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Short communication

Halogenated macroporous sulfonic resins as efficient catalysts for the Biginelli reaction

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ABSTRACT

A series of halogenated macroporous sulfonic resins A-15-Cl, A-15-Br and A-15-I were synthesized from the precursor Amberlyst 15 by a typical halogenation reaction, and they were evaluated for the catalytic activities of the halogenated macroporous sulfonic resins via the Biginelli reaction in detail. These modified resins possessed a larger contact angle of water droplet than the precursor and a significantly improved thermal stability, which contributed to their higher catalytic activity. In particular, the resin A-15-Br containing 31.27% bromine exhibited the best catalytic activity and excellent recyclability.

1. Introduction

Macroporous sulfonic resins are extensively used as catalysts in various chemical reactions because of their high catalytic activity, low toxicity, low cost and easy separation from the reaction system [1–4]. In general, they are sulfonated from the macroporous poly (styrene-co-divinylbenzene) using concentrated sulfuric acid as the sulfonating agent [5–8]. These resins can also be used as catalysts in aqueous or nonaqueous medium, where the catalytic mechanisms differ considerably [9,10]. In an aqueous medium, sulfonic groups of these resins are completely dissociated as sulfonate anions and protons, where the latter serve as active sites for the catalytic reaction. In a nonaqueous medium, several clusters are fabricated by intermolecular hydrogen bonds between the sulfonic groups on the polymer chains. Moreover, the clusters have a higher catalytic activity and better catalytic stability than the individual sulfonic groups because of the direct contact with the clusters due to the adsorption effect [11]. Of course, water is formed as the by-product for some special dehydration reactions such as condensation reaction, which not only affects chemical equilibrium of the reaction, but also causes damage to the sulfonic clusters in the polymer chains, thereby decreasing the catalytic performance of the sulfonic resins.

Recently, Stoerzinger et al. [12] have reported that intrinsic hydrophobicity of the catalysts should be considered in the design of highly active catalysts. They utilized the flexibility of the perovskite surface chemistry to show that the tendency of the perovskite surface toward hydroxylation was propitious to wetting and adverse to catalysis. Halogens are proved to be the feasible hydrophobic groups for increasing the hydrophobicity of the sulfonic resins [13], and the hydrophobic interaction of the gel cavities in the sulfonic resins may be enhanced as some special halogenated groups are introduced in the polymer chains. In particular, the sulfonic clusters are more stable because of the inductive effect of halogenated groups, which enhances the catalytic performance of the sulfonic resins.

In this study, the precursor Amberlyst 15 was halogenated by different compounds (Cl_2, Br_2, and I_2), and a series of halogenated macroporous sulfonic resins A-15-X (X = Cl, Br, or I) was synthesized. The Biginelli reaction was then selected as a model reaction to evaluate the catalytic performance of the halogenated macroporous sulfonic resins. The Biginelli reaction is well known for the synthesis of dihydropyrimidinones (DHPMs) [14–16]. It generally involves one-pot condensation of an aldehyde, β-diketonate, urea, or thiourea using catalysts [17–22], and water is produced as the by-product in this reaction. It is found that the Biginelli reaction catalyzed by sulfonic resins produces a relatively low yield, and the catalyst exhibits poor recyclability [23–25].

2. Experimental

2.1. Materials

Amberlyst 15 was supplied by Rohm and Haas Shanghai Chemical Industry Co., Ltd. and all other reagents were purchased from Aladdin Reagent Co., Ltd. (Shanghai), and used as received. Nitrogen adsorption experiments were conducted using a TriStar 3000 surface area and porosity analyzer. A TX 500 H spinning drop interfacial tensiometer was used to measure the contact angle of water in air on the surface of the sample.

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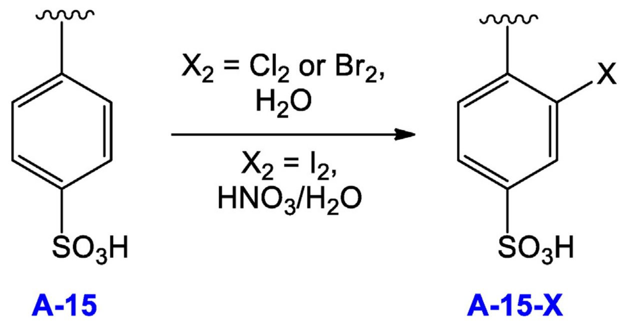


Scheme 1. Synthetic procedure for producing A-15-X.

2.2. Halogenation of Amberlyst 15

As shown in Scheme 1, the synthetic procedure for producing A-15-X was performed according to the method described in Refs. [26,27]. Amberlyst 15 (50 g) and water (80 mL) were placed in an agitated reaction vessel. Halogen (30 g) was mixed with the agitated suspension of the resins and the mixture was heated to 50 °C shielded from light and agitated at this temperature for different reaction times. The solid product was filtered and washed by a large amount of distilled water.

3. Results and discussion

3.1. Halogenation of Amberlyst 15

It is well known that halogenation of Amberlyst 15 follows the typical electrophilic substitution mechanism, which was similar to the halogenation of aromatic compounds such as benzene and toluene [28,29]. Furthermore, the halogen content of the modified resins (A-15-Cl and A-15-Br) was very low. It is interesting to observe that the synthesis of A-15-Cl and A-15-Br was successful in aqueous medium, and the electrophile X^+ can be easily formed and has a small ion radius. Furthermore, the sulfonic groups dissociate as sulfonate anions and protons, which have a smaller hindrance for X^+. However, synthesis of A-15-I requires an acidic oxidizing reagent, such as nitric acid, because of the chemical inertness of iodine.

3.2. Performance analysis of the catalysts

The halogen content (W_X), mass exchange capacity (Q_m), volume exchange capacity (Q_v) of the resins were measured using procedures reported in Refs. [30,31], whose results are summarized in Table 1. It is found that the exchange capacity of the halogenated resins is decreased after introduction of halogens in the benzene ring of the polymer chains. This might be attributed to the following two reasons: (1) the mass increase of the modified resins after introduction of the halogenated groups and (2) the hydrolysis of the sulfonic groups in the acidic aqueous solution. In addition, it is observed that the BET surface area, pore volume, and average pore size of the modified resins are similar to those of the precursor, implying that halogenation reaction has almost no effect on pore structure. Although the BET surface area and pore volume decreased slightly, theoretically, they increased in the absence of the mass of halogen, which may be attributed to the hydrophilicity and hydrophobicity of the halogenated sulfonic resins.

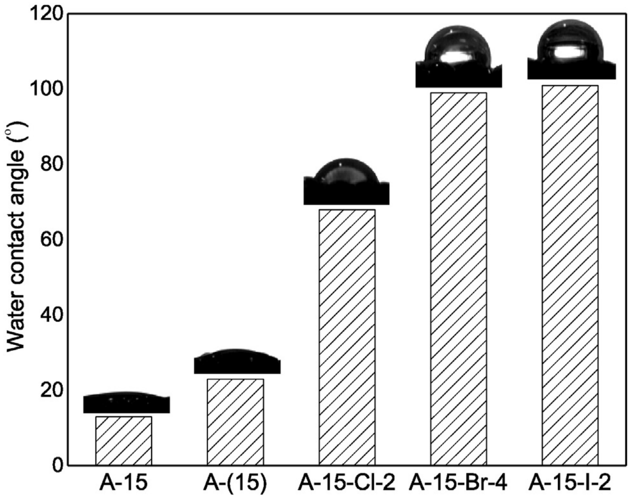


Fig. 1. Water droplet contact angle on Amberlyst 15, A-(15), and A-15-X.

After introduction of halogens on the surface of the sulfonic resins, a small amount of sulfonic groups will be removed during the halogenation reaction, and hence the hydrophilicity and hydrophobicity of the modified sulfonic resins would be slightly changed. Therefore, a sulfonic resin with a smaller cation exchange capacity, A-(15) (Q_v = 1.02 mmol/mL), was prepared by the desulfonation of Amberlyst 15. Moreover, the number of halogenated and sulfonic groups is shown to be the primary deciding factor of the hydrophilicity and hydrophobicity of sulfonic resins. Hence, halogenated resins having a similar molar ratio (~1.6: 1) of halogenated groups to sulfonic groups were chosen as the samples to measure the contact angle of water droplet. Fig. 1 shows the results of Amberlyst 15, A-(15), A-15-Cl-2, A-15-Br-4, and A-15-I-2 samples, respectively. It is evident from the figure that A-15-Cl-2, A-15-Br-4, and A-15-I-2 have higher contact angles, indicating their increased hydrophobic surface. As a result, hydrophobicity of the macroporous sulfonic resins was enhanced by the introduction of

Table 1
Characteristics of the sulfonic resins.

Sample	Time (h)	Cation exchange capacity		Halogen content (%)	$n_{(-X)}$: $n_{(-SO3H)}$ [a]	BET surface area (m^2/g)	Pore volume (cm^3/g)	Average pore size (nm)
		Q_m (mmol/g)	Q_v (mmol/mL)					
A-15	0	4.30	1.50	0	–	38.5	0.246	25.7
A-15-Br-1	2	3.58	1.39	10.03	0.35: 1	–	–	–
A-15-Br-2	8	3.13	1.35	16.20	0.65: 1	–	–	–
A-15-Br-3	24	2.72	1.12	26.79	1.23: 1	–	–	–
A-15-Br-4	36	2.45	1.08	31.27	1.60: 1	34.5	0.208	24.1
A-15-Br-5	48	2.32	0.98	34.94	1.88: 1	–	–	–
A-15-Br-6	72	1.97	0.64	38.98	2.47: 1	–	–	–
A-15-Cl-1	2	3.41	1.30	11.35	0.93: 1	–	–	–
A-15-Cl-2	6	3.10	0.95	17.90	1.63: 1	37.7	0.218	23.2
A-15-Cl-3	12	2.98	0.88	21.50	2.03: 1	–	–	–
A-15-I-1	48	2.35	1.20	30.58	1.02: 1	–	–	–
A-15-I-2	72	1.91	0.94	39.69	1.63: 1	29.4	0.183	24.8
A-15-I-3	96	1.73	0.72	42.36	1.93: 1	–	–	–

[a] Molar ratio of halogenated groups to sulfonic groups.

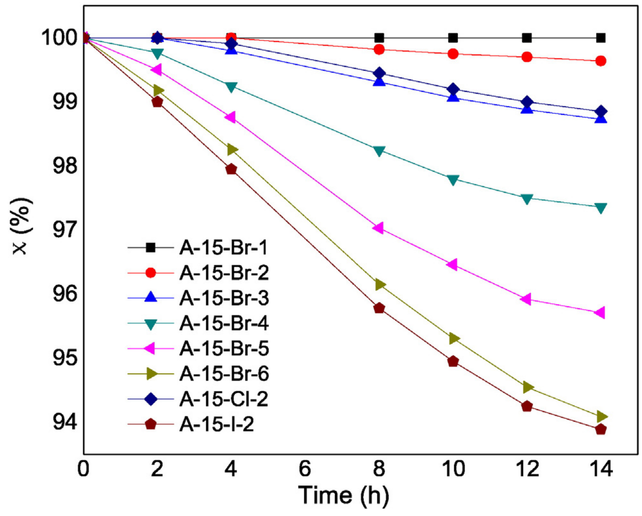


Fig. 2. Ratios (χ) of the halogen content at different heating times.

halogen in the polymer chains, and A-15-Br-4 and A-15-I-2 showed similar hydrophobicities.

The dehalogenating and desulfonating tendencies of A-15-Cl, A-15-Br, and A-15-I were measured under a pressure of approximately 8 atm and temperature of 170 °C in water, and the effect of heating time on the ratios (χ) of the halogen content after heating to the original content was studied and the results are shown in Fig. 2. It is obvious that the C–X bond has excellent stability for all halogenated resins. In addition, it is clear that a lower bromine content of the modified resin is more stabile, which may relate to the distribution of brominated groups. With an increase of bromine content, the brominated groups that are distributed close to the particle surface can be removed easily.

Fig. 3 presents the ratios (ψ) of the cation exchange capacity after heating to the original content in the resins at different time points. Notably, A-15-X possesses a higher thermal stability than the precursor Amberlyst 15. Moreover, it is clear that the stability of the sulfonic groups is significantly improved with the increase of bromine content, and A-15-Br with a bromine content of 31.27% shows the best thermal stability. However, its thermal stability shows a downward trend as the resins continue to be brominated, because debromination of the resins increases acidity of water, which promoted desulfonation of the resin via an aromatic electrophilic substitution reaction.

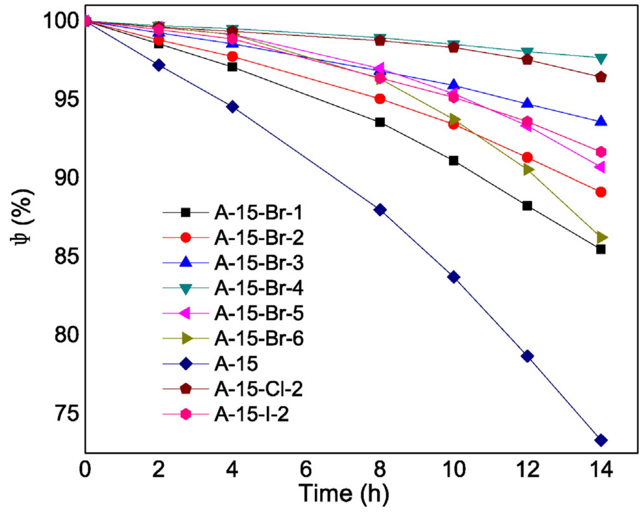
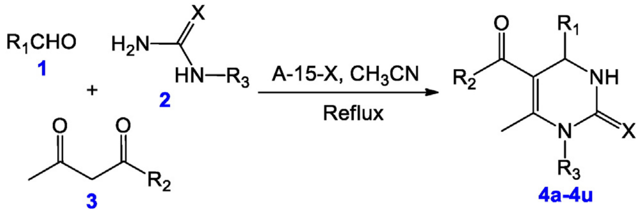


Fig. 3. Ratios (ψ) of the cation exchange capacities at different heating times.



Scheme 2. Synthesis of DHPMs catalyzed by A-15-X.

3.3. Catalytic activity of the catalysts toward the Biginelli reaction

The Biginelli reaction was chosen as a model reaction to test the catalytic activity of A-15-X. In order to evaluate the catalytic effect of various sulfonic resins, we used A-15-X (0.5 mmol of acid sites) to catalyze the model reaction of benzaldehyde (5.0 mmol), ethylacetoacetate (5.0 mmol), and urea (5.0 mmol) in refluxing acetonitrile to afford compound **4b** (Scheme 2).

It can be observed from Table 2 that A-15-Br containing 31.27% bromine shows an excellent catalytic performance, and as bromine content increases further, the yield of compound **4b** has no obvious change. The catalytic activity of the modified resins is better than that of the precursor and follows the order: A-15-Br > A-15-Cl ≈ A-15-I > Amberlyst 15. With regard to the inductive effect of chlorinated groups [32,33], A-15-Cl should display the best catalytic performance; by contrast, it is not as good as that of A-15-Br, which might be attributed to the fact that poor hydrophobicity of chlorinated groups cannot obviously improve catalytic activity of A-15-Cl. In addition, hydrophobicity of iodinated groups is excellent, whereas electronegativity of iodine is low.

We extended our study to different combinations of β-diketonates, aldehydes, and ureas or thioureas, whose results are summarized in Table 3. It is evident from the table that several β-diketonates reacted very well and had no noticeable effect on the reaction, and a variety of substituted aldehydes reacted in the presence of A-15-Br-4. Although the reaction proceeded smoothly to produce the corresponding DHPMs with moderate yields, there were some differences between these reactions. Aromatic aldehydes carrying electron-donating substituents, on the whole, reacted better than those carrying electron-withdrawing substituents (Table 3, entries 6 and 9–17). Unfortunately, steric hindrance was unfavorable for the process (Table 3, entries 7, 8, 11, and 15). A-15-Br-4 exhibited a general catalytic effect where the reactions involved aliphatic aldehydes (Table 3, entries 18 and 19). In addition, ureas reacted better than thioureas, particularly methyl substituted urea (Table 3, entries 20 and 21).

Table 2
Catalytic activity of different resins for the synthesis of compound **4b**.

Entry	Catalyst	Amount of catalyst [a] (g)	Time (h)	Yield [b] (%)
1	A-15-Br-1	0.14	2	77
2	A-15-Br-2	0.16	2	82
3	A-15-Br-3	0.18	2	88
4	A-15-Br-4	0.20	2	92
5	A-15-Br-5	0.22	2	93
6	A-15-Br-6	0.25	2	92
7	A-15	0.12	2	57
8	A-15-Cl-1	0.15	2	63
9	A-15-Cl-2	0.17	2	77
10	A-15-Cl-3	0.18	2	79
11	A-15-I-1	0.21	2	66
12	A-15-I-2	0.26	2	75
13	A-15-I-3	0.29	2	73

[a] Concentration of acid sites in all resins was 0.5 mmol.
[b] Isolated yields.

Table 3
A-15-Br-4 resin-catalyzed synthesis of compound **4b**.

Entry	R_1	R_2	R_3	X	Product	Time (h)	Yield [a] (%)
1	Ph	OMe	H	O	4a	2	90
2	Ph	OEt	H	O	4b	2	92
3	Ph	O-i-Pr	H	O	4c	2.5	90
4	Ph	O-t-Bu	H	O	4d	2.5	89
5	Ph	Me	H	O	4e	2	85
6	4-OMe-Ph	OEt	H	O	4f	2.5	88
7	4-OH-3-OMe-Ph	OEt	H	O	4g	3	85
8	3,4,5-triOMe-Ph	OEt	H	O	4h	5	80
9	4-Me-Ph	OEt	H	O	4i	2	90
10	4-Cl-Ph	OEt	H	O	4j	2	90
11	2-Cl-Ph	OEt	H	O	4k	2	83
12	4-F-Ph	OEt	H	O	4l	2	88
13	3-NO_2-Ph	OEt	H	O	4m	2	82
14	4-NO_2-Ph	OEt	H	O	4n	2	82
15	2-OH-Ph	OEt	H	O	4o	3	83
16	3-OH-Ph	OEt	H	O	4p	2.5	95
17	4-OH-Ph	OEt	H	O	4q	2.5	90
18	Me	OEt	H	O	4r	4	78
19	Et	OEt	H	O	4s	4	80
20	Ph	OEt	H	S	4t	3.5	83
21	Ph	OEt	Me	O	4u	1	98

[a] Isolated yields.

Table 4
Recycling of the catalyst used for the synthesis of compound **4b**.

Cycles	Time (h)	Yield [a] (%)	Catalyst recovered (%)	Cation exchange capacities Q_m (mmol/g)	Bromine content (%)
Native	2	92	99	2.45	31.27
1	2	92	98	–	–
2	2	90	97	–	–
3	2	89	95	–	–
4	2	88	92	2.32	31.12

[a] Isolated yields.

3.4. Reusability of the catalysts

After the reaction, the catalysts were filtered, washed by ethanol and dried under reduced pressure. They were reused without any further activation. The reaction proceeded in four cycles, whose results are shown in Table 4. The results presented in the table indicated that the reaction proceeded smoothly after four cycles, and no extension of reaction time or marked loss in yield was observed. There was also no appreciable loss of bromine content in the catalyst and cation exchange capacity.

4. Conclusions

A series of halogenated macroporous sulfonic resins were developed by the reaction of Amberlyst 15 with chlorine, bromine, and iodine, and they were used as catalysts for the Biginelli reaction. Their thermal stability and catalytic activity were much improved because of the positive inductive effect and hydrophobicity of the halogenated groups, among which A-15-Br containing 31.27% bromine showed the best catalytic activity, and its recyclability was excellent after four cycles.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.catcom.2016.01.010.

References

[1] G. Gelbard, Organic synthesis by catalysis with ion-exchange resins, Ind. Eng. Chem. Res. 44 (2005) 8468–8498.
[2] P. Barbaro, F. Liguori, Ion exchange resins: catalyst recovery and recycle, Chem. Rev. 109 (2008) 515–529.
[3] S.D. Alexandratos, Ion-exchange resins: a retrospective from industrial and engineering chemistry research, Ind. Eng. Chem. Res. 48 (2009) 388–398.
[4] E.R. Sacia, M. Balakrishnan, A.T. Bell, Biomass conversion to diesel via the etherification of furanyl alcohols catalyzed by amberlyst-15, J. Catal. 313 (2014) 70–79.
[5] R. Arshady, Beaded polymer supports and gels: I. manufacturing techniques, J. Chromatogr. A 586 (1991) 181–197.
[6] X. Ling, H.B. Li, H.W. Zha, C.L. He, J.H. Huang, Polar-modified post-cross-linked polystyrene and its adsorption towards salicylic acid from aqueous solution, Chem. Eng. J. 286 (2016) 400–407.
[7] S. Durie, K. Jerabek, C. Mason, D.C. Sherrington, One-pot synthesis of branched poly(styrene-divinylbenzene) suspension polymerized resins, Macromolecules 35 (2002) 9665–9672.
[8] X.-W. Lang, W.-Z. Jia, Y.-N. Wang, Z.-R. Zhu, Novel fluorination of polystyrene sulfonic acid resin by CF_3SO_3H for high stability and strong acidity, Catal. Commun. 70 (2015) 58–61.
[9] B. Corain, M. Zecca, K. Jeřábek, Catalysis and polymer networks—the role of morphology and molecular accessibility, J. Mol. Catal. A Chem. 177 (2001) 3–20.
[10] M. Granollers, J.F. Izquierdo, F. Cunill, Effect of macroreticular acidic ion-exchange resins on 2-methyl-1-butene and 2-methyl-2-butene mixture oligomerization, Appl. Catal. A 435-436 (2012) 163–171.
[11] K. Jerabek, K. Setinek, Polymer matrix influence on ion exchange resin- catalyzed reactions, J. Mol. Catal. 39 (1987) 161–167.
[12] K.A. Stoerzinger, W.T. Hong, G. Azimi, L. Giordano, Y.-L. Lee, E.J. Crumlin, M.D. Biegalski, H. Bluhm, K.K. Varanasi, Y. Shao-Horn, Reactivity of perovskites with water: role of hydroxylation in wetting and implications for oxygen electrocatalysis, J. Phys. Chem. C 119 (2015) 18504–18512.
[13] N. Goudarzi, M. Goodarzi, Application of successive projections algorithm (SPA) as a variable selection in a QSPR study to predict the octanol/water partition coefficients (K_{ow}) of some halogenated organic compounds, Anal. Methods 2 (2010) 758–764.
[14] P. Biginelli, Aldehyde-urea derivatives of aceto- and oxaloacetic acids, Gazz. Chim. Ital. 23 (1893) 360–413.
[15] K.S. Atwal, G.C. Rovnyak, J. Schwartz, S. Moreland, A. Hedberg, J.Z. Gougoutas, M.F. Malley, D.M. Floyd, Dihydropyrimidine calcium channel blockers: 2-heterosubstituted 4-aryl-1,4-dihydro-6-methyl-5-pyrimidinecarboxylic acid esters as potent mimics of dihydropyridines, J. Med. Chem. 33 (1990) 1510–1515.
[16] C.O. Kappe, Biologically active dihydropyrimidones of the Biginelli-type — a literature survey, Eur. J. Med. Chem. 35 (2000) 1043–1052.
[17] C.O. Kappe, 100 years of the Biginelli dihydropyrimidine synthesis, Tetrahedron 49 (1993) 6937–6963.
[18] C.O. Kappe, Recent advances in the Biginelli dihydropyrimidine synthesis. New tricks from an old dog, Acc. Chem. Res. 33 (2000) 879–888.
[19] M.M. Amini, A. Shaabani, A. Bazgir, Tangstophosphoric acid ($H_3PW_{12}O_{40}$): an efficient and eco-friendly catalyst for the one-pot synthesis of dihydropyrimidin-2(1 H)-ones, Catal. Commun. 7 (2006) 843–847.
[20] Z.-J. Quan, Y.-X. Da, Z. Zhang, X.-C. Wang, PS-PEG-SO_3H as an efficient catalyst for 3,4-dihydropyrimidones via Biginelli reaction, Catal. Commun. 10 (2009) 1146–1148.
[21] F. Zamani, E. Izadi, Synthesis and characterization of sulfonated-phenylacetic acid coated Fe_3O_4 nanoparticles as a novel acid magnetic catalyst for Biginelli reaction, Catal. Commun. 42 (2013) 104–108.
[22] J.K. Joseph, S.L. Jain, B. Sain, Ion exchange resins as recyclable and heterogeneous solid acid catalysts for the Biginelli condensation: an improved protocol for the synthesis of 3,4-dihydropyrimidin-2-ones, J. Mol. Catal. A Chem. 247 (2006) 99–102.
[23] H.-X. Lin, Q.-J. Zhao, B. Xu, X.-H. Wang, A green synthesis of dihydropyrimidinones by Biginelli reaction over nafion-H catalyst, Chin. Chem. Lett. 18 (2007) 502–504.
[24] H. Chandak, N. Lad, P. Upare, Recyclable amberlyst-70 as a catalyst for **B**iginelli reaction: an efficient one-pot green protocol for the synthesis of 3,4-dihydropyrimidin-2(1 H)-ones, Catal. Lett. 131 (2009) 469–473.
[25] S.R. Jetti, D. Verma, S. Jain, An efficient one-pot green protocol for the synthesis of 5-unsubstituted 3,4-dihydropyrimidin-2(1 H)-ones using recyclable amberlyst 15 DRY as a heterogeneous catalyst via three-component Biginelli-like reaction, ISRN Org. Chem. 2012 (2012) 8.
[26] V.J. Frilette, Sulfonated ion exchange resin having an electronegative NO_2 substituent, U. S. Patent 3, 256, 250. 1966.
[27] C.R. Costin, Thermally stable resins prepared by bromination or chlorination of aromatic polymer beads followed by sulphonation, U. S. Patent 4, 269, 943. 1981.
[28] P.B.D. De la Mare, Electrophilic Halogenation: Reaction Pathways Involving Attack by Electrophilic Halogens on Unsaturated Compounds, Cambridge University Press, New York, 1976.
[29] R. Taylor, Electrophilic Aromatic Substitution, John Wiley & Sons, New York, 1990.
[30] E.A. Burns, R.F. Muraca, Determination of small amounts of chloride by volhard titration: evaluation of operator determinate end-point error, Anal. Chim. Acta 23 (1960) 136–144.
[31] C.N. Rhodes, D.R. Brown, S. Plant, J.A. Dale, Sulphonated polystyrene resins: acidities and catalytic activities, React. Funct. Polym. 40 (1999) 187–193.
[32] I. Novak, B. Kovač, Halogens in competition: electronic structure of mixed dihalobenzenes, J. Phys. Chem. A 109 (2005) 3318–3324.
[33] C.-P. Ma, L. Yao, M.-F. Ge, Substituent effects of halopyridines, J. Mol. Struct. 881 (2008) 123–131.