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Influence of oxygen functionalities on the environmental impact of imidazolium based ionic liquids

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ABSTRACT

Several physico-chemical properties relevant to determine the environmental impact of ionic liquids – aqueous solubility, octanol-water partition coefficient and diffusion coefficients in water at infinite dilution – together with toxicity and biodegradability of ionic liquids based on 1-alkyl-3-methylimidazolium cations with or without different oxygenated functional groups (hydroxyl, ester and ether) are studied in this work. The presence of oxygen groups on the imidazolium cation reduces the toxicity of ionic liquids 1-alkyl-3-methylimidazolium with bis(trifluoromethylsulfonyl)imide or octylsulfate anions and simultaneously decreases the value of their octanol–water partition coefficient. The presence of ester functions renders the ionic liquids more easily biodegradable, especially for long alkyl side-chains in the cation but leads to hydrolysis with the formation of reaction products that accumulate. The imidazolium ring is resistant to biodegradability and to abiotic degradation. The oxygen functionalised ionic liquids are more soluble in water and, diffuse more slowly in this medium.

1. Introduction

Because of their unique properties, ionic liquids (ILs) can be used in a variety of applications [1]. Their wide use at an industrial scale requires further information on their environmental fate, toxicity and impact on ecosystems and human health. Although their negligible vapour pressure minimises their diffusion into the atmosphere, their presence in the environment may become a reality, for example in the case of accidental release or at the end of their life cycle.

The few published studies on the environment impact of ILs have enhanced the poor biodegradability of those based on the 1-alkyl-3-methylimidazolium cation [2], the most commonly used at present. Toxicological studies have also shown that imidazolium based ILs with alkyl chains longer than C6, for example 1-decyl-3-methylimidazolium tetrafluoroborate [C_{10}mIm][BF_4], and 1-methyl-3-tetradecylimidazolium chloride [C_{14}mIm][Cl], present high levels of toxicity to microorganisms, avoiding their biodegradation in the environment [3,4]. The experimental study of Deng et al. [5] showed that for the case of imidazolium based ILs, the introduction of ester groups does not significantly affect physico-chemical properties as the density or the solubility of gases like carbon dioxide. Furthermore, Pensado et al. [6] used molecular simulation and showed that the molecular properties of the functionalised ionic liquids do not differ significantly from those of the non-functionalised ones, although the molecular structure is slightly different with altered relative sizes of the polar and non-polar domains in the ILs [7].

The development of new ILs with low environmental impact (easily biodegradable, non-toxic, with low bioaccumulation levels) seems to be one of the requirements for their more frequently use. Several strategies have been developed to design ILs combining environmental scale requirements and human health security without loosing the chemical performance. Biodegradability has been improved by modifying the chemical structures of the cation (imidazolium, pyridinium, ammonium families) and/or anion as in the work of Gathergood et al. [8,9] with the addition of ester or ether groups to the alkyl side chains of 1-alkyl-3-methylimidazolium based ILs. The nature of the anion appears also as fundamental: the first 'ready biodegradable' IL was prepared using n-octyl sulfate as anion [10].

The criteria to assess biodegradability are often based on parameters like the dissolved organic carbon (DOC), the carbon dioxide production or the oxygen uptake by a mixed microbial population issued from a wastewater treatment plant as recommended

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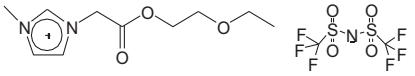
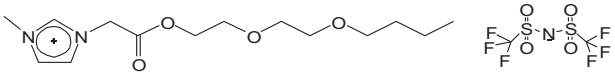
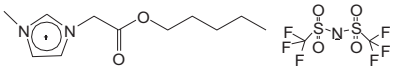
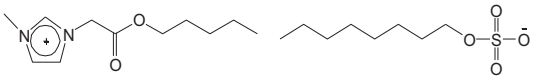
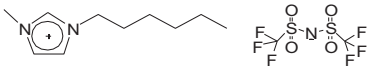
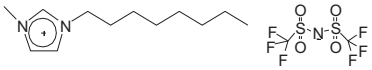
Table 1
Abbreviations, structures and molecular weights (M_w) of the studied ILs.

Abbreviation	Structure	M_w/g mol^{-1}
[$C_1COOC_2OC_2mIm$][Tf_2N]		493
[$C_1COOC_2OC_2OC_4mIm$][Tf_2N]		566
[C_1COOC_5mIm][Tf_2N]		491
[C_1COOC_5mIm][C_8SO_4]		421
[C_6mIm][Tf_2N]		447
[C_8mIm][Tf_2N]		475

by several OECD guidelines [11]. These parameters are followed at regular intervals during a pre-determined period of time and define the biodegradation of the ILs. For example, they are considered as 'readily biodegradable' if the biodegradation level is higher than 60% within 28 days. Except in the case of complete mineralisation, metabolism can lead to the formation of transformation products more toxic, more persistent and/or more hazardous than the starting material, a fact that is not taken into account in the tests recommended by OECD. This is one of the reasons why detailed investigations on biodegradation pathways of ILs are crucial. The identification of the chemical structures of the transformation products formed as well as the monitoring of IL disappearance kinetics are necessary for a better understanding of the potential environmental behaviour of ILs and their global impact. The toxicity of these compounds, if identified, can therefore be also tested. This approach has been investigated in a few other studies using mainly activated sludge microbial community and NMR or GC–MS as analytical tools [2,12–16]. Under these conditions, the difficulty is to know which microorganism is responsible of the degradation process, in particular with the objective of developing biodepollution treatments.

In addition to the toxicology and biodegradability of ILs, there are key physico-chemical properties that allow the characterisation of the transfer and transport of these chemicals in the environment. These properties include the vapour pressure, aqueous solubility, octanol–water partition coefficient and diffusivity in water [17,18]. The octanol–water partition coefficient (K_{OW}) is defined as the ratio of the equilibrium concentrations of the test substance in 1-octanol saturated with water (C_O) and in water saturated with 1-octanol (C_W) [19]. This parameter is directly related with the possibility of a chemical to accumulate in organisms because water-saturated octanol is considered as a realistic model of the physico-chemical environment in living organisms [20]. Diffusion of chemicals in water is a very important physical property that allows to understand their transport in environmental compartments, both water and soil. These physico-chemical properties are seldom determined for ionic liquids, the data being often imprecise and scattered, especially in the case of octanol–water partition coefficients [21]. The diffusion coefficient of ILs in water is rarely reported, the only ILs studied being based on 1-alkyl-3-methylimidazolium cations [22–24].

The objective of the present work is to study the environmental impact of a selection of six 1-alkyl-3-methylimidazolium based ILs with alkyl side chains of various lengths, modulated or not by the insertion of oxygenated functional groups in order to increase the chemical reactivity and the biodegradability (esters and/or ether moieties). We have focussed on the bis(trifluoromethylsulfonyl)imide anion ([Tf_2N]) but the octylsulfate anion ([C_8SO_4]) was also studied for comparison. Different data describing the environmental impact of these ILs are measured: aqueous solubility, octanol–water partition coefficient, diffusion coefficient in water, biodegradation pathways with different pure microbial strains and microbial toxicity. The originality of the study is the simultaneous use of biological and physico-chemical tools to characterise the environmental impact of ILs.

2. Experimental

2.1. Materials

The ILs used in this study are listed in Table 1. The functionalised ILs were synthesised by Gathergood's group (DCU, Ireland) from alcohols and glycols, thus leading to imidazolium ILs with oxygen in the side chain of the cation [25]. [C_6mIm][Tf_2N] and [C_8mIm][Tf_2N] were prepared from the appropriate chloride salt using the procedure described by Bonhôte et al. [26]. Their purity is 99% as determined by ^{1}H NMR. [$C_1COOHmIm$][Cl] was also synthesised at DCU from 1-methylimidazole and 2-chloroacetic acid, its purity being estimated as 98% by ^{1}H NMR.

1-Octanol (Fluka, purity >99.5%) and imidazole (Aldrich, purity 99%) were used without further purification.

2.2. Aqueous solubility measurements

Aqueous solubility was determined following the OECD Guideline 105 [27]. A mixture of IL and distilled water was stirred for at least 72 h at 27 °C and then stood for at least 24 h at 22 °C. The aqueous solution was then diluted and its absorbance was measured with a UV–vis spectrophotometer (UVIKON 941) to determine the concentration of IL.

2.3. Octanol–water partition coefficients

The octanol–water partition coefficients of the different samples were determined following the procedure described in the OECD guideline 123 [19] at room temperature (22 ± 1 °C). Both water and 1-octanol were mutually saturated prior to the experiment by stirring for at least two days, and then allowing the phases to separate.

Depending on the detection limit and solubility of the IL in octanol, different low concentration solutions of the IL were prepared using 1-octanol pre-saturated with water as solvent. Special care was taken to avoid the formation of microdroplets from 1-octanol in the aqueous phase and to minimise the vapour phase. Concentrations of ILs in each phase were measured with a UV–vis spectrophotometer (*UVIKON 941*). Samples were diluted if their concentration exceeded the calibration range.

2.4. Diffusion coefficient measurements

Diffusion coefficients were measured using the Taylor dispersion technique, using an apparatus previously described [22]. The apparatus was calibrated by measuring the diffusion of potassium chloride in water at 298 K and tested using NaCl and methanol. The values obtained at 298 K (1.55×10^{-9} m^2 s^{-1} and 1.52×10^{-9} m^2 s^{-1}, respectively) are in good agreement with the ones reported for NaCl [28] and methanol [29].

2.5. Growth conditions and incubation with ILs

Four microbial strains were tested for their potential capacity to degrade a wide range of xenobiotics: three bacteria *Rhodococcus rhodochrous* ATCC 29672, *Pseudomonas viridiflava* strain 14b14, *Nocardiaasteroïdes* strain 911 and the yeast *Candida parapsilosis* ATCC 20246. Nocardioforms [30], notably the genus *Nocardia*, and the genus *Rhodococcus* [31,32] have been described as potential degraders of aliphatic and aromatic hydrocarbons, long aliphatic chain (polyethylene), halogenated compounds, heterocyclic compounds and various herbicides. So far only Pseudomonas and related bacteria have been reported to possess comparable biodegradation abilities. *Pseudomonas* [33] are ubiquitous bacteria that can live under a wide range of environmental conditions and are characterised by their considerable catabolic versatility. *Candida* yeasts are known as models for alkane assimilation and have been widely used for metabolic studies as typical eukaryotic microorganisms.

R. rhodochrous ATCC 29672 and *P. viridiflava* strain 14B14 were grown in 100-mL portions of Trypcase-soy broth (bioMérieux, Marcy l'Etoile, France) in 500-mL Erlenmeyer flasks incubated at 27 °C and 200 rpm. The cells (300 mL of the culture medium) were harvested after 24 h of culture under sterile conditions and centrifuged at 8000 rpm for 15 min at 4 °C. The bacterial pellet was washed first with a NaCl solution (8 g L^{-1}) and then with Volvic® mineral water to keep a mineral composition constant. The resting cells (5×10^9 cells/mL) were incubated with 50 mL of the ionic liquid solution (1 mM in distilled water) in 250 mL Erlenmeyer flasks at 27 °C under agitation (200 rpm). Negative controls without cells (abiotic samples) or without substrate (cell blanks) were carried out under the same conditions. During the nine-week incubation, samples (1 mL) were taken regularly, centrifuged at 12,000 rpm for 5 min. The supernatants were immediately frozen and kept for subsequent NMR analysis.

The same procedure was followed for the yeast *C. parapsilosis* ATCC 20246 and the bacterium *Nocardiaasteroïdes* strain 911 except that they were grown in Medium200 (ATCC) and Yeast Malt medium (For 1 L: glucose 4 g; yeast extract 4 g; malt extract 10 g. The pH was adjusted to 7.4), respectively.

2.5.1. Cell counting

Tenfold serial dilutions were spread onto Trypcase-soy agar plates and incubated at 27 °C in the dark for at least 4 days, after which the number of colony forming unit (cfu) was counted in order to determine the viable number of cells.

2.5.2. Measurements of the nucleic acid contents

The absorbance (A_{260}) of supernatants was measured using a NanoDrop ND-100 spectrophotometer. None of the ILs tested absorbed at this wavelength.

2.5.3. ^{1}H nuclear magnetic resonance (NMR) analyses

The crude samples (540 μL) were supplemented with 60 μL of a 5 mM solution of tetradeuterated sodium trimethylsilylpropionate ($TSPd_4$, Eurisotop, Saint-Aubin, France) in D_2O. D_2O was used for locking and shimming. $TSPd_4$ constituted a reference for chemical shifts (0 ppm) and quantification.

^{1}H NMR was performed at 25 °C at 500 MHz on an Avance500 Bruker spectrometer (BrukerBiospin, Wissembourg, France) equipped with a triple-resonance (^{1}H, ^{13}C, ^{15}N) inverse probe with 5-mm-diameter tubes containing 600 μL of sample, with water being suppressed by a classical two phase-shifted pulse saturation sequence. 128 scans were collected (90° pulse, 7.3 μs; saturation pulse, 3 s; relaxation delay, 3 s; acquisition time, 4.679 s; 65,536 data points). A 1-Hz exponential line-broadening filter was applied before Fourier transformation, and a baseline correction was performed on spectra before integration using Bruker software (Topspin 2.0).

2.6. Toxicity

Five strains were tested to assess the antimicrobial activity of the ILs: four bacteria (*Bacillus cereus* ATCC 14579 and *R. rhodochrous* ATCC 29672 as Gram positive bacteria, *Pseudomonas aeruginosa* ATCC 17504 and *Escherichia coli* ATCC 11303 as Gram negative ones) and one yeast (*Candida albicans* CIP444). The minimum inhibitory concentrations (MIC) were determined by serial twofold dilutions using the conventional broth microdilution method. Inocula were prepared by growing the strains for 24 h in Mueller Hinton (*B. cereus*, *E. coli* and *P. aeruginosa*), Trypcase-soy (*R. rhodochrous*) or Sabouraud (*C. albicans*) broths. The final inoculum density for the MIC determination was approximately 10^5 organisms/mL.

Uninoculated broth (100 μL) was dispensed in wells of the line A (sterile controls) of a 96-well microtitre plate whereas inoculated broth (100 μL) was dispended in the others wells except in column 1. A solution of the IL to be tested (150 μL) was added in the wells of column 1 (except in line A: sterile control and line H: growth control). 100 μL of the IL solution was added in column 2, mixed in the wells by drawing up and down a number of times and then 100 μL was transferred in the column 3. This twofold dilution was repeated down to column 12. The microtitre plates were incubated at 27 °C (37 °C for *E. coli*) for 24–48 h. The MIC was the lowest concentration of IL inhibiting visible growth of the microorganisms. The MIC determinations were performed in triplicate.

The starting concentrations tested depend on the initial dissolution of the IL, considered as the maximum concentration of ILs soluble in water after stirring less than 20 min, varying from 40.6 mM for the most soluble ($[C_1COOC_2OC_2mIm][Tf_2N]$) to 2.8 mM for the less soluble one ($[C_8mIm][Tf_2N]$). All the initial concentrations were checked by ^{1}H NMR.

Table 2
Aqueous solubility (AS) both in mM and mole fraction (x) of functionalized ILs at 22 ± 1 °C (this work) or non-functionalized ILs at 23.5 ± 1 °C [34].

ILS	AS	
	mM	$x \times 10^4$
$[C_1COOC_2OC_2mIm][Tf_2N]$	44 ± 5	7.9 ± 0.9
$[C_1COOC_2OC_2OC_4mIm][Tf_2N]$	25 ± 3	4.5 ± 0.5
$[C_1COOC_5mIm][Tf_2N]$	63 ± 7	11 ± 1
$[C_1COOC_5mIm][C_8SO_4]$	Miscible	
$[C_4mIm][Tf_2N]$	17 ± 7 [34]	3.1 ± 1.3
$[C_6mIm][Tf_2N]$	5.1 ± 0.9 [34]	0.9 ± 0.1
$[C_8mIm][Tf_2N]$	4.0 ± 0.7 [34]	0.7 ± 0.1

3. Results and discussion

3.1. Solubility in water

The experimental values of the aqueous solubility are listed in Table 2. For the oxygenated $[Tf_2N]$ based ILs it ranges from 25 to 63 mM, which is nearly one order of magnitude higher than the aqueous solubility of ILs without oxygen groups, a fact explained by the enhanced polarity of the ILs due to the incorporation of oxygen groups in the apolar alkyl chain of the cation. An increase of the alkyl chain length on the imidazolium ring (lower polarity) leads to a decrease of the aqueous solubility, as previously observed [34,35]. The anion $[C_8SO_4]$ makes the IL totally miscible with water.

The imidazolium cations with an ester function react with water giving an hydrolysis product – the 3-methyl-1-(carboxymethyl)imidazolium ($[C_1COOHmIm]$) – totally miscible with water. This product is also detected by UV absorption. Given the extinction coefficients and wavelengths of maximum absorption of the ILs and of the hydrolysis product, it was impossible to estimate the contribution of each component separately. In these cases, the aqueous solubility was considered as the concentration, at equilibrium, of both the IL and its hydrolysis product. Kinetic studies were monitored by ^1H NMR and showed that the percentage of the hydrolysis product was less than 10% under the conditions used to determine the aqueous solubility.

3.2. Octanol–water partition coefficients

The experimental method for the determination of K_{OW} was validated with the measurement of imidazole ($C_3H_4N_2$) for which a value for $K_{OW} = 0.90 \pm 0.09$ was found in agreement with the literature data of 0.83 [18].

The partition coefficient was measured at different IL concentrations in the aqueous phase, C_{IL}, fitted as a function of this concentration and extrapolated at infinite dilution. All the data are presented in Table 3. A slight increase of the partition coefficient with concentration was observed despite the IL concentration being as low as 10^{-3} mol L^{-1}. This was also observed in literature using direct measurement methods [21,36,37]. Due to this variation and the uncertainty of the fitting, a precision of 10–30% was calculated on the partition coefficient. These high values can be explained by the difficulty of the measurement often attributed to the possibility of forming invisible micro droplets of octanol in water-rich phase.

As shown in Table 3, the partition coefficient of ILs with oxygenated functions varies from 0.01 to 1.18 ($\log K_{OW}$ from −2 to 0.07). These values are far below the bioaccumulation limit, thus the considered ILs are not very hydrophobic.

K_{OW} has been rarely investigated for ILs, the available literature data for imidazolium based ILs being presented in Table 4. The same order of magnitude was obtained for experimental of predicted K_{OW} in ILs with or without oxygen functionalisation. For ILs without oxygen functionalisation and sharing the same

Table 3
Experimental octanol–water partition coefficients, K_{OW} at different IL concentrations, C_{IL} and at infinite dilution, K_{OW}^{∞}, at 22 °C.

IL	C_{IL}/mM	K_{OW}	IL	C_{IL}/mM	K_{OW}
$[C_1COOC_2OC_2mIm][Tf_2N]$	1.13	0.06	$[C_1COOC_5mIm][Tf_2N]$	0.18	1.37
	1.18	0.03		0.19	1.30
$K_{OW}^{\infty} = 0.001$	1.20	0.06	$K_{OW}^{\infty} = 1.18$	0.23	1.09
	2.03	0.06		0.34	1.38
	2.21	0.06		0.37	1.10
	2.28	0.05		0.57	1.15
	2.70	0.09		0.60	1.40
	2.84	0.08		0.62	1.39
	2.99	0.10		0.71	1.57
	3.16	0.11		0.89	1.65
	3.37	0.13		0.91	1.62
	3.40	0.15		1.00	1.47
	3.41	0.11		1.09	1.41
	3.41	0.15		1.17	1.73
	3.58	0.12		1.45	1.45
				1.46	1.36
$[C_1COOC_2OC_2OC_4mIm][Tf_2N]$	0.69	0.26	$[C_1COOC_5mIm][C_8SO_4]$	0.37	0.53
	0.83	0.35		0.38	0.49
$K_{OW}^{\infty} = 0.11$	0.91	0.31	$K_{OW}^{\infty} = 0.57$	0.52	0.93
	1.25	0.39		0.53	0.89
	1.38	0.40		0.64	1.16
	1.47	0.45		0.68	1.02
	1.68	0.51		0.74	1.61
	1.87	0.55		0.77	1.28
	1.87	0.56		0.77	1.28
	1.97	0.57		0.87	1.25
	2.21	0.65			
	2.27	0.67			
	2.30	0.55			
	2.34	0.75			
	2.45	0.65			
$[C_1COOH\ mIm][Cl]$		<0.01			

Table 4
Octanol–water partition coefficients, K_{OW}, of 3-methyl-1-alkylimidazolium, [C_nmIm]-based ILs and of some organic compounds between 20 °C and 30 °C from the literature [21]. Slow-stirring method [36,37]; shake-flask method [34,35]; indirect method [38]; calculation method.

Compounds	K_{OW}	Compounds	K_{OW}
[C_2mIm][Tf_2N]	0.09–0.11 [21]	[C_3mIm][BF_4]	0.0182 [38]
[C_4mIm][Tf_2N]	0.11–0.62 [21] 0.02–3.16 [37]	[C_4mIm][BF_4]	0.0363 [38], 0.0030 [21]
[C_6mIm][Tf_2N]	1.42–1.66 [21]	[C_5mIm][BF_4]	0.0813 [38]
[C_8mIm][Tf_2N]	6.3–11.1 [21]	[C_6mIm][BF_4]	0.1950 [38]
[C_4mIm][Cl]	0.0040 [21]; 0.48 [35]	[C_2mIm][PF_6]	0.015 [36]
[C_8mIm][Cl]	0.54 [34]	[C_4mIm][PF_6]	0.02 [36]; 0.022 [21]; 0.004–0.1 [37]
[C_{10}mIm][Cl]	0.52 [35]	[C_4mIm][NO_3]	0.0038 [21]
[C_{12}mIm][Cl]	0.73 [35]	[C_4mIm][Br]	0.0033 [21]
[C_2mIm][$B(CN)_4$]	0.169 [34]		
C_2H_5OH	0.57 [20]	$Cl_2C=CH_2$	123 [20]
$(CH_3)_2CO$	0.50 [20]	$Cl_2C=CHCl$	263 [20]
1-C_4H_9OH	6.92 [20]	C_6Cl_6	275,423 [20]

anion, K_{OW} increases as the alkyl side chain on the cation increases. For the oxygen functionalised ILs [$C_1COOC_2OC_2$mIm][Tf_2N] has the lowest K_{OW} value and [C_1COOC_5mIm][Tf_2N] the largest. The values increase with the length of the alkyl chain of the imidazolium cation, beside the ether/ester function, not with the total length of the side chain of the imidazolium ring. For ILs with an equivalent number of carbon atoms (total carbon atoms in the case of non-functionalised ILs, carbons beside the oxygenated function in the case of modified ILs), the K_{OW} values of the ILs pairs [$C_1COOC_2OC_2$mIm][Tf_2N] and [C_2mim][Tf_2N], [$C_1COOC_2OC_2OC_4$mIm][Tf_2N] and [C_4mim][Tf_2N], [C_1COOC_5mIm][Tf_2N] and [C_6mim][Tf_2N], are of the same order of magnitude, but slightly lower in the presence of oxygen. The long apolar alkyl chains lead to higher K_{OW} values, while the presence of oxygen can break this effect. This result confirms the empirical statement of Soskic and Plavsic [39] who claim that the contributions to K_{OW} of heteroatom in the alkyl chains of the ions are usually negative.

Compared to some widely used chemicals (Table 4), K_{OW} values for ILs are similar to those of low-molecular weight polar solvents (except halogenated solvents), much lower than those of high molecular weight polar solvents and apolar solvents. From the analysis of K_{OW}, ILs seem to present a lower environmental impact than many traditional organic solvents, being less lipophilic and thus having a lower potential to accumulate or concentrate in the environment and in living organisms.

The K_{OW} of the hydrolysis product [C_1COOHmIm][Cl] was also measured, its concentration at equilibrium in the aqueous phase being below our detection limit. We can thus conclude that the K_{OW} value of [C_1COOHmIm][Cl] is less than 0.01, which is in favour of a minor environmental impact.

3.3. Diffusion coefficients

The diffusion coefficients for ILs in water at infinite dilution (D_{AB}) are listed in Table 5. The overall scatter of the data points to a precision of 0.02×10^{-9} m^2 s^{-1}, corresponding to a (1–2)% relative error. The total uncertainty of the diffusion coefficients is evaluated by error propagation as 5%.

The D_{AB} for all the ILs are in the same order of magnitude, varying from 0.74 to 0.96×10^{-9} m^2 s^{-1} at 303 K with a decrease, as expected, of this coefficient with the length of the alkyl chain on the cation. Compared to the non-functionalised ILs [22] (Table 5), the presence of an oxygenated function in the IL, leads to a decrease of the diffusion coefficient. The D_{AB} of ILs in water is comparable to the diffusion coefficient of low molecular weight alcohols in water (ethanol, 0.84×10^{-9} m^2 s^{-1}; n-butanol, 0.77×10^{-9} m^2 s^{-1} [40]). The experimental data were fitted to Arrhenius plots of the form:

$$\ln\ (D_{AB}) = \ln D_0 + \frac{E_a}{RT} \quad (1)$$

D_0 representing the diffusion coefficient at infinite temperature and E_a the activation energy of the solute for diffusion. The values for E_a and D_0 with the relative standard deviation (σ) are also listed in Table 5.

Wilke–Chang equation is commonly used for estimating diffusion coefficient of organic molecules (A) in a solvent (B) [22–24] as a function of temperature:

$$D_{AB}(T) = 7.4 \times 10^{-12} \frac{(\psi M_B)^{0.5} T}{\eta_B V_A^{0.6}} \quad (2)$$

where ψ is the association parameter for the solvent (water = 2.26 [23]). M_B and η_B are the molar mass and viscosity of solvent in g mol^{-1} and in mPa s. The viscosity values of water at 283.15 K, 293.15 K, 303.15 K are 1.307, 1.002 and 0.7975 mPa s, respectively [41]. V_A is the molar volume of the solute in cm^3 mol^{-1} at its normal boiling point. As in other studies [22–24], the Wilke–Chang equation underestimated the diffusion coefficient values in the present work. In order to improve the performance of the equation, we have

Table 5
Experimental diffusion coefficients, D_{AB}, for ILs in water at infinite dilution and parameters (E_a and D_0) for fitting Eq. (1) from 283 K to 303 K along with standard deviation σ. $\sigma = \Sigma|D_{AB}^{exp} - D_{AB}^{cal}|/_{AB}^{exp}/n$..

	$D_{AB}/10^{-9}$ m^2 s^{-1}			E_a (kJ mol^{-1})	D_0 (10^{-9} m^2 s^{-1})	σ%
	283 K	293 K	303 K			
[$C_1COOC_2OC_2$mIm][Tf_2N]	0.48	0.65	0.85	19.0	2889	0.0
[$C_1COOC_2OC_2OC_4$mIm][Tf_2N]	0.43	0.57	0.74	18.8	1389	0.3
[C_1COOC_5mIm][Tf_2N]	0.49	0.66	0.86	20.2	2610	0.1
[C_1COOC_5mIm][C_8SO_4]	0.45	0.59	0.77	18.9	1395	0.4
[C_4mIm][Tf_2N] [22]	0.60	–	0.96	16.80	752	
[C_6mIm][Tf_2N] [22]	0.58	–	0.90	16.38	612	
[C_8mIm][Tf_2N] [22]	0.57	–	0.87	15.03	342	

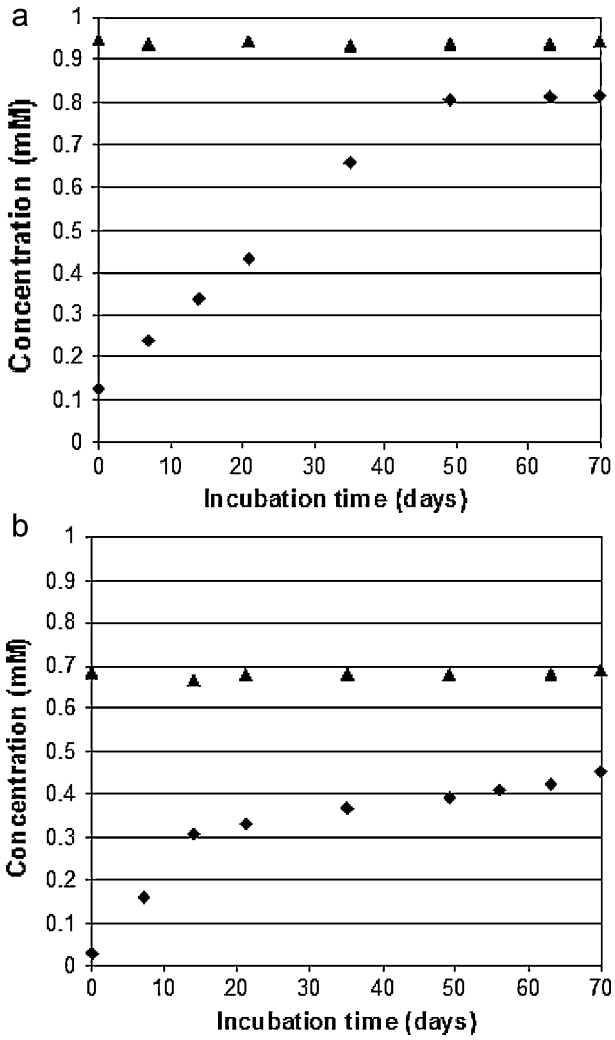


Fig. 1. Kinetics of [C_6mIm][Tf_2N] (a) and [C_8mIm][Tf_2N] (b) incubation under abiotic (▲) and biotic conditions (*R. rhodochrous* ATCC 29672) (♦). Mean values from 3 independent experiments.

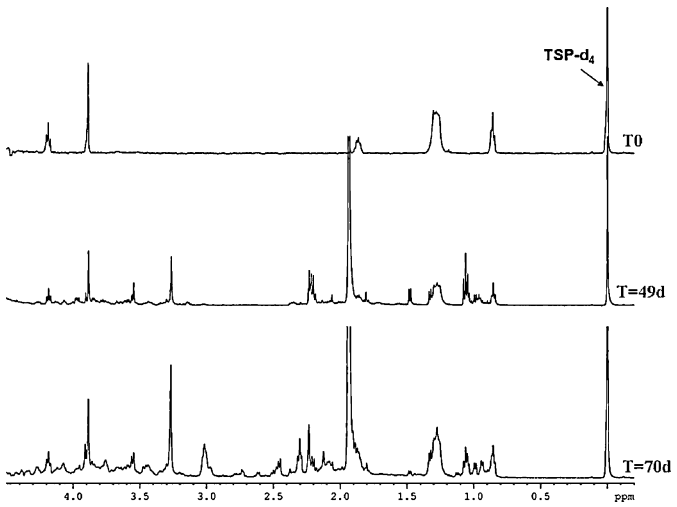


Fig. 2. ^{1}H NMR spectra (aliphatic region) recorded during the biodegradation of [C_8mIm][Tf_2N] by *R. rhodochrous* ATCC 29672 after T0, T49 and T70 days of incubation.

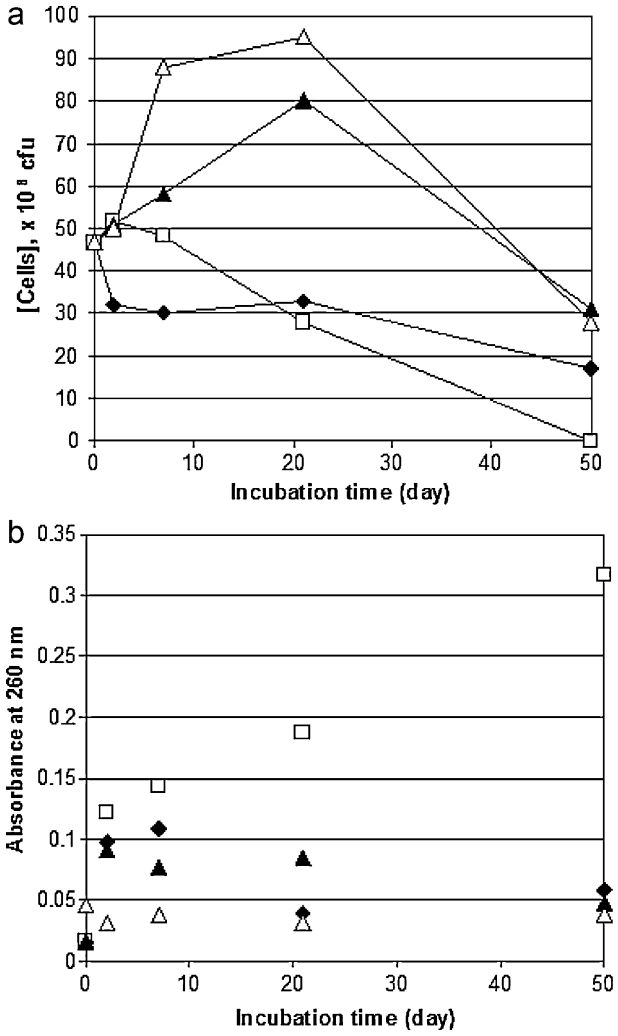


Fig. 3. Evolution of the cell number (a) and nucleic acid content (b) in the supernatant within the 50-day incubation with *R. rhodochrous* ATCC 29672. Negative control (♦); [C_8mIm][Tf_2N] (□); [C_1COOC_5mIm][Tf_2N] (▲) and [C_1COOC_5mIm][C_8SO_4] (△).

replaced V_A by the van der Waals volume (V_{vdw}), calculated using a simple model [42]:

$$V_{vdW} = \Sigma V_{vdW}^{atom} - 14.7R_A - 3.8R_{NA} - 5.92N_B \quad (3)$$

where V_{vdW}^{atom} is the van der Waals volume of each atom (considered as 6.04 g mol^{-1}) [42], R_A is the number of aromatic rings and R_{NA} is the number of non-aromatic rings. N_B is the number of bonds in a molecule, $N_B = N - 1 + R_g$. Where N is the total number of atoms and R_g is the total number of ring structures ($R_g = R_A + R_{NA}$).

The empirical coefficient is corrected by fitting our data together with that of 19 non-functionalised imidazolium based ILs with different anions reported in literature [22–24]. The equation proposed to predict D_{AB} as a function of temperature is:

$$D_{AB}(T) = 8 \times 10^{-11} \frac{T}{\eta_B V_{vdw}^{0.6}} \quad (4)$$

with an average prediction error of less than 5%. For ILs based on other anions, for example [C_2mim][C_2SO_4] [23], the predicted D_{AB} differs 27% from the experimental value, which suggests that experimental data are needed to improve the model.

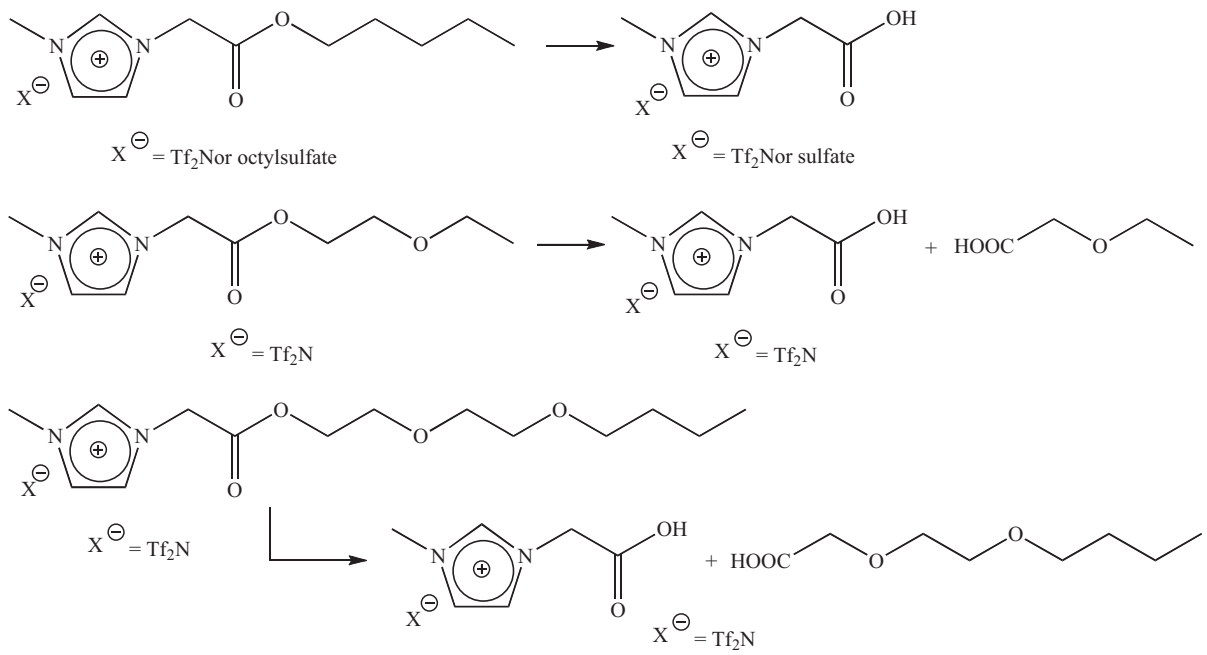


Fig. 4. Metabolic pathways of the studied ILs.

3.4. Biodegradation of the ILs studied

The biodegradation kinetics of each IL (1 mM in water) were monitored in resting-cell incubation experiments for each strain tested (*R. rhodochrous* ATCC 29672, *P. viridiflava* strain 14b14, *Nocardiaasteroïdes* strain 911 and the yeast *C. parapsilosis* ATCC 20246) and compared with incubation under abiotic conditions. Samples were taken regularly during a nine-week period and analysed by ^{1}H NMR. As the results obtained with the 4 strains tested were very similar, we have chosen to present in detail and illustrate the ones obtained with *R. rhodochrous* ATCC 29672, the intrinsic metabolites present in the medium remaining in traces with this strain within the incubation period conversely to the others (cell blanks).

3.4.1. Biodegradation of the long alkyl chain ILs

The long alkyl chain ILs, [C_6mIm] and [C_8mIm], were not degraded either under abiotic or biotic conditions (Fig. 1).

In fact, the IL concentration increased with time in the presence of microorganisms, reaching the expected initial concentration only after several weeks. Adsorption or strong interactions with the cells can be suggested to explain this result. The evolution of the ^{1}H NMR spectra recorded at different times of incubation can be significantly interpreted. The appearance of many new intense signals was observed in the presence of both ILs (in particular with [C_8mIm]) that are not present in the negative control with cells alone (Fig. 2). This class of ILs has been shown previously to act as detergents [43] and probably lead to cell lysis.

To further investigate the effect of long alkyl chain ILs on cells compared with the oxygen-functionalised ILs, the evolution of the cell number was estimated by cell counting on agar plate of incubation samples taken at different times in the negative cell control and in the presence of [C_8mIm][Tf_2N], [C_1COOC_5mIm][Tf_2N] and [C_1COOC_5mIm][C_8SO_4]. A measurement of the nucleic acid contents in the supernatants of the same samples was also carried out. The results are presented in Fig. 3.

A marked decrease of the cell number was observed in the case of [C_8mIm][Tf_2N], with a great increase of the nucleic acid amount present in the medium. No such observation was made in the negative control containing cells alone where these data were relatively stable during the 50-day monitoring.

These results confirm the cell lysis due to the detergent effect of [C_8mIm] on the cell walls leading to the release of intracellular compounds into the medium (Fig. 2). The [C_8mIm] itself is then slowly released into the medium as the cell walls are broken (Fig. 1). This effect on the membrane integrity has also recently been clearly evidenced on rat pheochromocytoma cells for even shorter alkyl chain length ([C_4mIm]) by measurement of lactate dehydrogenase release [44]. It was not observed for [C_1COOC_5mIm][Tf_2N] and [C_1COOC_5mIm][C_8SO_4].

3.4.2. Biodegradation of the oxygenated-functionalised ILs

The four ester-functionalised ILs tested were readily transformed under abiotic and biotic conditions. A major common metabolite was formed quantitatively as monitored by ^{1}H NMR and accumulated in the medium whatever the structure of the starting IL and the conditions. This compound was easily identified by LC–MS (m/z = 141.0669) and ^{1}H NMR as the hydrolysis product [C_1COOHmIm] (Fig. 4). The chemical structure of this compound was confirmed by its synthesis and its co-analysis by ^{1}H NMR with a sample obtained during the microbial incubation. Under biotic conditions, the pentanol released after hydrolysis of [C_1COOC_5mIm][Tf_2N] and [C_1COOC_5mIm][C_8SO_4] was detected only in the samples taken at short incubation times and degraded rapidly. In the case of [$C_1COOC_2OC_2OC_4$mIm][Tf_2N] and [$C_1COOC_2OC_2$mIm][Tf_2N], the alcohols with an ether alkyl chain released were rapidly oxidised into carboxylic acids that accumulate in the medium (Fig. 4).

The rate of the hydrolysis reaction kinetics, considered as first-order, was greatly enhanced in the presence of microorganism and the reaction was complete, proving the role of biological activity (Table 6).

The nature of the anion (octylsulfate versus Tf_2N) had a marked effect on the global biodegradation rate (decrease by a factor >4 with the octylsulfate anion) (upper plot in Fig. 5). The monitoring of the octylsulfate concentration in the case of [C_1COOC_5mIm][C_8SO_4] by ^{1}H NMR showed its disappearance only in the presence of microorganism. It was completely degraded within 5 days (lower

Table 6
Kinetics parameters of IL hydrolysis under abiotic and biotic (*R. rhodochrous* ATCC 29672) conditions. Mean values of 2 or 3 independent experiments.

	Abiotic conditions			Biotic conditions		
	K (d^{-1})	r	%hyd. after 70 d	K (h^{-1})	r	% hyd. (h)
$[C_1COOC_5mIm][Tf_2N]$	0.0098	0.997	51%	0.78	0.994	100% (4.5)
$[C_1COOC_5mIm][C_8SO_4]$	0.0096	0.977	53%	0.18	0.989	100%(12.5)
$[C_1COOC_2OC_2OC_4mIm][Tf_2N]$	0.032	0.998	89%	0.37	0.975	100% (23)
$[C_1COOC_2OC_2mIm][Tf_2N]$	0.030	0.991	81%	0.295	0.981	100% (23)

plot in Fig. 5). This IL was found as "readily biodegradable" with the "CO_2 headspace test" [10] contrary to $[C_1COOC_5mIm][Tf_2N]$, although in our case, the final product is the same and it is biotransformed less rapidly.

For the same chain length, the introduction of an ethereal moiety has also a negative effect on the global biodegradation rate (comparison of $[C_1COOC_5mIm][Tf_2N]$ and $[C_1COOC_2OC_2mIm][Tf_2N]$ in Table 6) but favours its hydrolysis under abiotic conditions.

The same metabolic pathways, as well as similar biodegradation rates, were obtained with the three other strains tested: *P. viridiflava* strain 14b14, *Nocardiaasteroïdes* strain 911 and the yeast *C. parapsilosis* ATCC 20246. This study demonstrates that the imidazolium ring was not degraded by the strains tested. This moiety has already been described as a factor of limiting biodegradability

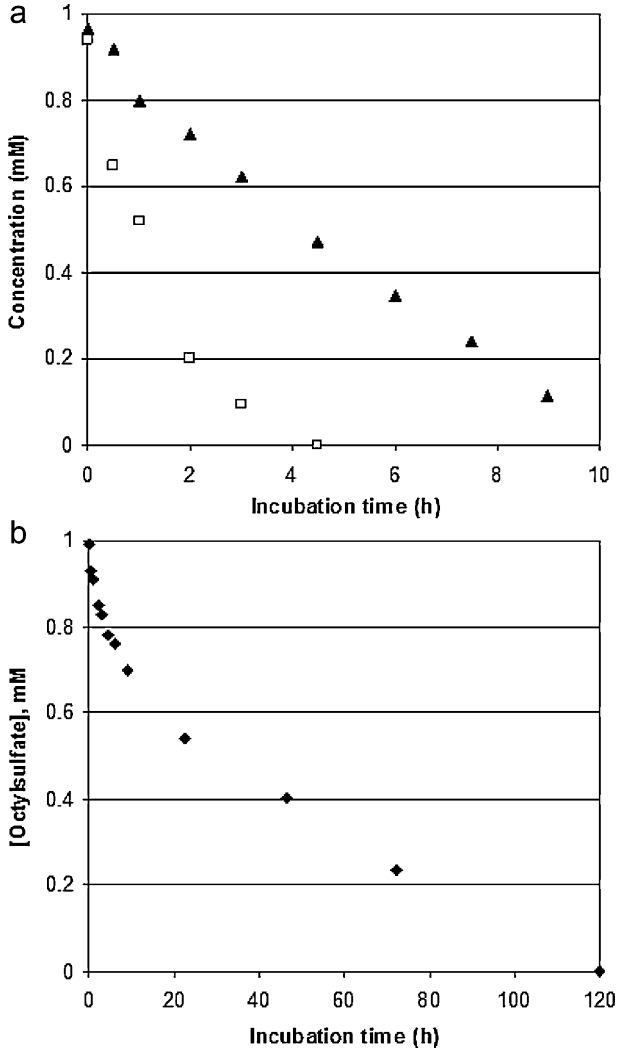


Fig. 5. Biodegradation kinetics by *R. rhodochrous* of: (a) $[C_1COOC_5mIm][Tf_2N]$ (□) and $[C_1COOC_5mIm][C_8SO_4]$ (▲); (b) octylsulfate anion. Mean values from 3 independent experiments.

[43]. The introduction of oxygen-functionalised side chains (ester) increases the biodegradability but leads to the accumulation of metabolites, in particular via hydrolysis reaction. This reaction that also occurs under abiotic conditions even with a slower rate can affect the performance of these ILs from a synthetic point of view. The presence of ethereal side chains was rather a disadvantage for biodegradation.

3.5. Toxicity studies

Five strains were tested to assess the antimicrobial activity of the ILs: four bacteria (*B. cereus* ATCC 14579 and *R. rhodochrous* ATCC 29672 as Gram positive bacteria, *P. aeruginosa* ATCC 17504 and *E. coli* ATCC 11303 as Gram negative bacteria) and one yeast (*C. albicans* CIP 444). The ILs tested present a wide range of solubility in water as shown previously. In order to avoid the effect of solvent or/and IL precipitation in the medium after solvent evaporation, the choice was made to adapt the starting IL concentration for MIC evaluation in function of its initial dissolution. The supposed initial IL concentration was checked by NMR. The minimum inhibitory concentrations (MIC) of ILs are listed in Table 7.

According to the results, the oxygen-functionalised ILs are not very toxic for the strains tested. In most cases, their MIC is superior to their solubility. The presence of oxygen in the alkyl chains reduced the toxicity of ILs. It is worth noting that in this study, the anion $[C_8SO_4^-]$ slightly increases the toxicity compared with $[Tf_2N^-]$. This result differs from the previous study of Morrissey et al. [45]. For the ILs with $[Tf_2N^-]$, similarly with K_{OW}, $[C_1COOC_5mIm][Tf_2N]$ is the most toxic whereas $[C_1COOC_2OC_2mIm][Tf_2N]$ presents the lowest MIC value. The toxicity increases with the length of apolar alkyl chain, beside the ether/ester function, not with the total length of the side chain of the imidazolium ring.

Differences were observed between strains: *E. coli* is the most sensitive and *P. aeruginosa* is the most resistant. A similar conclusion was obtained by Morrissey et al. [45] with 1-methyl-3-(decyloxycarbonyl)methylimidazolium bromide.

After 24 or 48 h of incubation, the final IL concentration was checked in each case and the hydrolysis percentage was determined. According to the strain and the IL structure, the hydrolysis product was more or less present. Its toxicity was therefore also tested and showed no important biological activity. Nevertheless, the results obtained with the hydrolysable ILs can be distorted by its

Table 7
Minimum inhibitory concentrations (MIC) of ILs (mM). B.c. *Bacillus cereus* ATCC 14579; P.a. *Pseudomonas aeruginosa* ATCC 17504; E.c. *Escherichia coli* ATCC 11303; R.r. *R. rhodochrous* ATCC 29672; C.a. *Candida albicans* CIP 444.

	B.c.	P.a	E.c	R.r.	C.a.
$[C_6mim][Tf_2N]$	2	>2	1	1	>2
$[C_8mim][Tf_2N]$	1.4	>1.4	0.7	0.3	1.4
$[C_1COOC_2OC_2mIm][Tf_2N]$	20.3	>20.3	10.1	10.1	>20.3
$[C_1COOC_2OC_2OC_4mIm][Tf_2N]$	>6.4	>6.4	6.4	6.4	>6.4
$[C_1COOC_5mIm][Tf_2N]$	>5.5	>5.5	5.5	5.5	>5.5
$[C_1COOC_5mIm][C_8SO_4]$	3.8	7.5	3.8	7.5	3.8
$[C_1COOHmIm][Cl]$	>23	>23	>23	>23	>23

percentage of presence, giving rather a lower toxicity to the starting IL.

4. Conclusions

The aim of this work was to assess the consequences on the environmental impact of the presence of oxygenated moieties (ester and ether groups) on the alkyl chain of imidazolium based ILs. A twofold strategy was followed with on one hand the determination of pertinent physico-chemical properties like the water solubility, the diffusivity in water and the octanol–water partition coefficient and, on the other hand, the evaluation of the toxicity and the biodegradability of the selected ILs.

The presence of both ester and ether groups on the 1-alkyl-3-methylimidazolium cation decreases the value of their octanol–water partition coefficient, which means that the lipophilicity of this family of ILs decreases when the alkyl side-chains contain these oxygen functionalities, and simultaneously reduces the toxicity of ionic liquids with $[Tf_2N]$ or $[C_8SO_4]$ anions. The known relationship between the toxicity and the value of K_{OW} for different chemicals is confirmed also for the families of ionic liquids studied herein. Further work is required in order to quantify this relationship and to use the octanol–water partition coefficient to estimate the toxicity of ILs.

For $[C_n mIm][Tf_2N]$ ionic liquids like the ones studied in this work, we can conclude that the presence of an ester function in the side chain renders the IL more easily biodegradable. Nevertheless these ester functions make the ionic liquid more susceptible to hydrolysis under abiotic and biotic conditions leading to the formation of chemical species that are more difficult to biodegrade by the strains used in the present work. A careful study of the degradation products indicates a resistance of the imidazolium ring to biodegradability and to abiotic degradation. The presence of side-chains with the ether function was rather a disadvantage for biodegradation.

The modification of the structure of the ILs also changes some of the physico-chemical properties relevant to determine their environmental impact. The oxygen functionalised ILs are more soluble in water and, because they are heavier and larger than the non-functionalised equivalent, diffuse more slowly in this medium. These two properties will surely affect their transport and transfer in the environmental compartments, namely in aqueous environment.

Acknowledgements

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