Synthesis of Polymer-Supported Quaternary Ammonium Salts and Their Phase-Transfer Catalytic Activity in Halogen-Exchange Reactions

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ABSTRACT: Polymer-supported quaternary ammonium salts were prepared, and their applications as phase-transfer catalysts in aqueous organic systems were investigated. The polymer-bound phase-transfer catalysts were prepared with polystyrene resins crosslinked with the bifunctional monomers divinylbenzene and 1,4-butanediol dimethacrylate. The polymers were functionalized with chloromethyl groups and quaternized with trialkylamines having different alkyl chains. The obtained phase-transfer catalysts were characterized with IR spectroscopy and elemental analysis. The thermal stability was also determined by the thermogravimetric method. The catalytic properties of the phase-transfer catalysts were studied in halogen-exchange reactions. The effects of the nature and extent of crosslinking of the polymer support, the alkyl groups of the trialkylamine, and the reaction conditions were investigated. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 112: 2750–2756, 2009

Key words: compatibility; diffusion; FT-IR; hydrophilic polymers; phase transfer catalysis

INTRODUCTION

Polymer-bound quaternary ammonium and phosphonium salts are effectively used as phase-transfer catalysts in aqueous organic biphasic reactions.[1–4] These catalysts are used to carry out reactions involving a water-soluble reagent and water-insoluble substrates. Polymer-bound quaternary ammonium salts retain most of their phase-transfer catalytic activity, and this permits catalytic recycling. A number of phase-transfer catalysts derived from polystyrene (PS) resins crosslinked with divinylbenzene (PS-DVB or 1a) have been reported.[5–7] The main problem associated with divinylbenzene-crosslinked polystyrene (DVB–PS) bound catalysts is the reduced reactivity due to the hydrophobic and rigid nature of the polymer support. 1,4-Butanediol dimethacrylate crosslinked polystyrene (BDDMA–PS) resins have been reported to be efficient supports for peptide synthesis[8–11] and the preparation of polymer-bound reagents. Investigations of the preparation of BDDMA–PS-supported quaternary ammonium salts and their applications as phase-transfer catalysts in halogen-exchange reactions are described in this article.

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EXPERIMENTAL

Materials and methods

Poly(vinyl alcohol) (PVA; molecular weight = 72,000–100,000), 1,4-butanediol dimethacrylate (BDDMA), diisopropylethylamine (DIEA), and triethylamine (TEA) were supplied by Aldrich Co. (USA). Styrene was provided by Fluka AG (Switzerland), and *N,N*-dimethylformamide (DMF), 1-bromooctane, 1-bromoheptane, and tributylamine (TBA) were purchased from E-Merck (Germany). Analytical-reagent-grade solvents were used after distillation and purification according to literature procedures.

Fourier transform infrared spectra were recorded on a Shimadzu IR 470 spectrophotometer with KBr pellets. Thermogravimetric analysis was carried out on a Delta series TGA-7 and on a Shimadzu D-40 thermal analyzer.

Preparation of DVB- and BDDMA-crosslinked styrene copolymers

A mixture of styrene (11.2 mL, 98 mmol), DVB (0.476 mL, 2 mmol), toluene (20 mL), and benzoyl peroxide (500 mg) was suspended in a 1% aqueous solution of PVA (350 mL) and kept mechanically stirred at 600 rpm under a nitrogen atmosphere at 85°C. After 6 h, the beaded resin was filtered and washed with hot water to remove PVA. The polymer was then subjected to Soxhlet extraction with acetone followed by methanol to remove linear

TABLE I
Preparation of PSQAs

Catalyst	Polymer support	Trialkylamine	Chloride capacity (mmol/g)	Time for 100% quaternization (h)[a]
1c₁	DVB–PS	TMA	1.58	30
1c₂	DVB–PS	TEA	1.76	24
1c₃	DVB–PS	TBA	1.76	18
1c₄	DVB–PS	TOA	0.80[b]	12
1c₅	DVB–PS	DIEA	—[c]	—[c]
2c₁	BDDMA–PS	TMA	1.60	16
2c₂	BDDMA–PS	TEA	2.49	12
2c₃	BDDMA–PS	TBA	2.50	5
2c₄	BDDMA–PS	TOA	0.91[b]	4
2c₅	BDDMA–PS	DIEA	—[c]	—[c]

[a] The time for the quantitative conversion of chloromethyl groups to the quaternary ammonium salt was considered the time for 100% quaternization.
[b] There was no complete quaternization.
[c] The quaternization percentage was very low even after 72 h.

polymers and low-molecular-weight products. The polymer beads were dried and meshed to the 200–400 range.

For the preparation of BDDMA–PS, BDDMA (0.44 mL) was added instead of DVB, and the same procedure was employed. Polymers with different cross-link densities of 1, 2, 4, 6, 8, and 10 (**I–VI**) were also prepared by the adjustment of the monomer/cross-linking agent molar ratio.

Chloromethylation of DVB- and BDDMA-crosslinked styrene copolymers (1b1 and 2b1)

The dry resin was swollen in dichloromethane (DCM; 10 mL), and to the swollen resin were added CMME (6 mL) and freshly prepared $ZnCl_2$[12–14] in tetrahydrofuran (THF; 0.1M, 0.3 mL). The mixture was refluxed at 50°C for 12 h with intermittent shaking. The resin was filtered, washed with THF, THF/H_2O (1 : 1), THF/HCl (1 : 1), and hot water until it was free from chloride, and finally washed with methanol. The resulting resin was further purified by Soxhlet extraction with THF. The chlorine capacities of the resins were determined by Volhard's method.

Preparation of polymer-supported quaternary ammonium salts (PSQAs)

Preparation of DVB–PS- and BDDMA–PS-supported benzyltriethylammonium chloride catalysts

To a suspension of chloromethylated PS resin (1 g, 1.76 mmol Cl) in DMF (15 mL), TEA (1.88 mL, 5 molar excess) was added, and the reaction mixture was stirred at 80°C. The extent of quaternization was followed by the determination of the free chlo-

ride ion in the catalyst with Volhard's titrimetric method. The reaction was found to be completed after 24 h (Table I). The polymer beads were filtered and washed with DMF (5 × 15 mL), DMF/water (1 : 1 v/v, 5 × 15 mL), water, and finally methanol (5 × 10 mL).

The polymer-bound catalysts derived from other trialkylamines such as trimethylamine (TMA), TBA, trioctylamine (TOA), and DIEA (**1c₁–1c₅** and **2c₁–2c₅**) were prepared by the same procedure. The details of the preparation are given in Tables I and II.

Conditioning of the polymer-bound phase-transfer catalyst for halogen-exchange reactions

For conditioning, the catalyst (1 g) was swollen in DCM for 15 min and stirred with a solution of KI (3.2 g/18 mL of water) for 5 h.

TABLE II
Details of the Preparation of Polymer-Supported Benzyltributylammonium Chloride Catalysts

Catalyst	Time (h)	Chloride-ion capacity (mmol/g)	Quaternization (%)
DVB–PS–TBA (**1c₃**)	2	0.37	20.7
	4	0.76	43.4
	6	0.90	51.4
	8	1.09	62.2
	12	1.42	81.1
	16	1.67	95.2
	18	1.76	100.0
BDDMA–PS–TBA (**2c₃**)	1	0.38	15.0
	2	0.96	38.4
	3	1.65	65.8
	4	2.25	89.7
	5	2.50	99.8

TABLE III
Halogen-Exchange Reactions Using 2% Crosslinked Benzyltributylammonium Chloride Catalysts

Substrate	Catalyst	Reaction time (h)	Boiling point of the product (°C)
1-Bromooctane	$1c_3$	40.0	219
	$2c_3$	15.0	
1-Bromoheptane	$1c_3$	41.0	203
	$2c_3$	15.5	
Benzyl chloride	$1c_3$	49.0	117
	$2c_3$	20.0	

Conversion of 1-bromooctane to 1-iodooctane

To the conditioned catalyst swollen in DCM (4.5 g, 5 molar excess), 1-bromooctane (0.52 mL, 3 mmol) was added with constant stirring. The reaction mixture was stirred at room temperature. The progress of the reaction was followed by thin-layer chromatography (TLC) analysis and was found to be 15 h (Table III). The reaction mixture was filtered and washed with DCM (3 × 5 mL) to remove the polymer-bound catalyst. The filtrate was transferred to a separating funnel, and the DCM layer was separated and dried over anhydrous $CaCl_2$. The organic layer on evaporation afforded the product 1-iodooctane. The product was characterized by its boiling point and comparison with authentic samples. A reaction with alcoholic $AgNO_3$ gave a yellow precipitate that was insoluble in NH_4OH. The boiling point of the product was 219°C.

The conversion of 1-bromoheptane to 1-iodoheptane was effected by the same procedure. The products were characterized by TLC with an authentic sample. Details are given in Table III.

Conversion of benzyl chloride to benzyl iodide

Here also the reaction was carried out by the same procedure mentioned previously, and 0.36 mL (3 mmol) of benzyl chloride was used for 4 g of the catalyst. The product was separated and characterized as in the earlier case. Details are given in Table III.

RESULTS AND DISCUSSION

DVB-crosslinked PS resin (**1a**) and BDDMA crosslinked resins (**2a_1–2a_6**), with different crosslink densities were prepared by suspension polymerization. The resins were functionalized by the incorporation of chloromethyl groups through the Friedel–Crafts reaction with chloromethylmethyl ether in the presence of Lewis acid catalyst $ZnCl_2$.[15–17]

The chloromethylated resins were characterized with elemental analysis and IR spectroscopy. The IR spectrum (Fig. 1) showed a band at 680 cm^{-1} for C—Cl stretching.

Preparation of PSQAs

Polymer-supported quaternary ammonium chloride was prepared through the stirring of a suspension of chloromethylated resin in DMF with trialkylamine at 80°C. DVB–PS and BDDMA–PS resins were quaternized with a series of trialkylamines (TMA, TEA, TBA, TOA, and DIEA; Scheme 1).

The absence of C—Cl stretching and H—C—Cl bending bands in the IR spectrum (Fig. 1) indicated the complete conversion of the chloromethyl resin. The appearance of a new C—N stretching band at 1378 cm^{-1} confirmed the formation of a quaternary ammonium salt (Fig. 2). The stability of the catalysts was studied by thermogravimetric analysis. The thermogram shows that the catalyst was stable up to 312°C (Fig. 3).

The chloride-ion capacities of the PSQAs ($1c_1$–$1c_5$ and $2c_1$–$2c_5$) were estimated by Volhard's titrimetric method[18] and were found to be quantitative.

The reaction period was found to be reduced by half in the case of BDDMA-crosslinked resins with 2% crosslinking in comparison with the DVB–PS resin having the same crosslink density. The polar, flexible BDDMA crosslinks permitted the smooth diffusion of soluble reagents through the swollen polymer matrix, thereby enhancing the reaction rates. In the case of quaternization with TOA, the complete reaction was not observed; instead, the quaternization reached a maximum of 66% in the case of the DVB–PS resin and 83% in the case of the BDDMA–PS resin. After that, the chloride-ion capacity decreased, and this decrease in capacity may have been due to the detachment of the TOA moiety from the support due to long alkyl chains.

The quaternization was complete within 5 h in the case of TBA, whereas with TEA and TMA, 12 and 16 h, respectively, were taken for 100% conversion
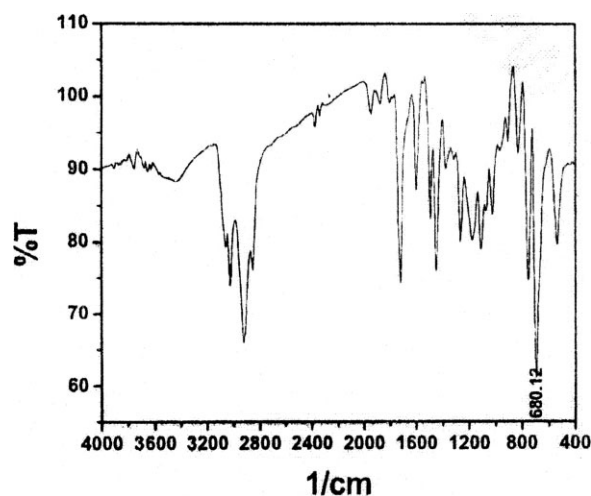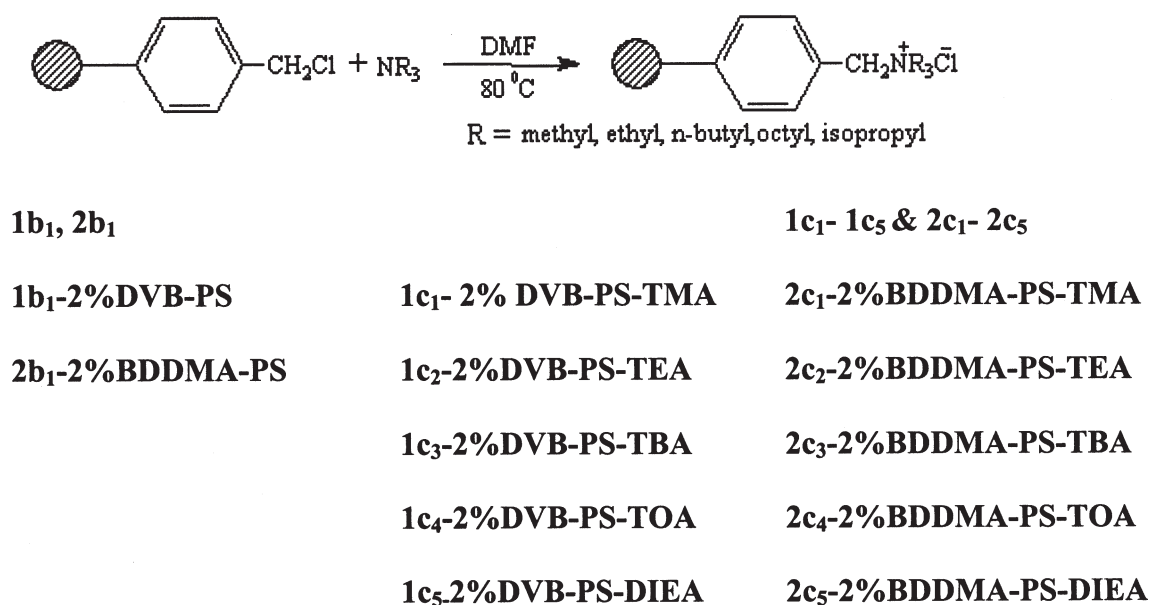

Figure 1 IR spectrum of chloromethylated BDDMA–PS.

$R = methyl, ethyl, n-butyl, octyl, isopropyl$

1b₁, 2b₁

1c₁- 1c₅ & 2c₁- 2c₅

1b₁-2%DVB-PS

1c₁- 2% DVB-PS-TMA

2c₁-2%BDDMA-PS-TMA

2b₁-2%BDDMA-PS

1c₂-2%DVB-PS-TEA

2c₂-2%BDDMA-PS-TEA

1c₃-2%DVB-PS-TBA

2c₃-2%BDDMA-PS-TBA

1c₄-2%DVB-PS-TOA

2c₄-2%BDDMA-PS-TOA

1c₅-2%DVB-PS-DIEA

2c₅-2%BDDMA-PS-DIEA

Scheme 1 Quaternization of chloromethylated resins with different trialkylamines.

(Table I). In the case of DIEA and TOA, the chloride capacity was very low, and this may have been due to steric hindrance imparted by the bulky groups. Increasing the number of methylene groups in the alkyl group increased the ease of formation of the quaternary ammonium salt. The electron density at the nitrogen atom was increased by the increase in the number of carbon atoms. The increase in the alkyl chain length increased the lipophilic character of the amine, which made it compatible with the polymer support.

The details of the quaternization of chloromethylated resins from 2% crosslinked DVB–PS and BDDMA–PS with TBA are summarized in Table II and Figure 4.
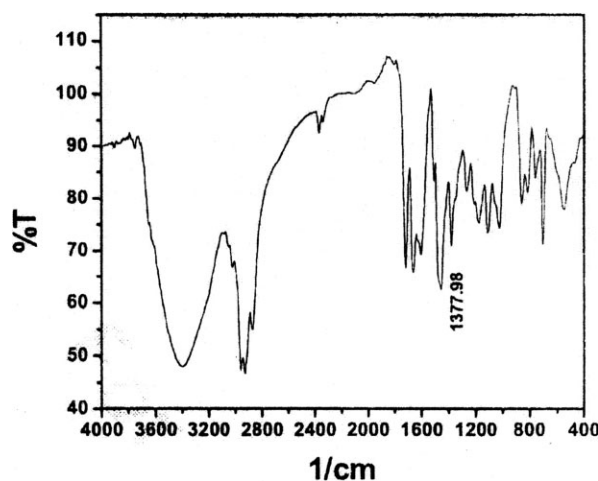
Application of PSQA in halogen-exchange reactions

By the choice of suitable reaction conditions, PSQAs can approach the reactivity of soluble phase-transfer catalysts. The efficiency of the prepared catalysts was investigated in halogen-exchange reactions. The conversions of 1-bromooctane to 1-iodooctane, 1-bromoheptane to 1-idoheptane, and benzyl chloride to benzyl iodide were effected by a treatment with aqueous KI in the presence of the polymer-supported benzyltributylammonium chloride catalyst. The catalyst was conditioned before the reaction. For this, a KI solution was added to a suspension of the catalyst in DCM, and it was stirred for 5 h. To the conditioned catalyst, the halide was added with constant stirring. The extent of conversion was followed by TLC analysis. Details of the reactions are given in Table III.
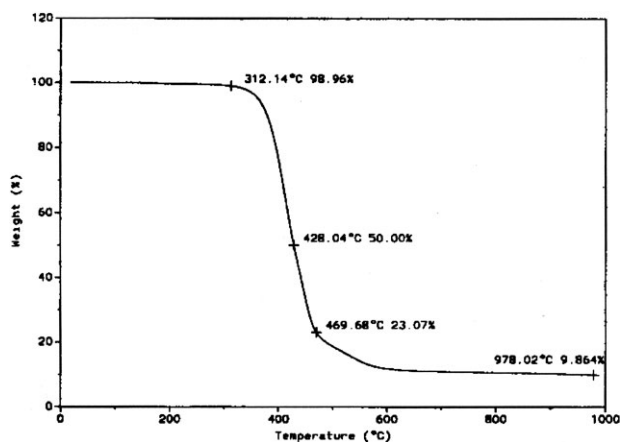

Figure 2 IR spectrum of the BDDMA–PS–TBA catalyst.

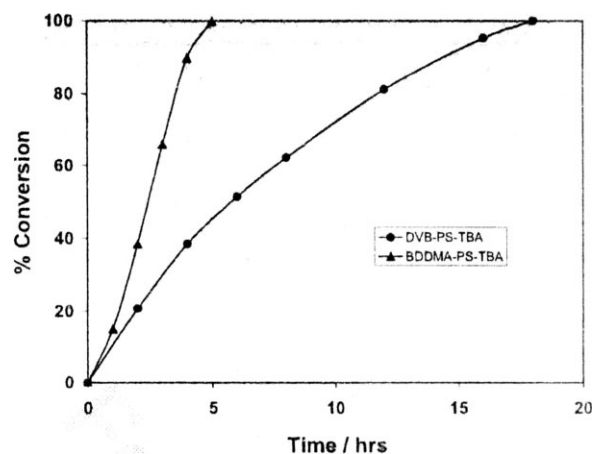**Figure 3** Thermogram of the BDDMA–PS–TBA catalyst.

Figure 4 Percentage conversion of DVB–PS–TBA and BDDMA–PS–TBA.

From these studies, it was found that the times for the conversions of 1-bromooctane to 1-iodooctane and 1-bromoheptane to 1-idoheptane were similar. However, with benzyl chloride, the reaction period increased considerably.

Effect of the polymer parameters and reaction conditions on the efficiency of the polymer-supported phase-transfer catalysts (PSPTCs)

To investigate the effects of the nature and structural characteristics of the polymer support, the nature of the trialkylamines used, and the reaction conditions, the conversion of 1-bromooctane to 1-iodooctane was taken as the model reaction.

Effect of trialkylamine

Details of the reaction of 1-bromooctane to 1-iodooctane with various PSPTCs are given in Table IV.

The aforementioned results showed that the rate of the reaction depended on both the nature of the trialkylamine and the polymer support. Here the time for complete conversion was reduced when the amine for quaternization was changed from TMA to TOA. In the case of TOA, quaternization was not complete, and a large amount of the catalyst was needed for the reaction. Therefore, TBA was taken as the optimum catalyst. The catalytic activity was increased when the catalyst-immobilized resin was changed from DVB–PS to BDDMA–PS. With catalyst $1c_3$, the time taken for the complete reaction was 40 h, whereas with catalyst $2c_3$, the time taken was 15 h.

Effect of the nature of the crosslinking agent

Investigations of the halogen-exchange reactions revealed that the nature of the crosslinking agent had a significant influence on the rate of the reac-

tion. Catalysts with long, flexible BDDMA crosslinks reduced the reaction period to a considerable extent in comparison with the rigid DVB-crosslinked catalysts (Table III). In the conversion of 1-bromooctane to 1-idooctane, the reaction time with a BDDMA-crosslinked catalyst ($2c_3$) was found to be 15 h, whereas with a DVB-crosslinked catalyst ($1c_3$), the reaction period was 40 h. Similar was the case with 1-bromoheptane and benzyl chloride. The same observation was found with reactions using catalysts with different trialkylamines (Table IV).

Effect of the extent of the crosslinking of the polymer support

BDDMA–PS-supported catalysts with different crosslink densities of 1, 2, 4, 6, 8, and 10 mol % (**I–VI**) were prepared under identical conditions and employed for the conversion reaction of 1-bromooctane to 1-iodooctane. The results showed that an increase in the crosslink density reduced the reactivity of the catalyst. An increase in crosslinking could reduce the mobility of the polymer chains and the accessibility of the catalytic sites to the soluble reagents and substrates. The catalyst prepared from 1% crosslinked polymer did not possess enough mechanical strength for stirring the reaction mixture for a long time. The polymer underwent deterioration, and the separation of the catalyst by filtration of the reaction mixture after the reaction was found to be time-consuming; therefore, the 2% crosslinked catalyst was found to be the most suitable one. The details of the results are summarized in Table V.

Effect of the solvent

The effect of the solvent on the activity of PSPTCs was investigated by the determination of the conversion of 1-bromooctane to 1-iodooctane in different solvents with the aid of catalyst $2c_3$. The reaction was carried out at room temperature under identical conditions in the solvents DCM, toluene, DMF,

TABLE IV
Conversion of 1-Bromooctane to 1-Iodooctane with Various PSQAs

PSQA catalyst	Crosslinking agent	Trialkylamine	Reaction time (h)
$1c_1$	DVB	TMA	53
$1c_2$	DVB	TEA	48
$1c_3$	DVB	TBA	40
$1c_4$	DVB	TOA	12
$2c_1$	BDDMA	TMA	25
$2c_2$	BDDMA	TEA	20
$2c_3$	BDDMA	TBA	15
$2c_4$	BDDMA	TOA	4

TABLE V
Effect of the Crosslink Density on the Reactivity of PSPTCs for the Conversion of 1-Bromooctane to 1-Iodooctane

PSPTC	Crosslink density (%)	Chloride-ion capacity (mmol/g)	Time for 100% conversion (h)
I	1	2.6	10
II	2	2.4	15
III	4	2.0	19
IV	6	1.8	24
V	8	1.6	30
VI	10	1.4	40

dioxane, nitrobenzene, and hexane. The details are given in Table VI.

Among the solvents, the maximum rate was observed when DCM was used as the solvent. This was due to the increased solvation of the polymeric catalyst in DCM, which arose from the mutual compatibility. Hence, DCM was used as the reaction medium in all studies.

Effect of the temperature

The conversion of 1-bromooctane to 1-iodooctane was carried out with catalyst $2c_3$ in toluene at 30, 40, 50, 60, 70, and 80°C. The time for complete conversion was noted in each case. The observed results are summarized in Table VII.

As expected in this reaction, the rate of reaction increased with an increase in the temperature. However, in our studies, the reactions were carried out at room temperature with DCM because of the easy removal of the solvent after reactions.

Conversion of benzyl chloride to benzyl iodide

The conversion of benzyl chloride to benzyl iodide was also effected in aqueous organic media under phase-transfer catalytic conditions with the PSPTCs. The reactions were performed with catalysts $1c_3$ and $2c_3$ and with the solvent DCM at room temperature. The reaction period was found to be more in the conversion of benzyl chloride to benzyl iodide than in the conversions of 1-bromoheptane to 1-iodoheptane and 1-bromooctane to 1-iodooctane. In this case,

TABLE VI
Effects of Solvents on PSPTC

Solvent	Time for 100% conversion (h)
DCM	15
Toluene	26
DMF	30
Dioxane	35
Nitrobenzene	38
Hexane	40

TABLE VII
Effect of Temperature on the Conversion of 1-Bromooctane to 1-Iodooctane

Temperature (°C)	Time for 100% conversion (h)
30	26.0
40	25.5
50	25.0
60	24.0
70	21.0
80	17.0

the reaction time was less with the BDDMA catalyst (20 h) than with the DVB catalyst (49 h). DCM was found to be the best solvent. When toluene was used as the solvent, the reaction time decreased at elevated temperatures. Reactions with BDDMA–PS-supported catalysts having different crosslink densities (**II–VI**) were carried out, and here also the reaction rate decreased with an increase in the degree of crosslinking. The details of the reactions are summarized in Table VIII.

Recycling of the catalyst

The spent catalyst was recovered at the end of the reaction by thorough washing with DMF, DMF/water (1 : 1), and methanol. After being washed, the resin was dried in a hot-air oven at 50°C for 24 h. For regenerating the catalyst, the dried resin was treated with concentrated HCl, washed with DMF, DMF/water (1 : 1), and methanol, and dried *in vacuo*.

The chloride capacity of the regenerated catalyst was determined, and no considerable loss in the chloride capacity was observed in comparison with the fresh catalyst (Table IX). The IR spectrum of the regenerated catalyst showed the C—N stretching band at 1378 cm^{-1}. The efficiency of the regenerated catalyst was checked in the conversion of 1-bromooctane to 1-iodooctane.

CONCLUSIONS

PSQAs were prepared and used as phase-transfer catalysts in halogen-exchange reactions in aqueous

TABLE VIII
Effect of the Crosslink Density on the Reactivity of PSPTCs for the Conversion of Benzyl Chloride to Benzyl Iodide

PSPTC	Crosslink density (%)	Chloride-ion capacity (mmol/g)	Time for 100% conversion (h)
II	2	2.4	20.0
III	4	2.0	21.5
IV	6	1.8	23.5
V	8	1.6	26.0
VI	10	1.4	30.0

TABLE IX
Chloride-Ion Content of 2c₃ After Recycling
and Time Taken for the Complete Conversion
of 1-Bromooctane to 1-Iodooctane

Number of cycles	Chloride-ion content (mmol/g)	Reaction time (h)
1	2.42	15.0
2	2.41	15.0
3	2.39	15.0
4	2.39	15.0
5	2.38	15.5

organic systems. The PSPTCs were prepared by quaternization of different trialkylamines with chloromethyl PS resins. The efficiency of the polymer-bound phase-transfer catalyst was analyzed by the variation of the nature and extent of crosslinking of the polymer supports, the nature of the trialkylamines, and the reaction conditions. The polymer-bound phase-transfer catalyst could be regenerated and reused several times without loss of their activity.

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