

Ecotoxicological risk profile of ionic liquids: octanol-water distribution coefficients and toxicological data

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Abstract

BACKGROUND: A knowledge of the toxicity of ionic liquids (ILs) and their influence on aquatic ecosystems must be assessed before an accurate judgment of their environmental benefits and prior to their industrial application. In the present work, the overall octanol-water distribution coefficients (D_{ow}) of imidazolium-based ILs were measured using the slow-stirring method. Biological tests were performed to establish the toxicity of some of these imidazolium-based ILs and to relate it with the D_{ow} .

RESULTS: The D_{ow} values of the ILs investigated are low and concentration dependent, indicating that these ILs, at low concentrations, will not accumulate or bioconcentrate in the environment. Moreover, it is shown that the most hydrophobic anions present higher D_{ow} and higher toxicity, which means lower EC_{50} values (the concentration of IL needed to decrease the luminescence of the marine bacteria *Vibrio fischeri* by 50% compared with the control organism luminescence).

CONCLUSIONS: A new and more accurate interpretation of the partition of ionic liquids between water and 1-octanol is presented. The work included measurement of new D_{ow} data and the study of their relation with water solubility and EC_{50} values.

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Keywords: ionic liquids; octanol–water partition coefficient; octanol-water distribution coefficient; ion pair extraction constant; EC_{50} .

INTRODUCTION

Volatile organic compounds (VOCs) released into the atmosphere by industrial chemical processes contribute to environmental pollution, climatic changes and human health-related problems. The growing environmental and health concerns have led to the creation of more stringent regulation of their emissions. This is spurring a growing interest in more environmentally friendly technologies, among which there is a major interest in identifying alternative solvents.¹ In the last few years, ionic liquids (ILs) have been looked upon as one of the most promising alternatives to traditional solvents.^{1–10} They are expected to help reduce the use of hazardous and polluting organic solvents in separation, synthesis and in the design of new products, owing to their unique characteristics.^{11–13} In spite of their undeniable interest, it should be noted that not all ILs are green or environment friendly. The general questions of ‘greenness’ and sustainability of the use of ILs as alternative reaction media were discussed by Jastorff *et al.*¹⁴ As for the organic solvents a risk analysis of these substances¹⁵ is imperative. The concept of a risk analysis requires that a certain minimum set of data about both exposure and the effects of a chemical under scrutiny is available. Since the large majority of ILs are still in a very early phase of development it is not yet clear which of them will be produced at an industrial scale. Thus, a more flexible method of risk analysis that can be applied to compounds with sparse and heterogeneous data, such as the ionic liquids, is needed. Such a method has been

devised for a comparative risk evaluation of chemical substances based on five risk indicators (release, spatiotemporal range, bioaccumulation, biological activity, and uncertainty) forming ecotoxicological risk profiles for each substance.^{16,17} The number of ionic liquids synthesized and the lack of information about their ecotoxicological risk profiles, requires that more studies are carried out. Finally, it must be noted that due to the structural variability of ILs, it is extremely important that researchers and industries consider not only their technological advantages but must take into account their (eco)toxicological risks.¹⁸

Nowadays, there are publications showing some results concerning the assessment of toxicity of different organisms and species – decomposers,^{19,20} producers^{20–23} and consumers.^{20,24,25} One of the most widely used toxicological tests is the Microtox[®] Acute Toxicity Test, which uses the gram negative marine bacterium *Vibrio fischeri*. The Microtox[®] Acute Toxicity Test is quick, simple, cost-effective and sensitive, and is widely accepted by

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industrial and academic communities for toxicity determination, providing a fast, yet accurate, estimate of the toxicity of a compound.²⁶ The endpoint of this methodology, EC_{50} , is the effective concentration value that corresponds to the concentration of chemical that produces 50% inhibition of light emission from a specific strain of bioluminescent bacteria. Some authors studied the toxicity of imidazolium-based ILs with chloride, hexafluorophosphate, tetrafluoroborate, bis(trifluoromethylsulfonyl)imide, octylsulfate and bis(1,2-benzenediolato)borate anions.^{19,20,27}

Before the unavoidable release of ILs into the environment, due to their use in processes and products, adequate knowledge is required about the mechanisms of 'attack' of the ILs to various organisms, their biodegradability, the distribution between different environmental compartments and the bioaccumulation.^{28,29}

This work is part of a project aiming at studying the properties of ionic liquids and attempting to relate them with their chemical structure. Because ionic species are fully dissociated in the aqueous phase when highly diluted it is not possible to define an octanol–water partition coefficient (K_{ow}) for the ionic liquids, instead, their octanol–water distribution coefficient, D_{ow} , is defined and measured for a number of hydrophobic ionic liquids. The effect of the anion, cation alkyl chain length and the concentration of different ILs in the D_{ow} values is discussed. Correlations between D_{ow} and the toxicological parameters (EC_{50}) were investigated, aiming at acquiring a better knowledge about the environmental risk profile of those imidazolium-based ILs.

Octanol–water partition (K_{ow}) and distribution (D_{ow}) coefficients

One of the most widely used parameters for assessing the environmental impact of a chemical specie is the octanol–water partition coefficient (K_{ow}). The 1-octanol is an amphiphilic solvent whose dielectric properties are similar to those of a generalized lipid phase.³⁰ This parameter is useful in the ecosystem risk analysis because partition coefficients in octanol–water systems display similarities to the partition of biological compounds between water and living organisms. Correlations between environmental parameters for natural systems and K_{ow} have been successful because the 1-octanol ability to mimic a lipid phase behaviour.

Many direct and indirect methods are available to measure K_{ow} experimentally, each being used by different authors for different purposes. K_{ow} values for several 1-alkyl-3-methylimidazolium ILs have been reported by several groups.^{31–35} The data are quite scattered and for given compounds sometimes differ by up to 2 orders of magnitude between authors. Differences in values have been related to different concentration ranges investigated,³⁵ and also the experimental method used. Domanska *et al.*³² estimated the K_{ow} values from the ratio of solubilities of ILs in pure 1-octanol and water using the synthetic and visual method, but the very small range of these data for ILs with cation chain lengths varying from 4 to 12, suggests that their method is not adequate. The values reported by Ropel *et al.*³⁵ seem to be carefully measured using the slow stirring method and are consistent with expectations concerning the influence of alkyl chain length and the anion hydrophobic nature. They are, however, strongly concentration dependent unlike a true K_{ow} value. Using an alternative approach Stepnowski and Storonik³⁶ suggested using the group contribution method of Hansch and Leo³⁷ for estimating $\log K_{ow}$ values for ionic liquids. However, since the imidazolium cation is not covered by the original method, they resorted to using the fragment constant for the nitrogen in quaternary ammonium compounds for both nitrogens in the

imidazolium ring. While the resulting $\log P$ parameters should not be used as absolute estimates of experimental $\log K_{ow}$ values, they do provide a measure of lipophilicity.³⁸

The major problem concerning the measurement of K_{ow} values is that most authors dealing with this subject treat the ionic liquids as non-ionizable compounds, failing to take into account that, at low concentrations, they may undergo an important dissociation in aqueous solution and even some dissociation in the organic phase. This precludes the use of K_{ow} values defined according to Equation (1) since the analytical techniques used will not account for the $[IL]_w$ only, but for the total amount of cation present in the water phase, both as ion pair and as dissociated ion. In this context, the available results are useless with regard to the effect of ILs in the bioaccumulation area. Contradicting these wrong ideas was the work of Lee and Lee³⁴ and, more recently, that of Gardas *et al.*³⁹ In these studies the importance of taking into account the ionic nature of the IL to establish the 1-octanol water distribution coefficients was recognized. However, Lee and Lee³⁴ failed to take the electroneutrality condition into account in their analysis.

The octanol–water partition coefficient refers specifically to the ratio of concentrations in both phases of the neutral, non-associated and non-complexed solute:

$$K_{ow} = \frac{C_{oct}}{C_w} \quad (1)$$

where C_{oct} and C_w are, respectively, the equilibrium concentrations of the compound in the 1-octanol and water rich phases.

In situations where competing equilibria (ionization, association, and complexation) participate, the partition coefficient must be replaced by the distribution coefficient also known as the apparent partition coefficient (K_{app}). The distribution coefficient (D_{ow}) is defined as the ratio of the sum of the concentrations of all solute forms (ionized plus unionized) in 1-octanol to the sum of the concentration of all solute forms in the aqueous phase, at a given pH.^{30,40}

$$D_{ow} = \frac{\sum (C_{oct})_i}{\sum (C_w)_i} \quad (2)$$

This coefficient is pH and concentration dependent, which is why the conditions at which it is measured must be specified. When the solute is non-ionic the identity

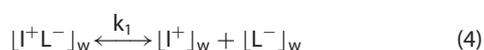
$$\log D_{ow} = \log K_{ow} \quad (3)$$

is valid at any pH value, otherwise the two values are different and $\log D_{ow}$ is inferior to $\log K_{ow}$.

D_{ow} should not be confused with the true K_{ow} , since it does not represent a true equilibrium constant of a single species between two phases. Turner and Williamson⁴⁰ presented interesting work on the relationship between D_{ow} and K_{ow} while Scherrer and Howard⁴¹ discussed the dependency of these coefficients on pK_a and pH for acids and bases.

When the dissociation of the ILs is taken into account, as it must be at low IL concentrations, a series of chemical equilibria must be considered in the determination of these partition or distribution coefficients. The chemical equilibria considered in the current study are presented below, where $I^+ L^-$ is the ion pair of the ionic liquid, I^+ corresponds to the imidazolium cation, L^- is the anion, subscripts w and oct denote the water and the 1-octanol rich phases, respectively. The first equilibrium to be considered is

the dissociation of the ionic liquid in the aqueous phase, with an equilibrium constant k_1 :



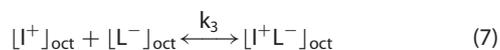
The second equilibrium refers to the distribution of the ion pair IL between both phases, being the respective equilibrium constant, the true K_{ow} .



Besides the distribution of the ion pair between both phases, one must also take into account the distribution of the ions between the two phases as described by Equation (6) below. To maintain the electroneutrality of the phases it is assumed that both ions have the same distribution constant, $\sqrt{k_2}$:



Finally, the formation of the ion pair in the 1-octanol phase is considered with an equilibrium constant k_3 .



From these equilibria the following expression for D_{ow} can be derived:

$$D_{ow} = \frac{K_{ow}[L^+]_w + k_1\sqrt{k_2}}{k_1 + [L^+]_w} \quad (8)$$

If the IL in the aqueous phase is very diluted, it is possible to assume that the ionic liquid is completely dissociated. If the ionic liquid concentration is lower than k_1 then the D_{ow} is described by

$$D_{ow} = (K_2K_3)[L^+]_w + \sqrt{k_2} = E[L^+]_w + \sqrt{k_2} \quad (9)$$

where, for the present system D_{ow} and E , are described by Equations (10) and (11) as:

$$D_{ow} = \frac{[L^+L^-]_{oct} + [L^+]_{oct}}{[L^+L^-]_w + [L^+]_w} \quad (10)$$

$$E = \frac{[L^+L^-]_{oct}}{[L^+]_w[L^-]_w} \quad (11)$$

If the distribution coefficients, D_{ow} , are measured in a broad concentration range it can be observed that for low concentrations they follow a linear relationship with the ionic liquid concentration as predicted by Equation (9) and shown in Fig. 1, and also observed in the work by Lee and Lee.³⁴ For high concentrations this relationship deviates from the linear dependency.³⁴ If data at various concentrations of ionic liquid in the linear region is measured it is possible to use these values to access the pair extraction constant E , defined by Equation (11), and also the equilibrium constants, k_2 and k_3 of Equations (6) and (7).

In the present work, the octanol–water distribution coefficients (D_{ow}) of several imidazolium-based ionic liquids at room temperature were measured by the slow-stirring method,⁴² for very dilute solutions. From the dependency of this data on the IL concentration in the aqueous phase, the equilibrium constants k_2 and k_3 and the ion pair extraction constant (E) were estimated. In addition, some of these ionic liquids were tested using the Microtox[®] procedure, and the respective EC_{50} data (15 min) were estimated.

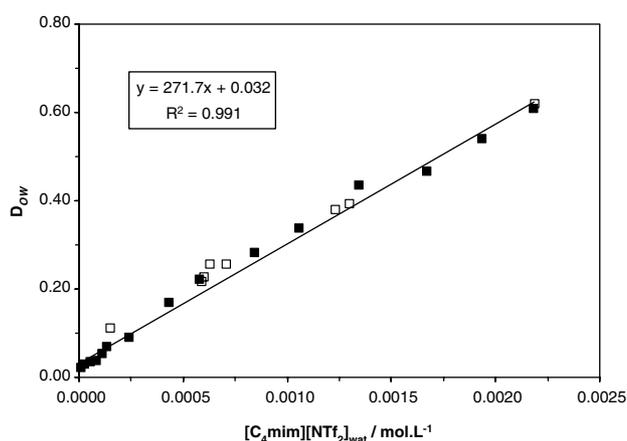


Figure 1. Experimental (■) and Ropel *et al.*³⁵ data (□) for octanol–water distribution coefficients at different $[C_4mim][NTf_2]$ concentrations.

EXPERIMENTAL

Material

The 1-octanol was acquired from Fluka with a purity $\geq 99.5\%$ (established by GC analysis). The water used was double distilled, passed by a reverse osmosis system and further treated with a Milli-Q plus 185 water purification apparatus. It has a resistivity of $18.2 \text{ M}\Omega \text{ cm}^{-1}$, a TOC smaller than $5 \mu\text{g L}^{-1}$ and it is free of particles greater than $0.22 \mu\text{m}$.

The ILs used in this work, based on the imidazolium family, 1-hexyl-3-methylimidazolium hexafluorophosphate – $[C_6mim][PF_6]$, 3-methyl-1-octylimidazolium hexafluorophosphate – $[C_8mim][PF_6]$, 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide – $[C_2mim][NTf_2]$, 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide – $[C_4mim][NTf_2]$ were acquired at Iolitec with purities $\geq 99\%$. The purities of all the ionic liquids used were checked by ^1H , ^{13}C and ^{19}F NMR spectroscopy.

Methods

Slow-Stirring measurements of D_{ow}

The 1-octanol and ultrapure water were mutually saturated prior to the experiment by equilibrating them for 48 h. Some 1-octanol saturated with ultrapure water was then used to dissolve the IL and form the stock solution (with defined concentration) used to prepare all the IL concentrations studied. All the solutions prepared to determine the D_{ow} had concentrations lower than $10^{-3} \text{ mol L}^{-1}$, to guarantee that complete dissociation of the IL in the aqueous phase is achieved. The slow-stirring equilibrium cell consists of a 120 mL glass vial containing a 1 cm Teflon coated magnetic stirrer, built for these determinations. Approximately 45 mL of double distilled, deionized water pre-saturated with 1-octanol was introduced in the vial and an equal volume of 1-octanol saturated with water containing a known amount of IL from the stock solution, was carefully added to the vial to avoid emulsification. The water-rich phase in the vials was slowly stirred to prevent emulsification of the system. These vials were kept at room temperature, $25 \pm 1^\circ\text{C}$.

To obtain the dependency of the measured D_{ow} on the concentration of the IL cation in the aqueous phase, multiple samples with different initial IL concentrations were used. Three vials with the same initial concentration of IL were used for each measurement to control the precision and repeatability of the experiment. The IL concentrations in each phase were measured

Table 1. Extinction coefficients, ϵ ($\text{L mol}^{-1} \text{cm}^{-1}$) for imidazolium-based ILs in water and octanol-rich phases

| Ionic liquid | $\epsilon_w/\text{L mol}^{-1} \text{cm}^{-1}$ | $\epsilon_{\text{oct}}/\text{L mol}^{-1} \text{cm}^{-1}$ |
|---|---|--|
| [C ₂ mim][NTf ₂] | 4526 ± 18 | 4498 ± 74 |
| [C ₄ mim][NTf ₂] | 4239 ± 13 | 4729 ± 60 |
| [C ₆ mim][PF ₆] | 4228 ± 19 | 4769 ± 92 |
| [C ₈ mim][PF ₆] | 4322 ± 32 | 4220 ± 24 |

Table 2. D_{ow} results for [C₂mim][NTf₂]

| Ionic liquid | D_{ow} | $[\text{IL}]_{\text{oct}} \times 10^4 \text{ mol L}^{-1}$ | $[\text{IL}]_w \times 10^3 \text{ mol L}^{-1}$ |
|---|----------|---|--|
| [C ₂ mim][NTf ₂] | 0.007 | 0.007 | 0.102 |
| | 0.009 | 0.018 | 0.204 |
| | 0.011 | 0.034 | 0.305 |
| | 0.013 | 0.053 | 0.406 |
| | 0.015 | 0.076 | 0.506 |
| | 0.019 | 0.144 | 0.757 |
| | 0.035 | 0.824 | 2.354 |
| | 0.046 | 2.143 | 4.659 |
| | 0.071 | 4.845 | 6.824 |
| | 0.093 | 8.295 | 8.919 |
| | 0.102 | 11.281 | 11.060 |
| | 0.107 | 14.129 | 13.205 |

at 211 nm using UV-VIS spectroscopy (Shimadzu UV-1700 Pharma-Spec Spectrometer) with a detection limit of 0.01 in absorbance. The same stock of solvents (both saturated 1-octanol and water) used in the preparation of the sample were used in the reference cell of the UV-VIS. The extinction coefficients (ϵ) of the ILs in 1-octanol and water-rich phase were determined, since they are required to determine the concentration of IL in each phase by interpolation with calibration curves. Samples were collected from the 1-octanol and water-rich phases from all vials during at least five sampling events occurring over a 20 to 40 day period to follow the evolution of the partitioning and ensure full equilibration. Sampling ceased when the concentrations in both phases were stable and constant. It is considered that equilibrium is attained when the distribution coefficient values do not vary more than 0.3, between measurements. The D_{ow} values at room temperature were determined for several imidazolium-based ILs, the validation of this method being done using the [C₄mim][NTf₂].

Though it is known that fluorinated anions such as [PF₆] are not water stable we have previously established that under the conditions used on this study the hydrolysis extent is very small.⁴³

Microtox® tests

The toxicities of the ILs were determined using the Microtox® Acute Toxicity Test.⁴⁴ This test is a prokaryotic microscale toxicity bioassay used to evaluate inhibition of the luminescence in the gram negative marine bacteria *Vibrio fischeri* (Beijerinck) Lehmann and Neumann. It was performed using a wide range of diluted IL aqueous solutions, from 0 to 1 (v : v) starting from the IL saturated aqueous solution. Note that the ILs studied are not completely miscible with water and therefore the aqueous solutions were previously saturated with each IL under slow stirring for at least 48 h. After 15 min exposure to the IL aqueous solution, the light

Table 3. D_{ow} results for [C₄mim][NTf₂]

| Ionic liquid | D_{ow} | $[\text{IL}]_{\text{oct}} \times 10^3 \text{ mol L}^{-1}$ | $[\text{IL}]_w \times 10^3 \text{ mol L}^{-1}$ |
|---|----------|---|--|
| [C ₄ mim][NTf ₂] | 0.021 | 0.002 | 0.094 |
| | 0.029 | 0.008 | 0.281 |
| | 0.034 | 0.019 | 0.559 |
| | 0.038 | 0.032 | 0.835 |
| | 0.052 | 0.057 | 1.099 |
| | 0.069 | 0.093 | 1.352 |
| | 0.090 | 0.216 | 2.405 |
| | 0.169 | 0.731 | 4.323 |
| | 0.220 | 1.273 | 5.786 |
| | 0.280 | 2.357 | 8.418 |
| | 0.336 | 3.551 | 10.568 |
| | 0.435 | 5.856 | 13.462 |
| | 0.467 | 7.819 | 16.742 |
| | 0.540 | 10.472 | 19.392 |
| | 0.608 | 13.269 | 21.824 |

Table 4. D_{ow} results for [C₆mim][PF₆]

| Ionic liquid | D_{ow} | $[\text{IL}]_{\text{oct}} \times 10^3 \text{ mol L}^{-1}$ | $[\text{IL}]_w \times 10^3 \text{ mol L}^{-1}$ |
|--|----------|---|--|
| [C ₆ mim][PF ₆] | 0.139 | 0.380 | 0.333 |
| | 0.146 | 0.759 | 0.662 |
| | 0.153 | 1.139 | 0.987 |
| | 0.160 | 1.518 | 1.308 |
| | 0.169 | 1.898 | 1.624 |
| | 0.185 | 2.847 | 2.403 |
| | 0.201 | 3.795 | 3.160 |
| | 0.225 | 5.693 | 4.649 |
| | 0.276 | 9.488 | 7.436 |
| | 0.324 | 13.284 | 10.029 |
| | 0.373 | 17.079 | 12.437 |
| | 0.429 | 22.772 | 15.932 |

output of the luminescent bacteria was measured and compared with the light output of a blank control sample. The toxicity was evaluated and a 50% reduction in luminescence was computed using the Microtox® Omni™ Software, version 4.3.0.1.⁴⁵ The EC_{50} results were determined according to the Basic Test.

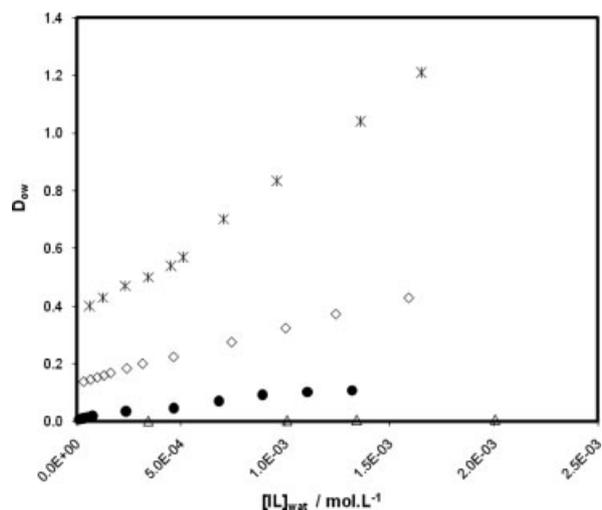
RESULTS AND DISCUSSION

The values of extinction coefficients (ϵ) used for the determination of the IL concentrations in each phase are reported in Table 1. All the ILs studied have a pronounced hydrophobic character and their extinction coefficients have approximately the same value of about $4500 \text{ L mol}^{-1} \text{cm}^{-1}$. A more careful examination of the data shows that the most hydrophilic ILs have higher extinction coefficients for octanol and water-rich phases.

For the ILs studied, the range of D_{ow} values at equilibrium are reported in Tables 2–5, along with the concentration of IL in octanol-rich phase at the initial stage, and in the water-rich phase at equilibrium. As shown in Fig. 1, the literature values of [C₄mim][NTf₂] obtained by Ropel *et al.*³⁵ are well reproduced by this study, which confirms the suitability of the apparatus and experimental technique used for D_{ow} determination.

Table 5. D_{ow} results for $[C_8mim][PF_6]$

| Ionic liquid | D_{ow} | $[IL]_{oct} \times 10^3 \text{ mol L}^{-1}$ | $[IL]_w \times 10^3 \text{ mol L}^{-1}$ |
|------------------|----------|---|---|
| $[C_8mim][PF_6]$ | 0.401 | 0.768 | 0.606 |
| | 0.430 | 1.535 | 1.261 |
| | 0.470 | 3.070 | 2.321 |
| | 0.500 | 4.605 | 3.438 |
| | 0.540 | 6.141 | 4.518 |
| | 0.570 | 7.676 | 5.096 |
| | 1.210 | 33.006 | 16.536 |

**Figure 2.** Experimental results for octanol–water distribution coefficients for various ILs, \diamond $[C_6mim][PF_6]$, $*$ $[C_8mim][PF_6]$, \bullet $[C_2mim][NTf_2]$, \triangle $[C_4mim][PF_6]$ ³⁴ and different concentrations.

The data collected here are plotted in Fig. 2. The linearity of the dependency of D_{ow} on the total cation concentration in the aqueous phase suggests that in the concentration range studied, the IL is completely dissociated. At higher IL concentrations the partition coefficient is no longer linear, as shown in the data reported by Lee and Lee.³⁴ At these low concentrations Equation (9) can be used to correlate the experimental data and extract the values for the equilibrium constants k_2 , k_3 and E . The values of these constants are reported in Table 6 for the ionic liquids studied. They show that, in contrast to observations in the aqueous phase, the dissociation of the organic phase is very small. Under these conditions the values of E are the true partition constants of the ILs between the two phases that are relevant for the analysis of the partition of ionic liquids between water and

1-octanol. An inspection of Equations (1) and (11) shows, however, the different nature of these two equilibrium constants and that their numerical values cannot be directly compared. Qualitatively their behavior will also present important differences. While K_{ow} will presuppose a constant relation between the concentrations in the two phases, E suggests that at concentrations below $1/E$ the compound will be preferentially present in the aqueous phase; above that concentration it will partition preferentially to the organic phase. This peculiar behavior can be observed in the data of Lee and Lee³⁴ for $[C_4mim][PF_6]$ where the E value reported here correctly estimates the concentration at which inversion of the partition between the two phases is observed. The E values measured show, with no surprise, that E increases with the hydrophobicity, represented as the ionic liquid water solubility in Fig. 3. This behavior follows the expected trends with the increase of the cation alkyl chain length and the anion hydrophobicity.

For analysis of the influence of the anions, a comparison between the D_{ow} values for $[C_4mim][PF_6]$ determined by Lee and Lee³⁴ and $[C_4mim][NTf_2]$ determined by our group was carried. In this case, it is possible to observe that the D_{ow} value is higher for the $[NTf_2]$ -based IL. This could easily be explained by the solubilities of these two ILs in water and 1-octanol, which, according to Lee and Lee,³⁴ were 71.0 and 16.0 mmol L^{-1} in water and, 6.7 and 143.2 mmol L^{-1} in 1-octanol, for the $[PF_6]$ and $[NTf_2]$, respectively. Since the solubility of the IL in 1-octanol increases from $[PF_6]$ to $[NTf_2]$, is expected that the latter has a greater affinity for 1-octanol, thus increasing the D_{ow} .

In this work, the pair extraction constant E values were compared with EC_{50} values measured by Microtox[®] and the IL aqueous solubility reported in Table 7. Very good correlation between the pair extraction constant E and the IL aqueous solubility was observed and is shown in Fig. 3. This result suggests that the partition between aqueous and organic phases is controlled by the ionic liquid solubility in water. The trend in EC_{50} dependency on the pair extraction constant E , reported in Fig. 4, is expected, with the toxicity increasing with increasing affinity of the ionic liquid for the organic phase. A higher affinity for 1-octanol would imply greater adherence of the IL to the living tissues, resulting in higher toxicity. However, this correlation is not as smooth as that observed for the aqueous solubility suggesting that other effects besides the affinity of the ionic liquid for the different phases plays a role in the ionic liquid toxicity as discussed in previous work.²⁷

CONCLUSIONS

The slow stirring method was used to measure the octanol–water distribution coefficient (D_{ow}) for different ionic liquids, it being confirmed that an approach based on the ion pair extraction constant, E , is more consistent for description of the partition.

Table 6. Reported values of k_2 , k_3 and E for the ILs studied

| Ionic liquid | k_2 | $k_3 / \text{mol}^{-1} \text{ L}$ | $E / \text{mol}^{-1} \text{ L}$ |
|--------------------|----------------------------|-----------------------------------|---------------------------------|
| $[C_2mim][NTf_2]$ | 0.00012 ± 0.000036 | 698742.4 ± 202511.7 | 81.0 ± 3.6 |
| $[C_4mim][NTf_2]$ | 0.0010 ± 0.0003 | 268184.3 ± 87574.6 | 271.7 ± 7.2 |
| $[C_6mim][PF_6]$ | 0.019 ± 0.003 | 9965.6 ± 180.4 | 186.7 ± 2.0 |
| $[C_8mim][PF_6]$ | 0.116 ± 0.006 | 4448.2 ± 254.1 | 514.9 ± 14.6 |
| $[C_4mim][PF_6]^a$ | 0.0000044 ± 0.00000082 | 573680.1 ± 115342.3 | 2.55 ± 0.21 |

^a Results from Lee and Lee.³⁴

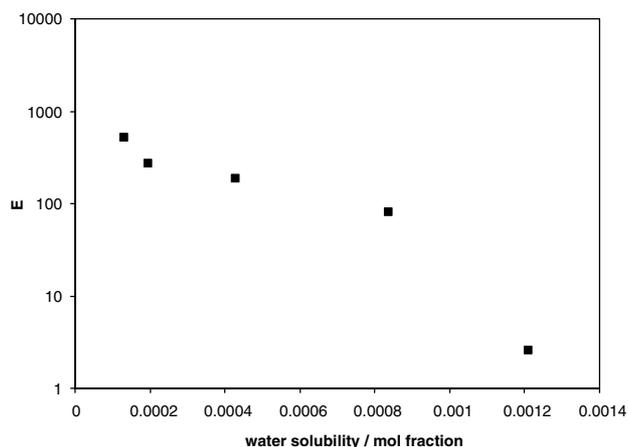


Figure 3. Experimental results for the ion pair extraction constant (E) and water solubility for the ILs studied described by Freire *et al.*^{46,47}.

Table 7. E results for some ILs and EC_{50} (mg L^{-1}) values after 15 min exposure to the luminescent marine bacteria *Vibrio fischeri*

| Ionic liquid | $E/\text{mol}^{-1} \text{ L}$ | Water solubility mol fraction $\times 10^4$ | $EC_{50}/\text{mg L}^{-1}$ (lower limit; upper limit) |
|---|-------------------------------|---|---|
| [C ₂ mim][NTf ₂] | 81.0 ± 3.6 | 8.38 ^b | 145.08 (101.63; 283.82) |
| [C ₄ mim][NTf ₂] | 271.7 ± 7.2 | 1.96 ^b | 141.99 (70.99; 141.99) |
| [C ₄ mim][PF ₆] ^a | 2.55 ± 0.21 | 12.10 ^c | 333.88 (300.34; 403.55) |
| [C ₆ mim][PF ₆] | 186.7 ± 2.0 | 4.30 ^c | 40.22 (20.45; 60.86) |
| [C ₈ mim][PF ₆] | 514.9 ± 14.6 | 1.30 ^c | 1.71 (0.00; 1.71) |

^a Results from Lee and Lee.³⁴

^b Results from Freire *et al.*⁴⁶

^c Results from Freire *et al.*⁴⁷

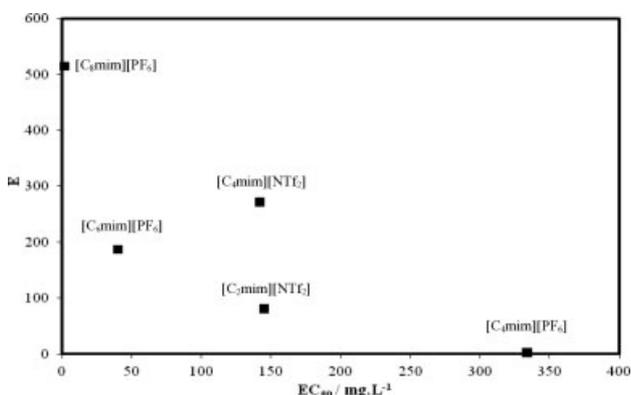


Figure 4. Experimental results for the ion pair extraction constant (E) and EC_{50} (mg L^{-1}) for the ILs studied.

The D_{ow} results of the imidazolium-based ILs investigated are concentration dependent and are much lower than many commonly used industrial solvents. An increase in the alkyl chain length on the cation or substitution of hydrogen atoms with methyl groups on the cation ring increases the distribution coefficient. The results indicate that for concentrations below $1/E$ the ionic liquid will partition preferentially towards the aqueous phase.

Combining the toxicological and partition information, results suggest that the hydrophobic imidazolium-based ionic liquids studied do not represent a serious environmental threat at low concentrations. However, more data is required for a full understanding of the environmental risk profile of ionic liquids.

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