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Novel iron and gallium salts of Aquivion[®] PFSA: Synthesis, characterization and some catalytic applications



Riccardo Tassini^a, Vikas D. Rathod^a, Stefano Paganelli^a, Eleonora Balliana^b, Oreste Piccolo^{c,*}

^a Dipartimento di Scienze Molecolari e Nanosistemi, Università Ca' Foscari Venezia, via Torino 155, 30170 Venezia Mestre, Italy

^b Dipartimento di Scienze Ambientali, Informatica e Statistica, Università Ca' Foscari Venezia, via Torino 155, 30170 Venezia Mestre, Italy

^c SCSOP, Via Bornò 5, 23896 Sirtori (LC), Italy

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ABSTRACT

The objective of this study was to prepare, characterize and test the catalytic properties of iron and gallium salts of Aquivion[®] PFSA (hereinafter Aquivion-H). The samples were characterized by the determination of metal loading in fresh and used materials, ATR-FTIR, and thermogravimetric analysis (TG-DSC). The salts were screened in Friedel–Crafts acylation of some heterocyclic compounds and compared with some homogeneous and heterogeneous Lewis acids as well as with pure Aquivion-H. These new salts revealed efficient catalytic activity and recyclability.

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1. Introduction

Lewis acid (LA) catalysed reactions are of great interest in organic synthesis [1]. A wide variety of these reactions have been developed and applied in the preparation of natural and unnatural compounds. However the use of traditional Lewis acid is often characterized by the high amount of waste formation and in certain cases by low reaction selectivity [2,3]. In order to improve these aspects, in 1991 the use of water-compatible lanthanide triflates, such as Lewis Acid, was described [4]. Since then, many triflates have been widely used. Unlike many traditional Lewis acids, these catalysts can be used in catalytic amounts in some reactions such as Friedel-Crafts acylation, and they can also work in organic solvents/water mixtures. Sometimes they can be recovered from the crude reaction mixture and reused. Despite these advantages, rare earth metals are expensive and for this reason other triflates have been investigated such as Zn, Fe, Ga and In triflates, as these metals are more commonly available and much cheaper than rare earth metals [4]. The use of functionalized polymers has also been extensively investigated both as Brønsted or Lewis acid catalysts [3,5,6]. Nafion[®] (hereinafter Nafion-H) is one of these polymers and was

E-mail address: orestepiccolo@tin.it (O. Piccolo).

http://dx.doi.org/10.1016/j.molcata.2015.10.033 1381-1169/© 2015 Elsevier B.V. All rights reserved. developed by W. Grot at DuPont in the 1960s. It is synthesized by the free radical copolymerization between tetrafluoroethylene and perfluorinated vinyl ether monomers [7]. The use of Nafion-H, as a Brønsted acid, and some salts (such as Nafion-Cr, -Ce or -Hg) are widely mentioned in the literature as catalysts for alkylation, acylation, nitration, sulfonation, polymerization, oxidation, hydration and other reactions [5,7–9]. The major drawbacks of this material is the very low surface area and the fact that its activity in nonswelling solvents can be very poor. This in turn has limited its application in Brønsted acid catalysed reactions. In order to increase the acid site accessibility, a class of solid acid catalysts, based on a high surface area, such as Nafion-H resin silica nanocomposites, has thus been developed, where nanometer sized Nafion-H resin particles are entrapped within a highly porous silica network [9-11]. The properties of other Nafion salts, such as Lewis acids, have been less investigated. It should thus be stressed that when these species are used, they are prepared by cation exchange from the corresponding Nafion-K salt; this procedure however forms aqueous salt wastes.

The preparation of Nafion-Fe [12] and Nafion-Ga [13] has recently been reported and these new species have been claimed to be efficient "green" Lewis acid catalysts in a Strecker reaction and in a Biginelli reaction, respectively. Also in these cases both catalysts were prepared by cation exchange reaction starting from Nafion-K and using FeBr₃ or GaCl₃ in non-environmentally friendly halogenated solvents at reflux. After the preparation, both catalysts were washed with the same solvents, and subsequently many times

^{*} Corresponding author at: Studio di Consulenza scientifica, Via Bornò 5, 23896 Sirtori (LC), Italy.

3 -RSO₃H + M
$$\xrightarrow{\text{MeCN}}$$
 -[RSO₃]₃M + 3/2 H₂
reflux, 48h

Scheme 1. Reaction between a metal and the sulfonic groups of Aquivion-H.

with water to remove soluble cations and anions. They were then washed with acetone to remove the excess water and finally dried at room temperature under vacuum for 16 h using a P_2O_5 trap.

In the present work, Aquivion-H, a perfluorinated ionomer commercialized by Solvay Specialty Polymers Italy S.p.A. (Fig. 1) [14] and currently used especially as a material for polymer electrolyte membranes, was used as the starting material for the preparation of some new Aquivion salt species, such as Aquivion-Fe and Aquivion-Ga. A simpler and more sustainable preparative approach was used, according to Scheme 1.

2. Experimental

2.1. Materials

2-Ethylthiophene, 5-bromoindole, propionic and acetic anhydride, acetyl chloride, gallium, iron, acetonitrile, deuterated chloroform, deuterated methanol, tin tetrachloride and silica were purchased from Aldrich and used without any treatment. *n*-Hexane and ethyl acetate were purchased from VWR and used without any treatment.

A powder sample of Aquivion-H (with a content of 1 equivalent of $-SO_3H$ group for about 870 g of polymer) was kindly provided by Solvay Specialty Polymers SpA. The same product is now available at Sigma–Aldrich as Aquivion[®] PW87S.

A pelletized sample of Nafion-H (with a content of 1 equivalent of $-SO_3H$ group for ≤ 1250 g of polymer) was purchased at Sigma Aldrich as Nafion[®] NR50 and used as such or after a freezing treatment with liquid nitrogen and manual crushing into smaller particles.

A sample of EPZG-10 was kindly provided by Contract Chemicals Ltd and activated before use following the supplier's instructions [15]. A sample of silica fume (4.18% of Zr) was kindly provided by Sunmix China and used without any treatment.

2.2. Analysis for Aquivion-H and Aquivion salts characterization

The determination of metal loading in fresh or used Aquivion-Fe and Aquivion-Ga was performed using ICP-OES (inductively coupled plasma optical emission spectrometry) by Solvay Specialty Polymers S.p.A. (Table 1).

The attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) spectra of these new species, as well as of Aquivion-H, were registered using a Thermo Nicolet FTIR NEXUS 750 instrument equipped with a Smart Endurance ATR diamond accessory, from 4000 to $400 \,\mathrm{cm^{-1}}$ and for 64 scans with a resolution of $4 \,\mathrm{cm^{-1}}$. Data were collected with Thermo Nicolet OMNIC 6.0a software and then elaborated with Origin 9 software (Fig. SM1, Supplementary material).

Thermogravimetry (TG) and differential scanning calorimetry (DSC) were performed simultaneously using a Netzsch 409/C apparatus. Data were collected with STA Netzsch software and then processed with Origin 9 software. The temperature program used was set up experimentally from 30 °C, 10 °C/min to 650 °C (660 °C). The instrument was purged with N₂ at a flow rate of 40 mL/min. The sample mass ranged around 16.21 \pm 0.56 mg; samples were massed in an aluminium crucible by the TG internal balance. Alumina was used for the internal calibration The thermograms obtained of these new species, as well as of Aquivion-H, are reported in Fig. 2. For comparison, the thermograms obtained of Nafion-Fe and Nafion-H are reported in supplementary material (Fig. SM2).

Microscopy images were registered using a Leitz Wetzlar microscope (10-40-100 magnification) (Figs. SM3–5, Supplementary material).

2.3. Instruments used in the Friedel–Crafts reaction analysis

GC analyses were performed on an Agilent Technologies 6850 series equipped with an HP-5 (Agilent) capillary column ($30 \text{ m} \times 0.32 \text{ mm} \times 0.25 \mu \text{m}$ film thickness) and flame ionizator detector (FID). Quantitative determinations were obtained using a calibration line using single standard solutions. GC–MS analyses were performed on a ThermoFinnigan (Trace CG 2000) equipped with an HP-5 capillary column ($30 \text{ m} \times 0.32 \text{ mm} \times 0.25 \mu \text{m}$ film thickness) and a quadrupole mass spectrometer (ThermoFinnigan Trace MS).



Fig. 1. Chemical structure of Aquivion-H and Nafion-H. (b) Schematic representation of an ionic cluster of Aquivion-Me⁺³.

Table 1

Metal content of fresh and used metallized Aquivion resins.

Sample	Theoretical metal loading (w/w%)	Found metal loading (w/w%)	Theoretical metal loading (mol/mol%)	Found metal loading (mol/mol%)	-SO3H exchanged (%)
Fresh Aquivion-Fe	2.140	2.053	33.33	32.01	96
Fresh Aquivion-Ga	2.670	3.033	33.33	37.85	114



Fig. 2. TG-DSC thermograms of Aquivion-H (a), Aquivion-Fe (b) and Aquivion-Ga (c).

¹H NMR spectra were recorded by Bruker Avance 300 operating at 300 MHz in deuterated chloroform or deuterated methanol.

2.4. Catalyst preparation: Aquivion-Fe and Aquivion-Ga

A total of 10g of Aquivion-H, 0.214g (3.8 mmol) of iron and 50 mL of acetonitrile were introduced into a 250 mL three-neck round bottom flask equipped with a mechanical stirrer and reflux condenser. The mixture was heated at reflux for 48 h. The acetonitrile was then removed under vacuum and the Aquivion-Fe was dried at 6 Pa. The recovered catalyst was ground on agate mortar to a yellow powder and stored in a bottle. Using the same procedure, but with 0.256 g (3.6 mmol) of gallium instead of iron, Aquivion-Ga was recovered as grey powder.

2.5. Catalyst activity test

2.5.1. Friedel–Crafts acylations of 2-ethyl-thiophene (I)

A total of 2 g (0.018 mol) of 2-ethyl-thiophene (I), 0.018 mol of acyl anhydride (acetic or propionic anhydride) and 1.57 g of Aquivion-Fe were introduced (substrate/catalyst 32/1 molar ratio) into a 50 mL two-neck round bottom flask equipped with a mag-

netic stirrer and a reflux condenser. The mixture was heated at 120 °C for 3 h, then the crude mixture was cooled, filtered on a sintered glass filter to recover the catalyst and distilled under vacuum at 6 Pa (b.p. 52 °C). The isolated yield of 5-acyl-2-ethyl-thiophene was 70–75 %.

GC–MS *m*/*z* of 2-acetyl-5-ethyl-thiophene (**II**): 154 [M]⁺; 139 [M-CH₃]⁺; 111 [M-CH₃CO]⁺.

¹H NMR (CDCl₃) of 2-acetyl-5-ethylthiophene (**II**), δ (ppm): 7.53 (d, 1H, CH arom, *J* = 3.77 Hz); 6.85 (d, 1H, CH arom, *J* = 3.77 Hz); 2.89 (q, 2H, CH₂, *J* = 7.38 Hz); 2.,52 (s, 3H, CH₃-CO); 1.34 (t, 3H, CH₃-CH₂, *J* = 7.68 Hz).

GC–MS m/z of 2-propionyl-5-ethyl-thiophene (III): 168 [M]⁺; 139 [M-CH₃CH₂]⁺; 111 [M-COCH₂CH₃]⁺.

¹H NMR (CDCl₃), of 2-propionyl-5-ethylthiophene (**III**), δ (ppm): 7.58 (d, 1H, CH arom, J = 3.77 Hz); 6.82 (d, 1H, CH arom, J = 3.77 Hz); 2.90 (m, 4H, CH₂-CH₃ and CH₃-CH₂-CO); 1.35 (t, 3H, CH₃- CH₂, J = 7.68); 1.25 (t, 3H, CH₃-CH₂-CO, J = 7.32 Hz).

The catalyst Aquivion-Fe recovered was re-used without any treatment, for three times, by adopting the above procedure (Table 2).

Adopting the same procedure reported above, the reaction was also performed with Aquivion-Ga and Aquivion-H as well as with R. Tassini et al. / Journal of Molecular Catalysis A: Chemical 411 (2016) 257-263



Scheme 2. Acylation of 2-ethyl-thiophene (I) and 5-bromo-indole (IV) with acyl anhydrides in the presence of Aquivion-Fe or Aquivion-Ga.

Synthesis of 2-acyl-5-ethyl-thiophenes.					
Run	Catalyst/solvent	R	<i>T</i> (°C)	% analytical yield (isolated yield) Product ^a	
1	Aquivion-Fe/neat	Me	120	(75%) II	
2	Aquivion-Fe/neat	Et	120	>99 % (75%) III	
3	Aquivion-Fe ^b /neat	Et	120	(75%) III	
4	Aquivion-Fe ^b /neat	Et	120	(70%) III	
5	Aquivion-Fe ^b /neat	Et	120	(66%) III	
6	Aquivion-Fe ^c /neat	Et	120	>99 % (75%) III	
7	Aquivion-Ga/neat	Et	120	>99% (72%) III	
8	Aquivion-Ga ^b /neat	Et	120	97% (70%) III	
9	Aquivion-H/neat	Et	120	(30%) III ^d	
10	SnCl ₄ /CH ₂ Cl ₂ ^e	Et	25	>99% (80%) III	
11	EPZG-10 ^{fg} /neat	Et	120	>99%(75 %) III ^h	
12 ⁱ	Aquivion-Fe/neat	Et	120	>99 % (85%) III	

^a <1% of 3-acylated derivative was formed, if not otherwise indicated.

^b Catalyst recovered from the previous run and used as such.

^c Using 0.157 g of this catalyst instead of 1.57 g used in run2.

^d Formation of oligomeric thiophene derivatives.

^e Reaction conditions: 1.12 g (0.01 mol) of I, 1.44 mL (0.012 mol) of SnCl₄, 0.87 mL (0.01 mol) of propionyl chloride in 20 mL of CH₂Cl₂ at room temperature for 2 h and then usual work-up with water, extraction and distillation.

^f 1.12 g (0.01 mol) of I, 1.28 mL (0.01 mol) of propionic anhydride and 0.112 g of activated EPZG-10 catalyst at 120 °C for 4 h and then, after filtration of the catalyst, distillation.

^g Catalyst activated before use by treatment with toluene to remove water azeotropically and then dried under vacuum.

^h About 7% of 3-acylated derivative.

 $^{\rm i}\,$ Reaction performed on a larger scale compared to run 2, using 10 g of I instead of 2 g.

a lower amount of Aquivion-Fe. The results obtained are reported in Table 2. Comparison experiments with SnCl₄ and with WPZG-10 were also carried out, using the experimental conditions reported in the footnotes in Table 2. In all experiments the starting material I was <1%.

2.5.2. Friedel-Crafts acylation of 5-bromo-indole (IV)

A total of 2.2 g (11.2 mmol) of 5-bromo-indole (IV), 4.6 g (45.2 mmol) of acetic anhydride and 98 mg of Aquivion-Ga were introduced (substrate/catalyst 100/1 molar ratio) into a 50 mL twoneck round bottom flask equipped with a magnetic stirrer and a reflux condenser. The mixture obtained was heated at 90 °C for 2 h. The reaction was monitored by GC and GC-MS until the starting material had been totally converted. The reaction mixture was then cooled to room temperature and filtered on a sintered glass filter. The catalyst was washed with diethyl ether to remove adsorbed products and acetic anhydride from the catalyst surface and finally dried under vacuum, ready for the recycle experiments. The filtrate was concentrated under vacuum to obtain the crude product as acetylated indole mixture (85% yield). A sample was purified by column chromatography using a mixture of n-hexane: ethyl acetate (80:20) as eluent to afford 1-(5-bromo-1H-indol-3-yl) ethanone (V) as a brownish solid.

GC–MS m/z of 1-(5-bromo-1H-indol-3-yl) ethanone (**V**): 237 [M]⁺; 222 [M -CH₃]⁺; 194 [M -CH₃CO]⁺; 169 [M -C₄H₄O]⁺.

¹H NMR (CD₃OD) δ (ppm) of 1-(5-bromo-1H-indol-3-yl) ethanone (**V**) 8.39 (s, 1H, CH arom), 8.19 (s, 1H, CH arom), 7.40-7.33 (dd, *J* = 13.5 Hz, 2H, CH arom), 2.52 (s, 3H, CH₃-CO).

Adopting the same procedure reported above, the reaction was also performed with Aquivion-Fe and Aquivion-H. The results obtained are reported in Table 3. in some experiments the reaction was also carried out with acetonitrile as diluent or using acetyl chloride as acylating reagent. Comparison experiments with Zirconia silica fume were also performed.

3. Results and discussion

Table 1 reports the experimental results of the metal content of fresh and used metallized resins. In the light of these values, preparation protocol developed here seems to be effective in quantitatively exchanging the sulfonic acid functions available in Aquivion-H. The slight differences from the 100% theoretical amount are probably due to the uncertainty of the actual amount of sulfonic groups or of the weight of metal used. The present procedure permits to obtain these Aquivion salts in a simple way, the reaction solvent can be easily recovered and the metallized poly-

Table 2

Table 3	
Synthesis of 3-acetyl-5-bromo-inde	ole

Run	Catalyst	Acylating agent ^a	$T(^{\circ}C)/t(h)$	Solvent ^a	Conv.[%]	V [%]	VI [%]	VII [%]
1	Aquivion-Ga	AA	90/2	AA	100	92	5	3
2	Aquivion-Ga ^b	AA	90/2	AA	100	92	5	3
3	Aquivion-Ga ^b	AA	90/2	AA	100	93	5	2
4	Aquivion-Ga ^b	AA	90/2	AA	92	92	4	4
5	Aquivion-Ga ^b	AA	90/2	AA	95	90	5	5
6	Aquivion-Ga ^c	AA	90/2	ACN	91	91	-	-
7	Aquivion-Ga ^c	AC	90/2	ACN	74	74	-	-
8	Aquivion-Ga ^c	AC	90/16	ACN	100	70	-	30
9	Aquivion-Fe	AA	90/2	AA	100	90	-	10
10	Aquivion-Fe ^b	AA	90/2	AA	100	94	4	2
11	Aquivion-Fe ^b	AA	90/2	AA	100	92	5	3
13	Aquivion-Fe ^b	AA	90 / 2	AA	99	92	5	2
14	Aquivion-Fe ^b	AA	90/2	AA	98	90	4	4
15	Aquivion-Fe ^c	AA	90/4	ACN	51	51	-	traces
16	Aquivion-H	AA	90/2	AA	91	73	5	13
17	Aquivion-H ^b	AA	90/2	AA	-	-	-	-
18	SiO ₂ /ZrO ₂ ^d	AA	90/2	AA	-	-	-	-
19	SiO ₂ /ZrO ₂ ^e	AC	90/22	ACN	20	20	-	-
20	Nafion-Fe ^f	AA	90/22	AA	99	92	4	3
21	Nafion-Fe ^g	AA	90/2	AA	100	88	5	7

^a AA = acetic anhydride, AC = acetyl chloride, ACN = acetonitrile.

^b Catalyst recovered from the previous run and used as such.

^c Reaction conditions: 2.22 g (0.011 mol) of **IV** in 3 mL of ACN and equimolar amount of acylating agent (AA or AC).

^d Reaction conditions: 2.22 g (0.011 mol) of **IV** in 3 mL of AA and 0.2 g of catalyst.

^e Reaction conditions: 2.22 g (0.011 mol) of **IV** in 3 mL of ACN and 0.89 g (0.011 mol) of AC and 0.2 g of catalyst.

^f Pelletized Nafion-Fe.

^g Coarse powder Nafion-Fe.

mer, after a rapid drying under vacuum, is ready for use as a Lewis catalyst. This protocol was also applied to prepare the corresponding Nafion salts. However, using commercial available pelletized Nafion-H, the reaction only led to a 28% transformation in the desired Nafion-Fe, as determined by the analysis, after many days and working also with a larger amount of acetonitrile. Conversely, after a freezing treatment with liquid nitrogen and manual crushing of commercial Nafion-H into a coarse powder, the reaction was successfully completed. The advantage of Aquivion-H compared to Nafion-H is that Aquivion-H is already sold as powder and does not require any difficult processing before use.

With ATR-FTIR useful information can be collected without any manipulation of the sample [16]; for this reason it was used for registering spectra of Aquivion-H and its salts (Fig. SM1 a–c, Supplementary material). The most interesting diagnostic zone seemed to be between 1800 cm⁻¹ and 1400 cm⁻¹, where the spectrum of Aquivion-H (a) presented a broad band centered at 1735 cm⁻¹ and both Aquivion-Fe and –Ga spectra (b and c respectively) had three peaks between 1660 and 1450 cm⁻¹. However, after treatment with acetonitrile at reflux temperature for 8 h, a sample of Aquivion-H powder was filtered with some difficulty (a film was formed instead of the starting powder), dried under vacuum and reanalyzed by ATR-FTIR; (Fig. SM1 d, supplementary material). In the spectrum obtained three peaks, instead of the previous broad band, were observed between 1800 cm⁻¹ and 1400 cm⁻¹.

One possible interpretation of this different result is that in spectrum (a) there were also bands due to a small amount of water originally present in Aquivion-H powder (signals could be attributed to the bending of -OH bond) and water was removed by treatment with acetonitrile. Thus no substantial difference was found between Aquivion-H and its salts with this technique.

Fig. 2 reports the TG-DSC curves of the Aquivion-H and its salts, obtained from 30 to $650 \,^{\circ}$ C under N₂ flow rate. All thermograms show three mass losses and a similar behaviour to Nafion-H and Nafion-Fe (Fig. SM2) and also in comparison with the literature [16,17]. The mass loss observed in the temperature range 180–300 $^{\circ}$ C may be related to the decomposition of $-SO_3$ groups, in

agreement with other studies [17]. This mass loss is clearly present in the TG-DSC Aquivion-H curve (Fig. 2a), however it is less evident for the Aquivion-Fe and Aquivion-Ga (Fig. 2b and c, respectively). Both the Aquivion salts seem to have a more stable temperature profile also in the range 300-400 °C with a minimum mass loss. This enhancement would enable both Aquivion salts to be also used in Lewis acid catalyzed gas phase reactions.

Finally, Aquivion-Fe and –Ga samples compared with Aquivion-H by optical microscopy show a nearly homogeneous distribution of metallic cationic species in the polymer, although the presence of small amounts of unreacted metallic particles cannot be ruled out (Figs. SM 3–5).

The application of these new Lewis acids in Friedel–Crafts acylation of two heterocylic compounds was studied (Scheme 2). A representation of mechanism of Friedel–Crafts acylation catalyzed by Aquivion-Fe is reported in Fig. 3.

Table 2 reports the results obtained in the acylation of the thiophene substrate I with Aquivion-H and its salts, compared with those found using the traditional Friedel-Crafts Lewis acid catalyst SnCl₄, used in stoichiometric amount, or a heterogeneous commercial acid catalyst EPZG-10, activated before use. If not otherwise indicated, the experimental conditions are those described in the experimental section. Two acylating agents and different kinds of catalysts were compared in this reaction. This application is interesting because it permits to obtain, in particular, 2-propionyl-5-ethyl-thiophene (III) which was originally prepared using EtCd and 5-ethyl-2-thiophenecarboxylic acid chloride [18]. This compound is a potential fragrance, with a pleasant anise olfactory note and a low odor threshold. Initially a general procedure described in the literature for thiophene acylation was followed [19] but carrying out the reaction at 25 °C in dichloromethane, instead of originally used CS₂ as solvent (Table 2, run 10). The catalyst, used in a stoichiometric amount, was SnCl₄ and the acylating agent was propionyl chloride. After 2 h, a quantitative conversion of the starting material into the desired product was observed and, after work-up, an 80 % yield of III was obtained (Table 2, run 10). This result is satisfactory but it should be underlined that the synthe-



Fig. 3. Schematic representation of mechanism of Friedel–Crafts acylation catalyzed by Aquivion-Fe.



Fig. 4. Progress of the acetylation reaction of IV with acetic anhydride used as acylating agent and solvent in presence of Aquivion-Ga.

sis was carried out in a non green solvent and, after the reaction, it was necessary to hydrolyse SnCl₄ thus producing waste. Consequently, EPZG-10, a heterogeneous acylating catalyst, was tested [20] (Table 2, run 11). This is a commercial catalyst produced by Contract Chemicals and is described as a zeolite doped with zinc salts, which has both Brønsted and Lewis acid characteristics [15]. The use of this catalyst enabled us to work without solvent and the reaction was carried out at 120°C for 4h using propionic anhydride as an acylating agent. The conversion obtained of the starting material I was quantitative but the formation of 7% of an isomeric by-product, probably 3-acyl derivative, was observed by GC-chromatography. In this procedure the work-up was very simple. After the reaction, the catalyst was filtered off and the solution was distilled under vacuum. The obtained isolated yield was 75%. However, the catalyst must be activated before use and before any recycling to remove traces of water that could affect its activity. Finally the use of Aquivion-Fe and Aquivion-Ga species was

checked. The acylation was carried out with acetic anhydride or propionic anhydride at 120 °C for 3 h without solvent. Irrespectively of the anhydride used, more or less the same yield was found (Table 2, runs 1 and 2) and no significant differences between the two catalysts were observed (Table 2, runs 2 and 7). Initially, a molar ratio substrate I/catalyst 32/1 (Table 2, run 2) was used but subsequently the ratio was increased to 320/1 (Table 2, run 6). In both cases the same result was obtained after 3 h of reaction. The use of a reduced amount of catalyst leads to a more sustainable procedure and a more efficient mixing. To emphasize this concept, it should be noted that when working with 2g of I and a 32/1substrate/catalyst ratio, a total of 1.57 g of Aquivion-Fe was used; whereas with a 320/1 ratio only 0.157 g of Aquivion-Fe was necessary. In all cases with the fresh catalyst, a quantitative conversion of starting material I after 3 h and a 72-85% isolated yield were observed, after distillation under vacuum, for II and III. All catalysts were ready for use after their preparation, because activation or other treatments were not required. After the reaction, the catalyst was recovered by filtration on a sintered glass filter and immediately reused. With Aquivion-Fe and Aquivion-Ga, catalyst recycling gave similar results to the use of fresh catalysts (Table 2 runs 2–5 or 7–8). After the first use, as reported in Table 1, the amount of iron in Aquivion-Fe was 1.952% w/w. The fresh Aquivion-Fe had 2.053% w/w metal loading, thus the catalyst was considered to be stable in these reaction conditions.

The acylation of **I** was also carried out with Aquivion-H. The reaction was performed at 120 °C for 3 h with a 10/1substrate **I**/-R(SO₃H) molar ratio, without solvent (Table 2, run 9). The acylating agent was propionic anhydride. After 3 h of reaction, the conversion of starting material **I** was quantitative but the isolated yield of desired product **III**, after distillation under vacuum, was only 30%. High-boiling by-products were found. In a further experiment, the substrate **I**/-R(SO₃H) ratio increased up to 50/1, but a high formation of high-boiling by-products was still observed. Under these experimental conditions, on this heterocycle substrate, these results show that the use of Aquivion salts as a catalyst is more efficient.

Thiophene substrate I and acylated products are liquid and thus it was possible to work under neat conditions. A more complex situation occurred using solid 5-bromo-indole (IV) (Table 3). If not otherwise indicated, the experimental conditions are those described in the experimental section. In these experiments an excess of acetyl anhydride, the acetylating agent, was used to also work as a solvent or, when an equimolar amount of acylating agent was utilized, the mixture was diluted with acetonitrile. Substrate/catalyst ratio with Aquivion salts or with Aquivion-H was always 100/1 and the principal product was 3-acetyl-5-bromoindole (V), as expected because the 3-position is the most reactive site for electrophilic attack [21,22]. Also in this reaction Aquivion salts work much better than Aquivion-H and are recyclable catalysts (Table 3 runs 1-5 and 9-14). In contrast, Aquivion-H was inactive in the recycle, probably because the acid sites were irreversibly coordinated by indole products or by-products. As expected the reaction rate was lower working with an equimolar amount of acetic anhydride in acetonitrile, but the selectivity was slightly better (Table 3 runs 1 vs 6 and 9 vs 15). Working under these conditions, Aquivion-Ga was more active than Aquivion-Fe and acetic anhydride is a more suitable acetylating agent than acetyl chloride (Table 3 runs 6 vs 7). Although zirconia silica fume is a very cheap catalyst, its activity in this reaction as a comparative example was null or very low. The results with Nafion-Fe clearly depend on the dimensions of the heterogeneous catalyst (Table 3 runs 8 vs 9). In any case, using our sustainable synthesis protocol, it is also possible to obtain an efficient Nafion based Lewis acid. Finally, a kinetic study was performed on the reaction catalysed by Aquivion-Ga in acetic anhydride used both as reagent and solvent (Fig. 4) in order to have a better idea of the selectivity of this reaction. Also at very low conversion, there were small amounts of 1-acetyl-5-bromo-indole (VI) and 1,3-diacetyl-5-bromo-indole (VII), but the amounts of these products also remained very low at the end of reaction although there was an excess of acylating reagent. One possible explanation of these results is, in our opinion, due to the steric hindrance of the catalyst structure which leads to a good regioselectivity, as in the above reported reaction with the thiophene derivative. It should also be underlined that with Aquivion-Ga or Aquivion-Fe no detectable amount of by-products due to self-polymerization of indole moiety was observed, unlike what is usually found with other Lewis acids [21,22 and references cited therein]. After purification by column chromatography, an isolated yield of about 85% of V was determined.

4. Conclusions

Our aim to prepare new and "green" heterogeneous Lewis acids, with a sustainable production protocol, was successful and could lead to a broader application in different reactions and uses for the production of fragrances, pharmaceuticals, agrochemicals and other fine chemicals. As Aquivion-Fe and Aquivion-Ga are reusable, environmentally friendly, highly effective and accessible catalysts, this could significantly contribute to cleaner and more sustainable synthetic processes. Their preparation is simpler than that starting from commercial Nafion-H. Specifically the performances of these catalysts in Friedel–Crafts acylation of electronrich heterocycles, working under solvent-free conditions or using acylating reagent also as solvent, permitted to obtain products of a high purity, good yield, simple work-up and with less waste.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.molcata.2015.10.033.

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