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The use of polymeric sulfides as catalysts for the *para*-regioselective chlorination of phenol and 2-chlorophenol

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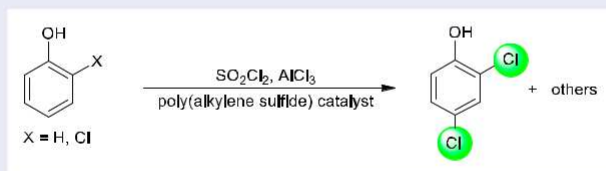
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ABSTRACT

Various poly(alkylene sulfide)s have been synthesized and used as catalysts to enhance the *para*-regioselectivity in chlorination of phenol and 2-chlorophenol using freshly distilled sulfuryl chloride in the presence of AlCl₃ as an activator. Poly(alkylene sulfide)s having alternating spacers, one having three methylene groups and the second having three, six or nine methylene groups were the most *para*-regioselective catalysts in chlorination of both phenol and 2-chlorophenol. For example, chlorination of phenol and 2-chlorophenol in the presence of optimal examples of such poly(alkylene sulfide)s gave 4-chlorophenol and 2,4-dichlorophenol as the major products in 94.8 and 95.4% yields, respectively, compared with 75.4 and 55.0% yields in the absence of catalysts. In addition, double chlorination of phenol in the presence of poly(alkylene sulfide)s gave 2,4-dichlorophenol in up to 97.1% yield compared with only 58.6% in the absence of catalysts.

KEYWORDS

Para-regioselective chlorination; catalysts; aluminum chloride; 2,4-dichlorophenol; phenol; poly(alkylene sulfide)s



1. Introduction

Chlorophenols are used in the production of many industrial products such as herbicides, pharmaceuticals and dyes [1]. For example, 2,4-dichlorophenoxyacetic is used in weed control for many crops such as maize and rice [2,3]. It is still widely used mainly due to its low production cost and can be produced from the reaction of molar equivalents of chloroacetic acid and 2,4-dichlorophenol (2,4-DCP) in the presence of an excess

of sodium hydroxide [4]. Therefore, there is continuing interest in the development of low-cost processes for the selective production of chlorophenols.

Recently, several processes have been developed for the selective halogenation of aromatic compounds [5–10]. For example, chlorination systems involving the use of [*bis*(trifluoroacetoxy)iodo]benzene and aluminum chloride (AlCl₃) in acetonitrile [5], 1,3-dichloro-5,5-dimethylhydantoin in the presence of ammonium chloride in toluene [6], hydrogen chloride, manganese(II) sulfate and hydrogen peroxide in water [7], and *N*-chlorosuccinimide and Nagasawa's bithiourea catalyst in chlorinated solvent [8] have been reported. However, such systems are often selective towards the *ortho*-isomers and involve use of solvent, which are not applicable for the commercial production of bulk chlorophenols.

We have reported a number of efficient processes that employ solid catalysts to enhance the regioselective production of *para*- or linear isomers in electrophilic substitution of aromatic compounds [11–25]. Sheldon's group has used a similar approach for chlorination of phenol (P) using SO₂Cl₂ in the presence of L type zeolite in isooctane to give 2-chlorophenol (2-CP) and 4-chlorophenol (4-CP) in 10.7 and 85.3% yields, respectively [26]. Under similar reaction conditions, the use of Al-pillared montmorillonite clay as a catalyst gave 2-CP and 4-CP in 13.4 and 75.7% yields, respectively [26]. Others have adopted different approaches to chlorination of phenols with various chlorinating agents [27,28]. However, one of the most promising approaches for commercially relevant selective *para*-chlorination of phenols involves the use of sulfur-containing catalysts.

Selective chlorination of phenols using SO₂Cl₂ in the presence of sulfur-containing catalysts and Lewis acids was first reported by Watson [29,30]. For example, monochlorination of P using SO₂Cl₂ in the presence of diphenyl sulfide (Ph₂S) and AlCl₃ at 25°C gave 2-CP and 4-CP in 8.5 and 89.5% yields, respectively [29,30]. Similarly, chlorination of 2-CP in the presence of ferric chloride (FeCl₃) at 35°C gave 2,4-DCP and 2,6-dichlorophenol (2,6-DCP) in 94.0 and 4.2% yields, respectively [29,30]. Double chlorination of P using SO₂Cl₂ in the presence of Ph₂S and FeCl₃ at 25°C gave 2,4-DCP (97.3%), 2,6-DCP (0.4%) and 2,4,6-trichlorophenol (2.0%) [29,30].

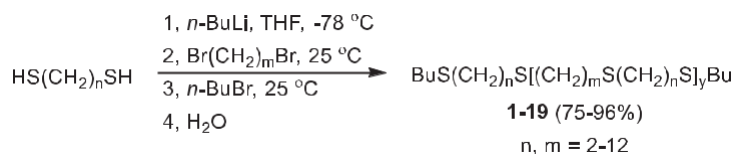
Since then, various other sulfur compounds have been investigated as catalysts in the chlorination of P and 2-CP. For example, chlorination of P using SO₂Cl₂ and di-*n*-butyl sulfide in the absence of a Lewis acid at 25°C gave 2-CP, 4-CP, and 2,4-DCP in 8.7, 84.8, and 1.0% yields, respectively, along with unreacted starting material (5.4%) [31,32]. Chlorination of P using SO₂Cl₂ in the presence of the cyclic disulfide 1,2-dithiocane and AlCl₃ at 25°C gave 2-CP (7.4%), 4-CP (91.2%), and 2,4-DCP (1.1%) [33], while use of the polymeric equivalent, poly(hexamethylenedisulfide), under similar conditions gave 2-CP, 4-CP and 2,4-DCP in 8.8, 89.0, and 2.2% yields, respectively [33]. The use of tetrahydrothiopyran as catalyst in chlorination of P using SO₂Cl₂ in the presence of AlCl₃ at 25°C gave 2-CP and 4-CP in 5.0 and 89.0% yields, respectively [34], while chlorination of P using SO₂Cl₂ in the presence of 5,18-dithiadocosane and AlCl₃ at 35°C gave 2-CP and 4-CP in 6.6 and 76.4% yields, respectively, along with unreacted starting material (11.4%) [35,36]. Methylthio alcohols, methoxy(methylthio)alkanes, and *bis*(methylthio)alkanes have also been investigated as catalysts in chlorination of P using SO₂Cl₂ in the presence of AlCl₃ at 25°C and led to the production 2-CP (8.2–12.7%) and 4-CP (83.1–88.8%) along with 2,4-DCP (1.6–2.3%) [37].

We have previously had occasion to synthesize a series of poly(alkylene sulfide)s [38], which we have used to make stable borane complexes [39,40], and in the patent literature we have also reported a more complex poly(alkylene sulfide) with a repeating unit [(CH₂)₈S(CH₂)₆S] [36]. Such solid sulfur-containing materials could combine some of the advantages of solid reagents (such as ease of removal by filtration, lack of odor) with some of the benefits of sulfur compounds (as regioselective catalysts). Therefore, we now report the preparation of further examples of more complex poly(alkylene sulfide)s having alternating alkylene groups of different chain lengths and their use, along with the use of symmetrical poly(alkylene sulfide)s, in the regioselective chlorination of phenol and 2-chlorophenol using SO₂Cl₂ and AlCl₃.

2. Results and discussion

A range of poly(alkylene sulfide)s was synthesized using two different synthetic approaches. The first one involved lithiation of 1,ω-alkanedithiols (one mole equivalent) using *n*-butyllithium (*n*-BuLi; two mole equivalents) in tetrahydrofuran (THF) at low temperature followed by reaction with 1,ω-dibromoalkanes (0.9 mole equivalent) and 1-bromobutane (0.2 mole equivalent) at room temperature (Scheme 1). Such a procedure allowed the production in 75–96% yields of poly(alkylene sulfide)s **1–19** that have alternating spacer units of different chain lengths (number of methylene groups) (Table 1). The second procedure involved reaction of 1,ω-dibromoalkanes (one mole equivalent) and sodium sulfide nonahydrate (Na₂S·9H₂O; 1.4 mole equivalents) under reflux conditions for 4 h (Scheme 2), in accordance with the reported procedure [38]. This method was used to synthesize poly(alkylene sulfide)s **20–24** that had just one type of spacer unit in 83–97% yields (Table 2). This method was successfully applied for the production of poly(alkylene sulfide)s that had 2–8 methylene units as spacers. The latter approach was also used on an equimolar mixture of two different dibromoalkanes, resulting in a poly(alkylene sulfide) **25** with two different spacer groups, but not uniformly distributed (Scheme 3). The general natures of the synthesized poly(alkylene sulfide)s **1–25** were confirmed by the use of ¹H NMR spectral data and where comparisons were possible were consistent with those previously reported [38].

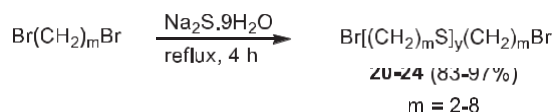
Chlorination of P (100 mmol) using distilled SO₂Cl₂ (110 mmol) in the presence of poly(alkylene sulfide)s (100 mg) as catalysts and AlCl₃ (100 mg) as a Lewis acid in the absence of solvent was attempted at 25°C (Scheme 4; route a). In addition, the reaction was carried out in the absence of poly(alkylene sulfide)s under the same conditions for comparison. The yields of the chlorinated products obtained (2-CP, 4-CP and 2,4-DCP) are reported in Table 3.



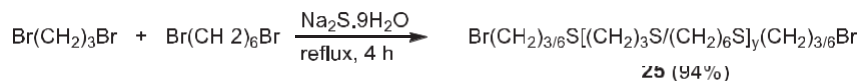
Scheme 1. Synthesis of poly(alkylene sulfide)s **1–19** using alkanedithiols.

Table 1. Synthesis of poly(alkylene sulfide)s **1–19** according to Scheme 1.

Polymer	n	m	Melting point (°C)	Yield (%)
1	2	2	165–168	75
2	3	3	64–67	82
3	3	4	60–63	94
4	3	6	63–65	83
5	3	9	71–73	84
6	3	12	83–85	93
7	4	4	68–70	90
8	4	6	69–72	80
9	4	8	75–78	95
10	4	10	80–84	92
11	4	12	86–90	96
12	5	5	69–70	96
13	6	6	74–77	84
14	6	8	74–77	92
15	6	10	78–81	93
16	6	12	78–83	89
17	8	8	82–84	88
18	8	10	78–81	90
19	8	12	85–88	91

**Scheme 2.** Synthesis of poly(alkylene sulfide)s **20–24** using sodium sulfide.**Table 2.** Synthesis of poly(alkylene sulfide)s **20–24** according to Scheme 2.

Polymer	m	Melting point (°C)	Yield (%)
20	2	185–186	90
21	3	55–57	90
22	4	66–69	83
23	6	70–77	97
24	8	58–64	94

**Scheme 3.** Synthesis of mixed poly(alkylene sulfide) **25** using sodium sulfide.

The yield of 4-CP was only 75.4% when the reaction was carried out in the absence of any catalyst (Table 3). The yield of 4-CP improved in all cases when a poly(alkylene sulfide) was used as a catalyst. Catalysts containing at least one shorter spacer unit (at most three methylene groups) invariably provided higher yields of 4-CP (87.2–91.4%) than those having only longer spacers containing at least five methylene groups (78.2–85.0%). Catalysts in which the shortest spacer group was four methylene units provided intermediate yields (82.4–90.3%), depending on the length of the longer spacer group (catalysts with longer second spacers giving lower yields of 4-CP). The same trends can be seen in the 4-CP/2-CP ratios (*p/o* ratios). Poly(alkylene sulfide) **5**, which contains alternating spacers of three

Table 3. Chlorination of phenol according to Scheme 4 (route a).^a

Polymer	Repeating units		Terminal group	Yield (%) ^b				<i>p/o</i> ratio	Mass balance (%) ^c
	<i>n</i>	<i>m</i>		<i>P</i>	2-CP	4-CP	2,4-DCP		
–	–	–	–	0.3	21.9	75.4	2.4	3.4	100
1	2	2	Bu	3.5	8.3	87.2	0.4	10.5	99.4
20	–	2	Br	0.7	9.7	88.5	0.8	9.1	99.7
2	3	3	Bu	3.9	5.9	89.8	0.2	15.2	99.8
21	–	3	Br	0.2	7.9	90.9	0.8	11.5	99.8
3	3	4	Bu	0.5	8.3	90.5	0.4	10.9	99.7
4	3	6	Bu	5.9	5.2	88.3	–	17.0	99.4
25	–	3/6	Br	–	7.5	91.3	1.0	12.2	99.8
25^d	–	3/6	Br	–	7.6	90.9	1.4	12.0	99.9
25^e	–	3/6	Br	–	7.5	90.8	1.5	12.1	99.8
5	3	9	Bu	3.4	4.8	91.4	–	19.0	99.6
5^f	3	9	Bu	–	4.7	94.8	–	20.2	99.5
5^g	3	9	Bu	3.8	5.3	90.1	0.3	17.0	99.5
6	3	12	Bu	6.0	5.6	87.9	–	15.7	99.5
7	4	4	Bu	3.6	5.9	90.0	0.1	15.2	99.6
22	–	4	Br	0.6	8.5	90.3	0.5	10.6	99.9
8	4	6	Bu	4.8	8.3	85.6	0.8	10.3	99.5
9	4	8	Bu	2.4	12.7	83.4	1.0	6.6	99.5
10	4	10	Bu	3.5	12.2	83.0	0.8	6.8	99.5
11	4	12	Bu	–	13.9	82.4	3.1	5.9	99.4
12	5	5	Bu	5.9	9.4	84.1	0.5	8.9	99.9
13	6	6	Bu	5.0	13.0	80.5	1.0	6.2	99.5
23	–	6	Br	1.5	12.5	85.0	0.8	6.8	99.8
14	6	8	Bu	4.0	11.4	83.4	0.7	7.3	99.5
15	6	10	Bu	2.8	13.2	82.2	1.3	6.2	99.5
16	6	12	Bu	4.0	9.7	85.0	0.8	8.8	99.5
17	8	8	Bu	1.7	16.7	79.7	1.5	4.8	99.6
24	–	8	Br	5.3	15.6	78.2	0.7	5.0	99.8
18	8	10	Bu	1.5	17.5	79.1	1.6	4.5	99.7
19	8	12	Bu	0.7	17.0	80.5	1.2	4.7	99.4

^aSulfuryl chloride (8.90 ml, 110 mmol) was slowly added to a mixture of phenol (9.41 g, 100 mmol), AlCl₃ (100 mg) and poly(alkylene sulfide)s (100 mg) at RT over 2 h.

^bYield (%) based on quantitative GC.

^cTotal yield (%) for all identified products, to confirm no other significant products formed.

^dPolymer **25** (50 mg) was used.

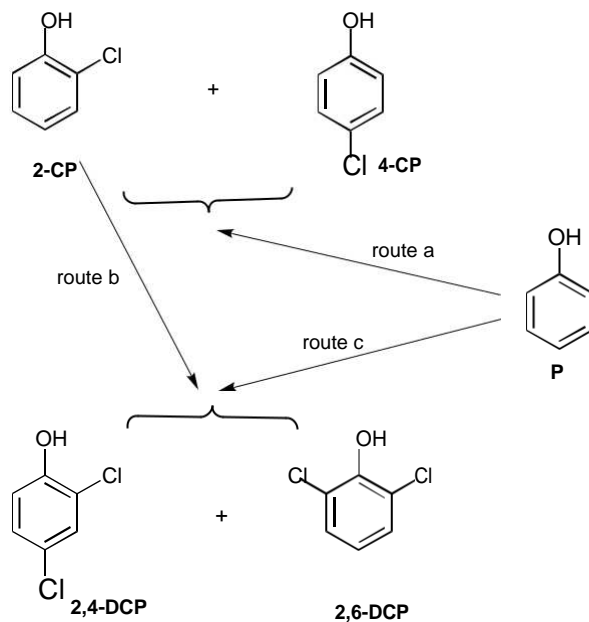
^ePolymer **25** (20 mg) was used.

^fSulfuryl chloride (105 mmol) was used.

^gSulfuryl chloride (105 mmol) and polymer **5** (50 mg) were used.

and nine methylene groups (*i.e.* *n* = 3, *m* = 9), was the most *para*-regioselective catalyst in chlorination of **P**, producing 4-CP in 91.4% yield under the standard conditions, which increased to 94.8% when the mixture was stirred at 55°C for 1 h before work-up. This was the highest 4-CP yield achieved from any of the reactions. Reducing the quantity of **5** to 50 mg and SO₂Cl₂ to 105 mmol led to the production of 4-CP in 90.1% yield along with a significant quantity of unreacted **P** (3.8%). Poly(alkylene sulfide) **25** (*m* = 3/6) was also highly selective, leading to the production of 4-CP in 91.3% under the standard conditions and giving very similar results with lower quantities (50 mg or 20 mg) of **25** under otherwise similar reaction conditions.

Polymers with similar spacer groups but prepared by the different methods, one major difference therefore being the nature of the terminal group (Bu or Br), gave broadly similar results when direct comparisons were possible, suggesting that the length of the spacer groups has more effect than the nature of the terminal groups or the method of preparation. Nevertheless, in the cases with at least one short spacer group (at least one group being no



Reagents used in different routes (all at RT for 2h unless otherwise stated)

route a: P (100 mmol), SO₂Cl₂ (110 mmol), polymer **1-25** (0.1 g), AlCl₃ (0.1 g)

route b: 2-CP (100 mmol), SO₂Cl₂ (110 mmol), polymer **1-25** (0.1 g), AlCl₃ (0.1 g)

route c: P (100 mmol), SO₂Cl₂ (210 mmol), polymer **1-25** (0.1 g), AlCl₃ (0.1 g)

Scheme 4. Chlorination of phenol (P) or 2-chlorophenol (2-CP) using sulfuryl chloride in the presence of poly(alkylene sulfide)s **1-25** and AlCl₃.

longer than trimethylene, or both being tetramethylene, which were the polymers giving higher *p/o* ratios), the *p/o* ratio was somewhat greater with the polymer made using the alkanedithiol route shown in Scheme 1 (*i.e.* **1** > **20**; **2** > **21**; **4** > **25**; **7** > **22**). By contrast, for polymers with longer spacers, which generally did not give high *p/o* ratios, the polymer made using Scheme 2 gave a somewhat greater *p/o* ratio than the corresponding example made by the alkanedithiol route (*i.e.* **23** > **13**; **24** > **17**).

The fact that the presence of any of the polymers resulted in a higher *p/o* ratio than in their absence is consistent with the previously expressed view that the sulfur-containing catalyst forms a bulky electrophilic complex with the AlCl₃ and SO₂Cl₂ that attacks the P at the least hindered 4-position to produce 4-CP as the major product [29,30]. However, this simplistic idea does not explain the subtleties displayed by the polymers with different spacer groups.

In view of the commercial importance of 2,4-dichlorophenol, and in recognition that further chlorination of 4-CP would give virtually exclusively 2,4-DCP, it was of interest to investigate the further chlorination of 2-CP (Scheme 4, route b), which could give both 2,4-DCP and 2,6-DCP, under similar conditions to those used for the chlorination of P. The yields and *p/o* ratio for the chlorinated products (2,4-DCP and 2,6-DCP) are reported in Table 4.

Under the standard conditions, in the absence of any poly(alkylene sulfide), the yields of 2,4-DCP and 2,6-DCP were 55.0 and 12.5%, respectively, along with a high proportion

Table 4. Chlorination of 2-chlorophenol according to Scheme 4 (route b).^a

Polymer	Repeating units		Terminal group	Yield (%) ^b			<i>p/o</i> ratio	Mass balance (%) ^c
	n	m		2-CP	2,4-DCP	2,6-DCP		
–	–	–	–	32.4	55.0	12.5	4.4	99.9
2	3	3	Bu	11.5	84.0	4.2	20.0	99.7
2^d	3	3	Bu	0.4	95.4	3.7	25.8	99.5
5	3	9	Bu	9.6	84.1	5.7	14.8	99.4
7	4	4	Bu	5.9	84.6	8.5	10.0	99.0
7^d	4	4	Bu	2.0	90.7	6.8	13.3	99.5
22	–	4	Br	13.0	80.7	5.9	13.7	99.6
8	4	6	Bu	9.9	84.5	5.3	15.9	99.7
8^a	4	6	Bu	1.4	92.1	5.7	16.2	99.2
9	4	8	Bu	3.7	89.8	6.0	15.0	99.5
10	4	10	Bu	8.0	85.7	6.1	14.0	99.8
11	4	12	Bu	19.6	73.7	6.4	11.5	99.7
13	6	6	Bu	13.9	76.8	8.9	8.6	99.6
14	6	8	Bu	12.1	76.3	11.1	6.9	99.5
15	6	10	Bu	17.2	72.6	9.9	7.3	99.7
16	6	12	Bu	17.6	71.9	10.0	7.2	99.5
17	8	8	Bu	14.3	78.8	6.6	11.9	99.7
18	8	10	Bu	19.0	70.8	9.7	7.3	99.5
19	8	12	Bu	16.4	70.5	12.1	5.8	99.0

^aSulfuryl chloride (8.90 ml, 110 mmol) was slowly added to a mixture of 2-chlorophenol (12.86 g, 100 mmol), AlCl₃ (100 mg) and poly(alkylene sulfide) (100 mg) at RT over 2 h.

^bYield (%) based on quantitative GC.

^cTotal yield (%) for all identified products, to confirm no other significant products formed. ^dThe

mixture was stirred at 55°C for 1 h before work-up.

(32.4%) of unreacted 2-CP (Table 4). In the presence of any one of the poly(alkylene sulfide)s, the yield of 2,4-DCP increased significantly (up to 89.9%) while the yield of 2,6-DCP decreased, leading in all cases, therefore, to a higher *p/o* ratio. However, there were significant differences in the level of selectivity observed with the different poly(alkylene sulfide)s. Generally, poly(alkylene sulfide)s with shorter spacers (*n* = 3, 4 and *m* = 3–8) led to higher yields of 2,4-DCP and higher *p/o* ratios than the ones with longer spacer units (*n* = 6, 8 and *m* = 6–12). However, a significant quantity (3.7–19.0%) of unreacted 2-CP still remained in the product mixtures and this could complicate the interpretation of the results. For example, with the only poly(alkylene sulfide) prepared by the sodium sulfide method (Scheme 2), polymer **22**, 13% of 2-CP remained, resulting in a lower yield of 2,4-DCP (80.7%) than for the corresponding polymer prepared according to Scheme 1 (*i.e.* **7**, 84.6%), despite giving a higher *p/o* ratio (13.7 compared to 10.0). Therefore, three of the poly(alkylene sulfide)s that produced high yields of 2,4-DCP were used in reactions conducted under more forcing conditions (stirred at 55°C for 1 h before work-up). The yield of 2,4-DCP increased to over 90% in all three cases and poly(alkylene sulfide) **2** (*n*, *m* = 3) provided a *p/o* ratio of 25.8 and the highest yield of 2,4-DCP (95.4%) ever recorded on chlorination of 2-CP using SO₂Cl₂.

With the benefit of the information derived from monochlorination of phenol and chlorination of 2-CP, it was of interest to investigate the direct double chlorination of phenol. A significant quantity of starting material was recovered in chlorination of 2-CP under the general conditions, which negatively affected the yield of 2,4-DCP. Therefore, for the double chlorination of P (100 mmol) (Scheme 4, route c) a small excess of SO₂Cl₂ (210 mmol) was used, along with a poly(alkylene sulfide) and AlCl₃, in an attempt to produce 2,4-DCP

Table 5. Double chlorination of phenol according to Scheme 4 (route c).^a

Polymer	Repeating units		Terminal group	Yield (%) ^b				<i>p/o</i> ratio	Mass balance (%) ^c
	<i>n</i>	<i>m</i>		2-CP	4-CP	2,4-DCP	2,6-DCP		
—	—	—	—	9.0	29.2	58.6	3.0	19.5	99.8
1	2	2	Bu	0.4	3.7	95.1	0.7	135.9	99.9
20	—	2	Br	0.3	4.6	94.0	0.7	134.3	99.6
2	3	3	Bu	1.6	37.8	59.7	0.4	149.2	99.5
21	—	3	Br	0.8	23.0	75.7	0.4	189.3	99.9
3	3	4	Bu	0.8	21.7	76.9	0.4	192.3	99.8
4	3	6	Bu	2.0	34.4	62.9	0.6	104.8	99.9
25	—	3/6	Br	0.4	18.7	80.4	0.4	201.0	99.9
5	3	9	Bu	1.1	28.3	69.9	0.2	349.5	99.5
5^d	3	9	Bu	0.4	9.6	89.2	0.3	279.3	99.5
5^e	3	9	Bu	—	5.5	93.3	0.3	331.0	99.1
5^f	3	9	Bu	—	2.1	96.6	0.3	321.7	99.0
5^g	3	9	Bu	0.4	0.4	97.1	0.9	107.9	98.8
6	3	12	Bu	1.8	28.5	68.9	0.7	98.4	99.9
7	4	4	Bu	1.8	31.9	65.6	0.2	328.0	99.5
22	—	4	Br	1.3	37.6	60.4	0.2	302.0	99.5
8	4	6	Bu	4.5	27.4	66.7	1.1	60.6	99.7
9	4	8	Bu	6.6	36.5	54.9	1.6	34.3	99.6
10	4	10	Bu	3.6	24.4	70.1	1.5	46.7	99.6
11	4	12	Bu	4.3	32.2	61.4	1.6	38.4	99.5
13	6	6	Bu	5.6	25.8	66.0	2.1	31.4	99.5
23	—	6	Br	2.5	18.3	77.1	2.0	38.6	99.9
14	6	8	Bu	4.8	24.4	67.9	2.3	29.5	99.4
15	6	10	Bu	4.9	29.4	63.3	1.8	35.2	99.4
16	6	12	Bu	4.1	21.5	71.8	2.1	34.2	99.5
17	8	8	Bu	8.7	39.4	49.4	2.0	24.7	99.5
24	—	8	Br	2.3	9.9	84.3	3.2	26.3	99.7
18	8	10	Bu	6.9	28.8	61.2	2.5	29.0	99.4
19	8	12	Bu	4.5	18.1	74.1	2.7	27.4	99.4

^aSulfuryl chloride (17.00 ml, 210 mmol) was slowly added to a mixture of phenol (9.41 g, 100 mmol), AlCl₃ (100 mg) and poly(alkylene sulfide) (100 mg) at RT over 2 h.

^bYield (%) based on quantitative GC.

^cTotal yield (%) for all identified products, to confirm no other significant products formed. ^dThe mixture was stirred at 55°C for 1 h before work-up.

^eSulfuryl chloride (220 mmol) was used and the mixture was stirred at 55°C for 1 h before work-up. ^fSulfuryl chloride (230 mmol) was used and the mixture was stirred at 55°C for 1 h before work-up. ^gSulfuryl chloride (215 mmol) was used and the reaction was carried out at 55°C.

directly in one step and in high yield without over-chlorination. The yields of 2,4-DCP and 2,6-DCP obtained are recorded in Table 5.

In the absence of poly(alkylene sulfide) and AlCl₃, the yields of 2-CP, 4-CP, 2,4-DCP, and 2,6-DCP were 9.0, 29.2, 58.6, and 3.0%, respectively, and the 2,4-/2,6-DCP ratio was less than 20 (Table 5). The yield of 2,4-DCP under the general conditions increased in all cases when poly(alkylene sulfide)s were used and the yield was highest for poly(alkylene sulfide)s containing at least one short spacer unit (*n* = 2 or 3 and *m* = 2-9). For example, poly(alkylene sulfide)s **1** and **20** (*n*, *m* = 2) provided the highest yields of 2,4-DCP (94.0 and 95.1%, respectively) with a 2,4-/2,6-DCP ratio of *ca.* 135 in each case. Even higher 2,4-/2,6-DCP ratios of over 300 were achieved when poly(alkylene sulfide)s **5** (*n* = 3, *m* = 9), **7** (*n* = *m* = 4), or **22** (*m* = 4) were used under the standard conditions, but in these cases the second chlorination step was slow and there were substantial quantities of 4-CP remaining, so that the actual yields of 2,4-DCP were not particularly high. The highest ratio (349.5) was with polymer **5**, so in this case a period at higher temperature (55°C) and/or addition of extra sulfuryl chloride were used to try to increase the yield of

2,4-DCP. Indeed, the yield of 2,4-DCP increased from 69.9 to 89.2% when the standard mixture was stirred at 55°C for 1 h before work-up. The 2,4-DCP yield increased further (to 93.3–96.6%), with little change in the 2,4-/2,6-ratio, when more sulfuryl chloride was used and the reaction mixture was stirred at 55°C for 1 h before work-up. The highest yield of 2,4-DCP was 97.1%, achieved when the amount of SO₂Cl₂ was 215 mmol for 100 mmol of P and the reaction was heated at 55°C for 1 h before work-up, but it is not clear why in this case the selectivity was lower (possibly poorer temperature control). Increasing the reaction time in the double chlorination of P at RT showed little significant effect on the yield of 2,4-DCP.

Clearly, polymer **5** was the most efficient catalyst in both monochlorination and double chlorination of phenol in terms of *para*-selectivity and yields of 4-CP and 2,4-DCP, respectively. The best 4-CP/2-CP ratio obtained from monochlorination of phenol was *ca.* 20 (Table 3), while, the 2,4-DCP/2,6-DCP ratio obtained from double chlorination of phenol was *ca.* 320, when polymer **5** was used. Therefore, this catalyst provides a *ca.* 16-fold increase in *para*-selectivity during the second chlorination step.

3. Conclusion

Highly *para*-regioselective chlorination systems for the chlorination of phenol and 2-chlorophenol have been developed. The systems consist of a poly(alkylene sulfide), aluminum chloride and sulfuryl chloride. Such systems provide high yields of the *para*-chlorinated phenols compared with those obtained in the absence of a poly(alkylene sulfide). The length of the spacer units (number of methylene groups) within the poly(alkylene sulfide) was found to be important for the regioselectivity of the chlorination reactions. High yields of the corresponding *para*-chlorinated phenols were obtained when at least one of the spacer units in the poly(alkylene sulfide) was short (2-4 methylene groups long). By use of one such poly(alkylene sulfide) it was possible to achieve direct double chlorination of phenol to give over 96% of 2,4-dichlorophenol with a 2,4-/2,6-DCP ratio of over 300. The polymers are odorless, used at a low concentration, and can be recycled and reused at a commercial scale; therefore, such catalysts have potential for industrial use.

4. Experimental section

4.1. General

Chemicals and reagents were purchased from Aldrich Chemical Company. Sulfuryl chloride was freshly distilled under nitrogen. The GC analyses were performed on a Shimadzu GC-2014 Gas Chromatograph using a capillary ZB Carbowax column (30 m, 0.32 mm ID) and tetradecane was added as a standard. The column temperature was adjusted at 40°C for 3 min, ramped to 220°C (10°C/min) and held for 10 min. The injector and detector temperatures were 300 and 250°C, respectively.

4.2. Synthesis of poly(alkylene sulfide)s

4.2.1. Alkanedithiol method (Scheme 1)

A solution of *n*-butyllithium in hexane (24.00 ml, 2.5 M, 60.00 mmol) was added over 10 min to a stirred solution (–78°C) of the appropriate alkanedithiol (30.00 mmol) in

dry THF (40 ml) under nitrogen. The mixture was stirred for 30 min at -78°C and then allowed to warm to room temperature. The appropriate dibromoalkane (27.00 mmol) was added and the mixture was stirred at room temperature for 60 min. 1-Bromobutane (0.82 g, 6.00 mmol) was added and the mixture was stirred for 18 h at room temperature. The white solid obtained was collected by filtration, washed successively with water (3×25 ml), and dried at 50°C under reduced pressure to give a white solid. The melting points of the solids were recorded (see Table 1) and their proton NMR spectra were recorded in order to confirm the general nature of the polymers.

4.2.2. Sodium sulfide method (Schemes 2 and 3)

A mixture of an appropriate dibromoalkane (or an equimolar mixture of two dibromoalkanes; 3.00 mol in total) and sodium sulfide nonahydrate (1000 g, 4.17 mol) were placed in a round bottom flask (3 l) equipped with a magnetic bar and a water condenser. The mixture was heated under reflux for 4 h with vigorous stirring, by which time a very viscous material resulted. The mixture was poured into a clean beaker and cold water (350 ml) was added slowly with stirring, and the mixture was left to cool. The solid obtained was collected by filtration, washed thoroughly with water (3×200 ml), and dried at 50°C under reduced pressure to give a white solid. Again, melting points of the solids were recorded (see Table 2) and their proton NMR spectra were recorded.

4.3. Chlorination of phenol

To a stirred mixture of melted phenol (9.41 g, 0.10 mol), AlCl_3 (100 mg) and the appropriate poly(alkylene sulfide) (100 mg), SO_2Cl_2 (8.90 ml, 0.11 mmol) was slowly added over 2 h at room temperature (RT). The mixture was stirred at RT for 2 h and then quenched with water (20 ml). The products were extracted using Et_2O (3×30 ml) and the combined solution was dried over MgSO_4 . The drying reagent was removed by filtration and the solvent was removed under reduced pressure until the weight was constant. A weighed aliquot of the products and a known quantity of tetradecane were used for the GC analysis. In some cases (see results and discussion) the mixture was warmed to 55°C for 1 h prior to work up or extra SO_2Cl_2 was used in the reaction.

4.4. Chlorination of 2-chlorophenol

The procedure was identical to that used for phenol, but 2-chlorophenol (12.86 g, 0.10 mol) was used instead of phenol.

4.5. Double chlorination of phenol

The procedure was identical with that used for phenol except that SO_2Cl_2 (17.00 ml, 0.21 mmol) was used instead of 8.90 ml.

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Disclosure statement

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