Benaglia, V. Chiroli, Green Chem. 15 (2013) 1790–1813;
(c)K. Wilson, A.F. Lee (Eds.), Heterogeneous Catalysts for Clean Technology: Spectroscopy, Design and Monitoring, Wiley-VCH, Weinheim-Germany, 2013;
(d) P. Agrigento, M.J. Bejer, J.T.N. Knijnenburg, A. Baikerb, M. Gruttadauria, J. Mater. Chem. 22 (2012) 20728–20735;
(e) V. Sans, F. Gelat, M.I. Burquete, E. Garcia-Verdugo, S.V. Luis, Catal. Today 196 (2012) 137–147;
(f) M.T. Gokmen, F. Du Prez, Prog. Polym. Sci. 37 (2012) 365–405;
(g) V. Sans, F. Gelat, N. Karbass, M.I. Burquete, E. Garcia-Verdugo, S.V. Luis, Adv. Synth. Catal. 352 (2010) 3013–3021;
(h) T.E. Kristensen, T. Hansen, Eur. J. Org. Chem. (2010) 3179–3204;
(i) A. Kirschning, Topics Curr. Chem. (2004) 242.
[2] R.B. Merrifield, J. Am. Chem. Soc. 85 (1963) 2149–2154.
[3] (a) J. Lu, P.H. Toy, Chem. Rev. 109 (2009) 815–838;
(b) B.M.L. Dioos, I.F.J. Vankelecom, P.A. Jacobs, Adv. Synth. Catal. 348 (2006) 1413–1446;
(c) F. Cozzi, Adv. Synth. Catal. 348 (2006) 1367–1390;
(d) M. Benaglia, A. Puglisi, F. Cozzi, Chem. Rev. 103 (2003) 3401–3430;
(e) C.A. McNamara, M.J. Dixon, M. Bradley, Chem. Rev. 102 (2002) 3275–3300.
[4] D.C. Sherrington, Chem. Commun. (1998) 2275–2286.
[5] K. Kamahori, K. Ito, S. Itsuno, J. Org. Chem. 61 (1996) 8321–8324.
[6] (a) J. Burchardt, M. Meldal, Tetrahedron Lett. 39 (1998) 865;
(b) M. Renil, M. Meldal, Tetrahedron Lett. 37 (1996) 6185–6188.
[7] M.E. Wilson, K. Paech, W.-J. Zhou, M.J. Kurth, J. Org. Chem. 63 (1998) 5094–5099.
[8] K.S. Kumar, V.N.R. Pillai, Tetrahedron 55 (1999) 10437–10446.
[9] For representative recent examples see: (a) H.-L. Liu, H.-F. Jiang, Tetrahedron 64 (2008) 2120–2125;
(b) H.-L. Liu, H.-F. Jiang, L. Xu, H.-Y. Zhan, Tetrahedron Lett. 48 (2007) 8371–8374;
(c) T.Y.S. But, Y. Tashino, H. Togo, P.H. Toy, Org. Biomol. Chem. 3 (2005) 970–971;
(d) L.-J. Zhao, C.K.-W. Kwong, M. Shi, P.H. Toy, Tetrahedron 61 (2005) 12026–12032;
(e) H. Matsushita, S.-H. Lee, M. Joung, B. Clapham, K.D. Janda, Tetrahedron Lett. 45 (2004) 313–316;
(f) S.-H. Lee, H. Matsushita, G. Koch, B. Clapham, K.D. Janda, J. Comb. Chem. 6 (2004) 822–827;
(g) L.-J. Zhao, H.S. He, M. Shi, P.H. Toy, J. Comb. Chem. 6 (2004) 680–683.
[10] (a) M. Alonzi, M.P. Bracciale, A. Broggi, D. Lanari, A. Marrocchi, M.L. Santarelli, L. Vaccaro, J. Catal. 309 (2014) 260–267;
(b) C. Pavia, E. Ballerini, L.A. Bivona, F. Giacalone, C. Aprile, L. Vaccaro, M. Gruttadauria, Adv. Synth. Catal. 355 (2013) 2007–2018;
(c) S. Bonollo, D. Lanari, T. Angelini, F. Pizzo, A. Marrocchi, L. Vaccaro, J. Catal. 285 (2012) 216–222;
(d) S. Bonollo, L. Lanari, J.M. Longo, L. Vaccaro, Green Chem. 14 (2012) 164–169;
(e) T. Angelini, D. Lanari, R. Maggi, F. Pizzo, G. Sartori, L. Vaccaro, Adv. Synth. Catal. 354 (2012) 908–916.
[11] (a) F.M. Kerton, R. Marriott, Alternative Solvents for Green Chemistry, second ed., RSC Publishing, U.K., 2013;
(b) K. Tanaka, Solvent-Free Organic Synthesis, second ed., Wiley-VCH, Weinheim, 2009;
(c) K. Tanaka, F. Toda, Chem. Rev. 100 (2000) 1025–1074.
[12] W. Su, J. Chen, H. Wu, C. Jin, J. Org. Chem. 72 (2007) 4524–4527.
[13] F. Fringuelli, F. Pizzo, C. Vittoriani, L. Vaccaro, Chem. Commun. (2004) 2756–2757.
[14] W.J. Gee, Eur. J. Inorg. Chem. 2011 (2011) 3755–3760.
[15] G.W. Yeager, D.N. Schissel, Synthesis 1 (1991) 63–68.