Deep eutectic solvents *vs* ionic liquids: Similarities and differences

Justyna Płotka-Wasylka[1,*], Miguel de la Guardia[2], Vasil Andruch[3], Mária Vilková[4]

[1] Department of Analytical Chemistry, Faculty of Chemistry, Gdańsk University of Technology, PL-80-233 Gdańsk, Poland

[2] Department of Analytical Chemistry, University of Valencia, Valencia 46100, Spain

[3] Department of Analytical Chemistry, Institute of Chemistry, Faculty of Science, Pavol Jozef Šafárik University in Košice, SK-04154, Košice, Slovakia

[4] Laboratory of NMR, Institute of Chemistry, Faculty of Science, Pavol Jozef Šafárik University in Košice, SK-04154, Košice, Slovakia

**corresponding author: juswasyl@pg.edu.pl; plotkajustyna@gmail.com*

Abstract

Deep eutectic solvents (DES) were introduced as an alternative to ionic liquids (IL) to overcome the drawbacks of IL solvents. However, some authors consider them to be a subclass of ILs. In contrast, other authors emphasize that these are by their nature independent, different groups of substances. Thus, the question arises: Which solvent group should DESs belong to? Maybe a new class should be added to the existing ones. The aim of this work is to attract the attention of researchers using DES in their studies to the need for a proper use of terms.

Keywords

Deep eutectic solvents; ionic liquids; analytical chemistry; solvents

1 Introduction

At the beginning of our century, Abbott's group published a few papers that triggered research in the area we call today *Deep Eutectic Solvents* (DES) [1-3]. They examined the properties of these systems and also indicated the possibility of their use as solvents with interesting features. There are also other terms and denominations, **which may or may not denote** the substances we now consider to be DESs: Low Transition Temperature Mixtures (LTTM) [4], Low Melting Mixtures (LMM) [5] or Deep Eutectic Ionic Liquids (DEIL) [6]. When a DES is composed of components of natural origin, it is defined as a natural deep eutectic solvent (NADES) [7, 8].

On the other hand, *Ionic Liquids* (IL), which could be considered as the parents of DESs, were reported for the first time by Paul Walden in 1914 [9]. At that time, no one knew that ILs would become a very hot topic of chemistry one century later. Nowadays, some important fundamental points of view are different from the original concepts, as insights into the nature of ILs have become deeper. For instance, ILs were known to be non-volatile, non-flammable and stable on air and in water, and were considered as green solvents. Recently, it is well known that many of them are, in fact, volatile, flammable, unstable and even toxic. This situation is attributed to the large combinations of cations and anions that meet the definition of ILs, leading to an adverse suite of behaviors. As the chemical variety of ILs has grown, they have been further divided into many types. Worth mentioning are: task-specific ILs (TSILs) [10], room-temperature ILs (RTILs) [11] and polyionic liquids (PILs) [12]. Very recently Singh and Savoy summarized the literature on the structural classification of ILs, their synthesis pathways and the potential applications [13].

DESs were introduced as an alternative to ILs to overcome the drawbacks of ILs. Some authors consider them to be a subclass of ILs, and sometimes they consider these terms interchangeable. On the other hand, other authors emphasize that despite the many similarities (See Figure 1), they are by their nature independent, different groups of substances [14, 15]. Thus, the question arises: Which solvent group should DESs belong to? The aim of this work is to attract the attention of researchers using DES in their studies to the need for a proper use of terms. Although ILs and DESs have a lot in common, especially when it comes to physical properties as well as applications, from the chemical point of view, these are two separate groups of substances. Therefore, it is still necessary to understand the specific chemical nature of DES systems in order to prevent a mechanistic understanding of how these systems work. In our opinion there are many more differences than similarities. In considering the differences between these two type of solvents, the chemical formation process as well as the source of their starting materials need to be mentioned [16].

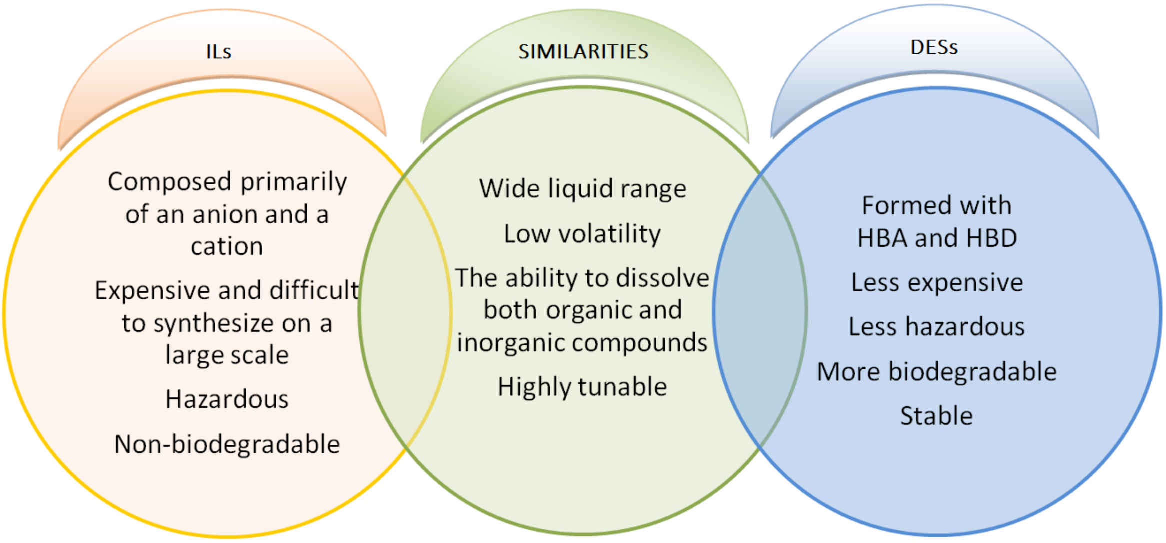


Figure 1. Similarities and differences of ILs and DESs

2 Starting materials and mechanism of synthesis

DESs differ from ILs in two basic ways, namely the nature of the starting materials and the methods of their formation. ILs are a combination of organic heterocyclic cations and organic or inorganic anions (Figure 2), while DESs are a combination of various hydrogen bond acceptors (HBAs) (Figure 3) and hydrogen bond donors (HBDs) (Figure 4). The number of potential mixtures is virtually unlimited for both ILs and DESs [17]. With such a large number of suitable starting materials as well as their possible combinations, they have both advantages and disadvantages which allow the properties of these substances to be changed to meet the requirements of specific application (which is precisely why both ILs and DESs have found wide use in various fields of science, research and technology). The huge advantage of DESs, however, is that they are made of generally nontoxic, easily accessible, cheap and sustainable compounds. Furthermore, common components of DESs are naturally occurring biocompatible compounds that are not hazardous if they are released back into nature [18]. It is also important to note that the components of DESs, unlike ILs, must not react with each other; therefore, it is necessary to avoid combinations of such compounds where this is possible.

The synthesis of ILs often involves several synthetic steps using various reagents, organic volatile solvents; in addition, by-products and waste are generated. Generally, the reaction time is long (up to 48 h) with the temperature varying from 25 to 100 °C. The synthesis of ILs (Figure 5) consists of two main steps: (i) cation formation (by protonation of the amine by an acid or quaternization reaction of the amine with a haloalkane) and (ii) anion exchange (by treatment of halide salt with a Lewis acid or by anion metathesis) [19]. In contrast, DESs can be simply prepared by heating or the grinding method (Figure 6). The heating method is the most used; the compounds are mixed and heated at temperatures between 50 °C to 100 °C under constant stirring for times spanning from minutes to hours until a homogeneous liquid forms. The grinding method is based on mixing the compounds at room temperature and grinding them in a mortar with a pestle. A liquid formed by the heating or grinding method is obtained with a yield of 100% and with an atom economy of 100% [20]. Another method – freeze-drying (Figure 2) – is also known, but it is a bit more complicated. The separated aqueous solutions of components are mixed together, frozen and freeze-dried to form a clear viscous liquid [21]. From the above stated, it is clear that ILs and DESs differ not only in the nature of the components, but also in the methods of their formation.

The synthesis of ILs is, in general, more costly and difficult than the preparation of DESs. The production of DESs is relatively straightforward and inexpensive and does not pose any significant post purification or disposal problems.

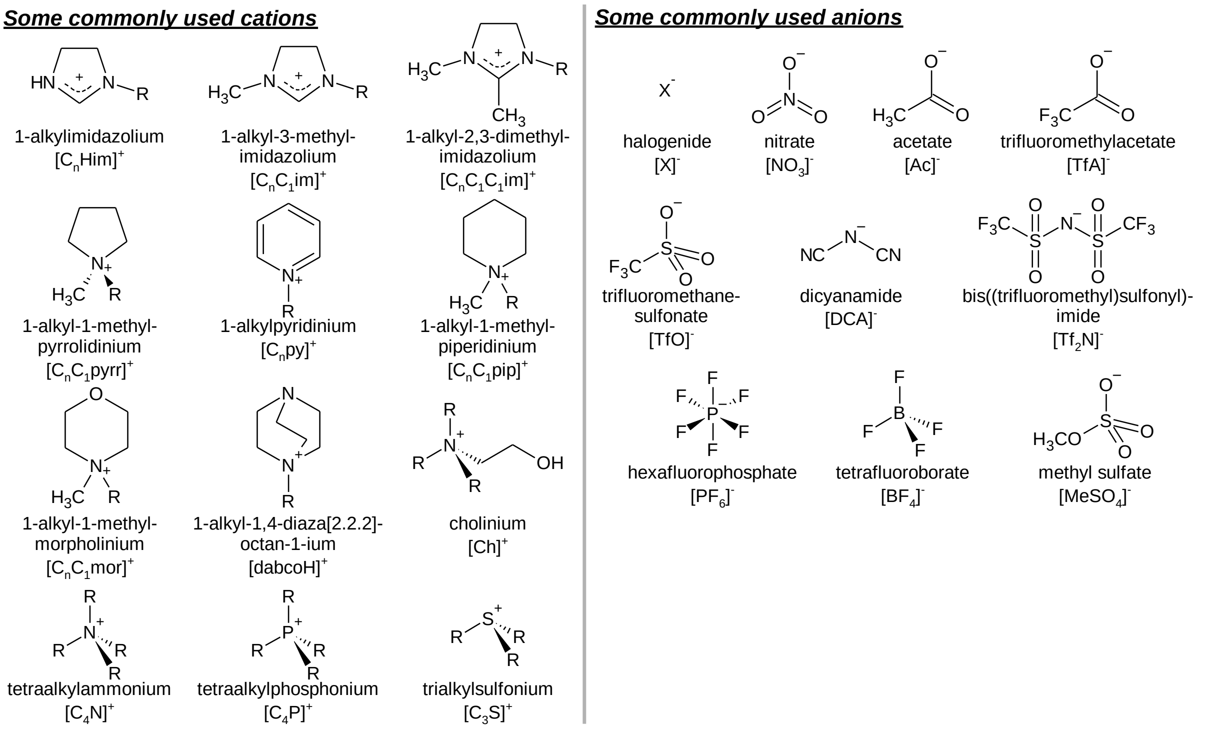


Figure 2. Selected cations and anions used for the synthesis of ILs

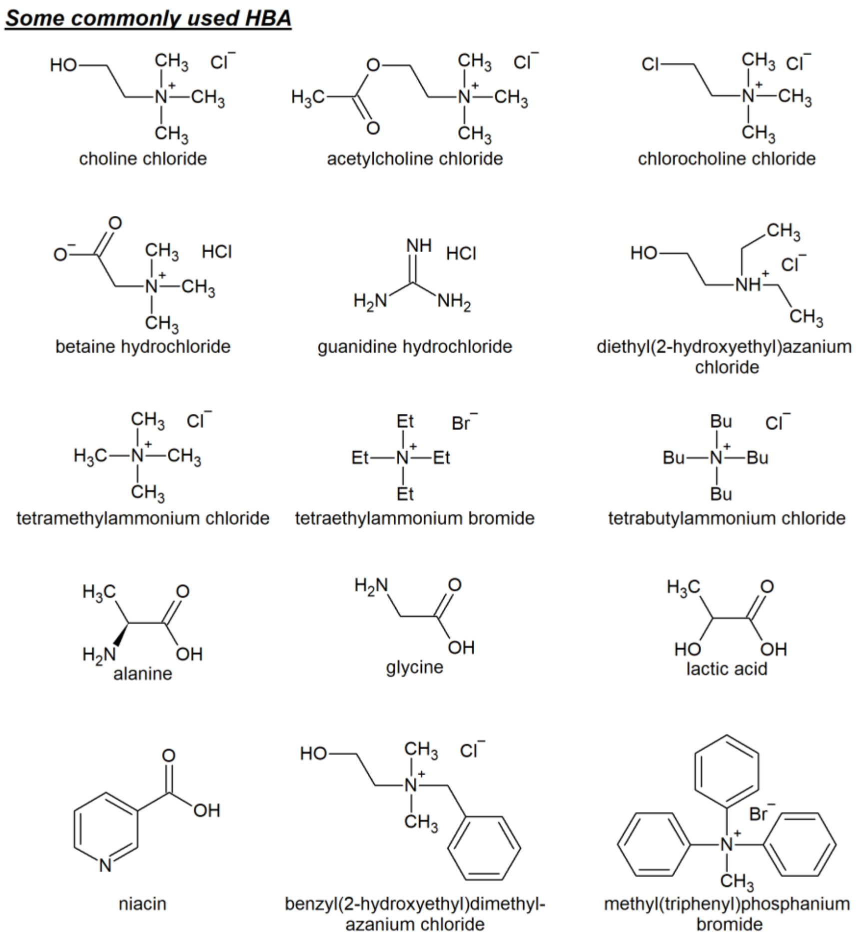


Figure 3. Selected HBAs for the synthesis of DESs

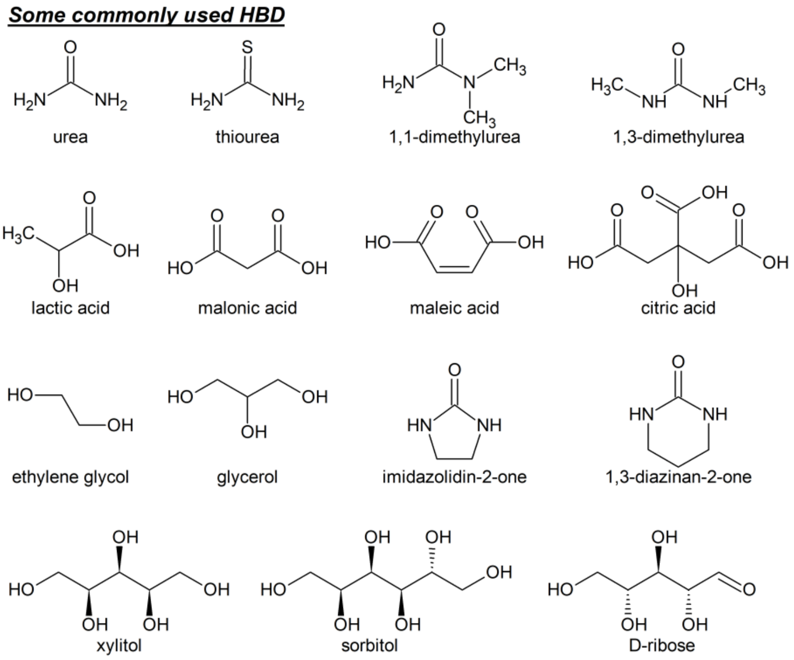


Figure 4. Selected HBDs for the synthesis of DESs

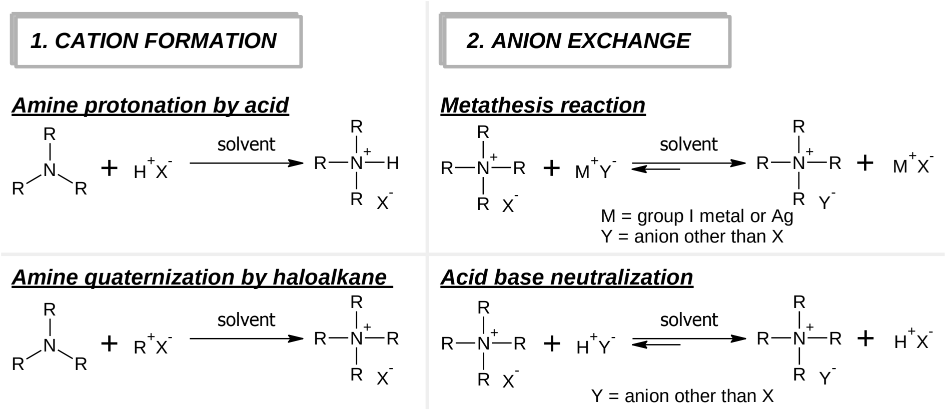


Figure 5. The main methods of preparing ILs

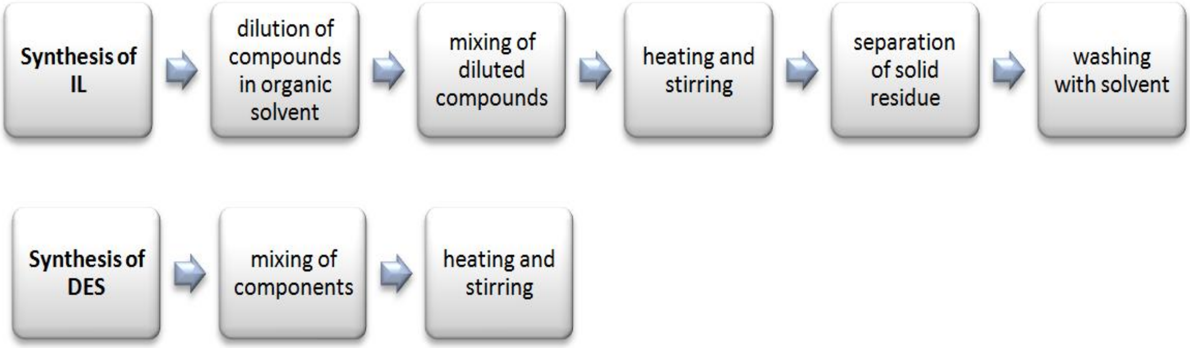


Figure 6. A comparison of the main synthesis processes of ILs and DESs.

3 Properties

The structure and properties of ILs as well as DESs are determined by intermolecular interactions: Coulomb forces, hydrogen bonding and dispersion forces. By definition, the behavior of ILs is dominated by ionic interactions (Coulomb forces), whereas DESs, as eutectic mixtures of two or more distinct components, exhibit a strong contribution from hydrogen bonding [22]. Although ILs and DESs differ in the nature of their constituents and the type of dominant intermolecular forces, they share many interesting properties, which can be adjusted by selecting the nature and ratio of the constituents.

However, due to the large number of possible ILs and DESs resulting from the large number of possible combinations of starting substances, it is very difficult to unambiguously characterize and generalize their physical properties. We can only define some general rules and conclusions. Both ILs and DESs have low melting points. ILs melt below 100 °C, while the melting temperature of DES is far below that of either individual component. The density and viscosity of these solvents also have similar values and are strongly dependent on their composition and temperature. Therefore, the selection of IL and DES constituents is essential, since high viscosity and density are the main drawbacks for the practical use of these solvents [23-25]. Although the viscosity problem can be solved quickly and easily in the case of DESs by using water as an additional component, a large excess of water can in some cases lead to the complete decomposition of the DES [26]. In general, ILs and DESs present high polarity. This is a great advantage of both solvents, because they can solubilize a wide range of organic and bioactive substances. On considering other similarities between DESs and ILs, it could be highlighted that both systems concern a low vapor pressure and wide liquid range. Moreover, they are highly tunable.

As we can see, the physical properties of ILs and DESs are close to each other, and what is even more important, thanks to the large number of possible combinations of starting materials, they are also highly tunable depending on the requirements for specific use. On the other hand, this makes it impossible to generalize about their chemical properties, such as toxicity, stability, biodegradability, flammability, greenness, etc. From an environmental perspective, DESs are superior to ILs due to their higher biodegradability and lower toxicity. The natural origin of the constituents gives DESs a great edge over ILs, because they are clearly less toxic and more environmentally friendly. Whereas IL components are onium salts, which show high toxicity [27]. Beside toxicology, biodegradability and recyclability factors, there are several other assessments that influence the green-chemistry quality of ILs: the long reaction time at high temperatures, the use of volatile and non-renewable solvents, the large quantities of chemicals, large quantity of by-products as waste, and high stability in water (ILs become persistent pollutants in wastewaters). Moreover, their different chemical properties encourage application areas which are significantly more varied (for example many enzymes exhibit both high activity and unexpected promising stability in DESs [28]).

4 Applications in analytical chemistry

Without a doubt, DESs and ILs share many interesting properties [20] which allow them to be applied in many fields of analytical chemistry (Figure 7) [29, 30]. These solvents are used in analytical chemistry mainly at the sample preparation stage for solvent-based and sorption-based extraction of target analytes from aqueous or solid samples, as stationary phase modifiers in GC, and also as mobile phase additives in LC, but in the case of DESs also for the dissolution or digestion of solid samples.

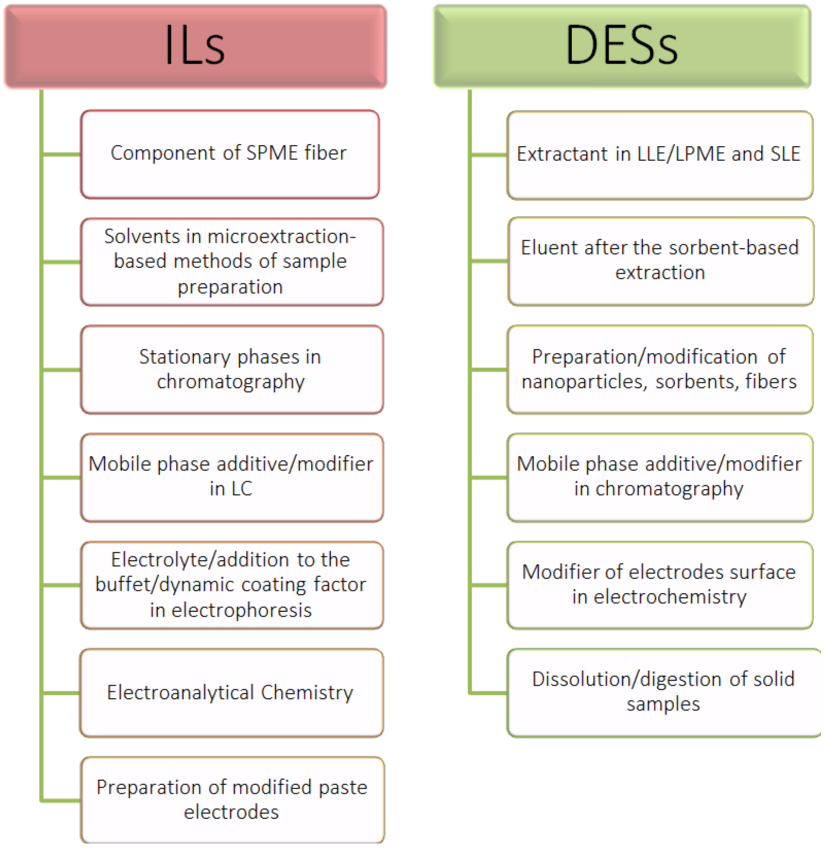
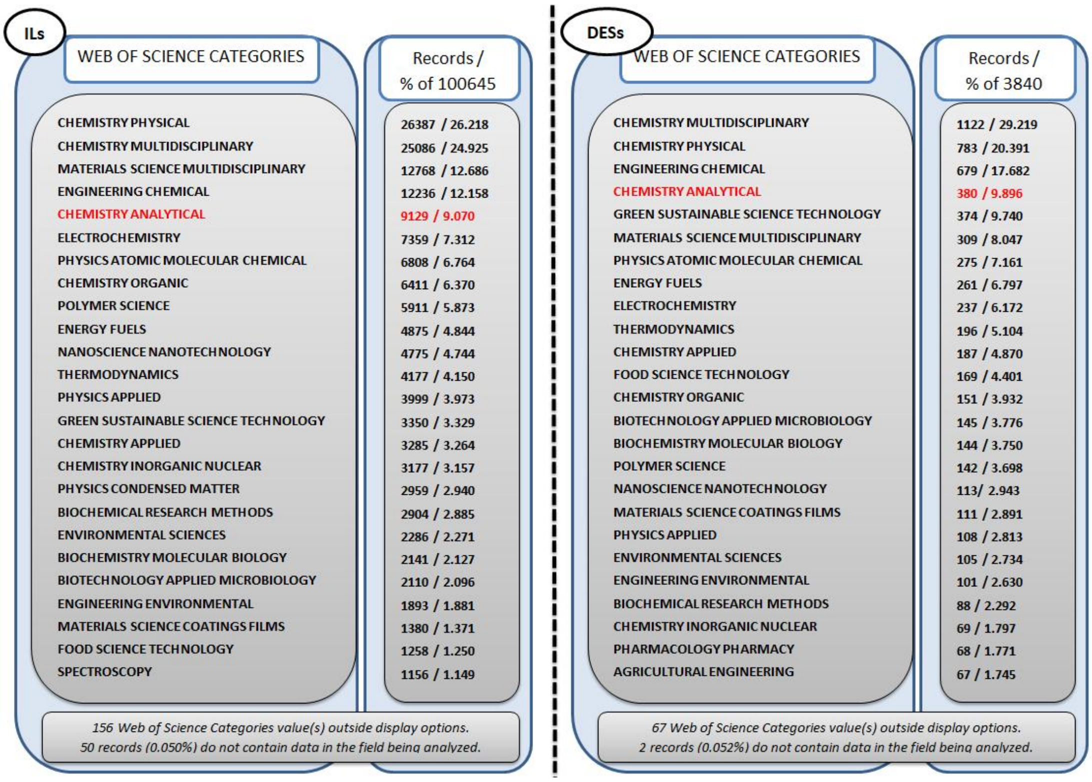


Figure 7. Application of ILs and DESs in the analytical chemistry

Despite the fact that the application areas of DESs are very close to those of ILs [13], the number of publications devoted to ILs is more than one order of magnitude higher than for DESs (Figure 8) especially concerning their use in analytical chemistry. This is probably because IL compounds were introduced into analytical science several years before the introduction of DESs. However, if we do not compare the absolute number of published papers in each category but their percentage distribution, the order of the categories for both solvents becomes very close. The category “chemistry analytical” is in the highest positions for both solvents. However, for example, the category of “green sustainable science technology” is much higher for DES than for IL.



ILs

WEB OF SCIENCE CATEGORIES	Records / % of 100645
CHEMISTRY PHYSICAL	26387 / 26.218
CHEMISTRY MULTIDISCIPLINARY	25086 / 24.925
MATERIALS SCIENCE MULTIDISCIPLINARY	12768 / 12.686
ENGINEERING CHEMICAL	12236 / 12.158
CHEMISTRY ANALYTICAL	9129 / 9.070
ELECTROCHEMISTRY	7359 / 7.312
PHYSICS ATOMIC MOLECULAR CHEMICAL	6808 / 6.764
CHEMISTRY ORGANIC	6411 / 6.370
POLYMER SCIENCE	5911 / 5.873
ENERGY FUELS	4875 / 4.844
NANOSCIENCE NANOTECHNOLOGY	4775 / 4.744
THERMODYNAMICS	4177 / 4.150
PHYSICS APPLIED	3999 / 3.973
GREEN SUSTAINABLE SCIENCE TECHNOLOGY	3350 / 3.329
CHEMISTRY APPLIED	3285 / 3.264
CHEMISTRY INORGANIC NUCLEAR	3177 / 3.157
PHYSICS CONDENSED MATTER	2959 / 2.940
BIOCHEMICAL RESEARCH METHODS	2904 / 2.885
ENVIRONMENTAL SCIENCES	2286 / 2.271
BIOCHEMISTRY MOLECULAR BIOLOGY	2141 / 2.127
BIOTECHNOLOGY APPLIED MICROBIOLOGY	2110 / 2.096
ENGINEERING ENVIRONMENTAL	1893 / 1.881
MATERIALS SCIENCE COATINGS FILMS	1380 / 1.371
FOOD SCIENCE TECHNOLOGY	1258 / 1.250
SPECTROSCOPY	1156 / 1.149

156 Web of Science Categories value(s) outside display options.
50 records (0.050%) do not contain data in the field being analyzed.

DESs

WEB OF SCIENCE CATEGORIES	Records / % of 3840
CHEMISTRY MULTIDISCIPLINARY	1122 / 29.219
CHEMISTRY PHYSICAL	783 / 20.391
ENGINEERING CHEMICAL	679 / 17.682
CHEMISTRY ANALYTICAL	380 / 9.896
GREEN SUSTAINABLE SCIENCE TECHNOLOGY	374 / 9.740
MATERIALS SCIENCE MULTIDISCIPLINARY	309 / 8.047
PHYSICS ATOMIC MOLECULAR CHEMICAL	275 / 7.161
ENERGY FUELS	261 / 6.797
ELECTROCHEMISTRY	237 / 6.172
THERMODYNAMICS	196 / 5.104
CHEMISTRY APPLIED	187 / 4.870
FOOD SCIENCE TECHNOLOGY	169 / 4.401
CHEMISTRY ORGANIC	151 / 3.932
BIOTECHNOLOGY APPLIED MICROBIOLOGY	145 / 3.776
BIOCHEMISTRY MOLECULAR BIOLOGY	144 / 3.750
POLYMER SCIENCE	142 / 3.698
NANOSCIENCE NANOTECHNOLOGY	113/ 2.943
MATERIALS SCIENCE COATINGS FILMS	111 / 2.891
PHYSICS APPLIED	108 / 2.813
ENVIRONMENTAL SCIENCES	105 / 2.734
ENGINEERING ENVIRONMENTAL	101 / 2.630
BIOCHEMICAL RESEARCH METHODS	88 / 2.292
CHEMISTRY INORGANIC NUCLEAR	69 / 1.797
PHARMACOLOGY PHARMACY	68 / 1.771
AGRICULTURAL ENGINEERING	67 / 1.745

67 Web of Science Categories value(s) outside display options.
2 records (0.052%) do not contain data in the field being analyzed.

Figure 8. Schematic representation of the type of chemistry categories versus percentage number of publications for ILs and DESs *(performed by application of Web of Science with permission. Keywords: Ionic Liquid, Deep Eutectic Solvent)*.

4. Advantages and drawbacks

ILs and DESs were found to be greener options when compared to conventional solvents. In comparison to ILs, the advantages of DESs concern their easy synthesis by simply mixing the components with gentle heating. In addition, no future purification is required, in contrast to ILs. Additionally, the cost of production is low due to the low prices of synthetic raw materials. Unfortunately, their high viscosity and solid state at room temperature could be detrimental. However, the physicochemical properties of DESs can be tailored by the selection of proper HBA and HBD and their molar ratio or the addition of water.

Although authors often report that most of these solvents, both ILs and DESs, are non-toxic, biocompatible and biodegradable, others state that more investigation is required on this matter, since the toxicity and cytotoxicity of DESs vary depending on the components. Therefore, cautious handling of the terms *non-toxicity* and *biodegradability* must be considered [31]. However, despite everything, DESs are believed to be more effective and environmentally friendly solvents than ILs.

While ILs are well understood, there are still some aspects that need further studies. In the case of DESs, studies are still limited and many unknowns exist. This is why there is a continuous need for research in this area. On the other hand, the potential of the solvents described herein opens interesting perspectives for further research in analytical chemistry as well as in industrial applications.

Conclusions

The aim of this work is to attract the attention of researchers using DES in their studies to the need for a proper use of terms. Although ILs and DESs have a lot in common, especially when it comes to physical properties and applications, from a chemical point of view, these are two separate groups of substances. However, from our point of view, it is important to focus on the mechanisms of DESs and ILs formation, as this could explain a lot of unknowns, e.g. their differences. It also would help to look for new applications in many fields of chemistry and, especially in analytical chemistry, while at the same time, correctly evaluating the greenness of these new solvent systems. Considering DESs as a subtype of ILs will lead to the forming of confused criteria for the selection of the applications in which they can be employed to enhance analytical perspectives.

In addition to analytical chemistry, we can expect new applications of DESs in pharmacy, medicine, cosmetics, food science and, very importantly, new knowledge in the field of theoretical study of DESs concerning their composition and extraction mechanism as well.

References

[1] A.P. Abbott, G. Capper, D.L. Davies, H.L. Munro, R.K. Rasheed, V. Tambyrajah, Preparation of novel, moisture-stable, Lewis-acidic ionic liquids containing quaternary ammonium salts with functional side chains, Chem. Commun. (19) (2001) 2010-2011.
[2] A.P. Abbott, G. Capper, D.L. Davies, R.K. Rasheed, V. Tambyrajah, Novel solvent properties of choline chloride/urea mixtures, Chem. Commun. (1) (2003) 70-71.
[3] A.P. Abbott, D. Boothby, G. Capper, D.L. Davies, R.K. Rasheed, Deep Eutectic Solvents formed between choline chloride and carboxylic acids: Versatile alternatives to ionic liquids, J. Am. Chem. Soc. 126(29) (2004) 9142-9147.
[4] M. Francisco, A.S.B. González, S.L. García De Dios, W. Weggemans, M.C. Kroon, Comparison of a low transition temperature mixture (LTTM) formed by lactic acid and choline chloride with choline lactate ionic liquid and the choline chloride salt: Physical properties and vapour-liquid equilibria of mixtures containing water and ethanol, RSC Adv. 3(45) (2013) 23553-23561.
[5] G. Imperato, E. Eibler, J. Niedermaier, B. König, Low-melting sugar-urea-salt mixtures as solvents for Diels-Alder reactions, Chem. Commun. (9) (2005) 1170-1172.
[6] H.R. Jhong, D.S.H. Wong, C.C. Wan, Y.Y. Wang, T.C. Wei, A novel deep eutectic solvent-based ionic liquid used as electrolyte for dye-sensitized solar cells, Electrochem. Commun. 11(1) (2009) 209-211.

[7] Y.H. Choi, J. van Spronsen, Y. Dai, M. Verberne, F. Hollmann, I.W.C.E. Arends, G.J. Witkamp, R. Verpoorte, Are natural deep eutectic solvents the missing link in understanding cellular metabolism and physiology?, Plant Physiology 156(4) (2011) 1701-1705.
[8] I.M. Aroso, A. Paiva, R.L. Reis, A.R.C. Duarte, Natural deep eutectic solvents from choline chloride and betaine – Physicochemical properties, J. Mol. Liq. 241 (2017) 654-661.
[9] P. Walden, Über die Molekulargrösse und elektrische Leitfähigkeit einiger geschmolzener Salze, Bull Acad Imper Sci (St Petersburg) (8) (1914) 405-422.
[10] K.N. Ruckart, R.A. O'Brien, S.M. Woodard, K.N. West, T.G. Glover, Porous Solids Impregnated with Task-Specific Ionic Liquids as Composite Sorbents, J. Phys. Chem. C 119(35) (2015) 20681-20697.
[11] J.P. Hallett, T. Welton, Room-temperature ionic liquids: Solvents for synthesis and catalysis. 2, Chem. Rev. 111(5) (2011) 3508-3576.
[12] W. Qian, J. Texter, F. Yan, Frontiers in poly(ionic liquid)s: Syntheses and applications, Chem. Soc. Rev. 46(4) (2017) 1124-1159.
[13] S.K. Singh, A.W. Savoy, Ionic liquids synthesis and applications: An overview, J. Mol. Liq. 297 (2020) 112038.
[14] E.L. Smith, A.P. Abbott, K.S. Ryder, Deep Eutectic Solvents (DESs) and Their Applications, Chem. Rev. 114(21) (2014) 11060-11082.
[15] X.H. Yao, D.Y. Zhang, M.H. Duan, Q. Cui, W.J. Xu, M. Luo, C.Y. Li, Y.G. Zu, Y.J. Fu, Preparation and determination of phenolic compounds from Pyrola incarnata Fisch. with a green polyols based-deep eutectic solvent, Sep. Purif. Technol. 149 (2015) 116-123.
[16] T. El Achkar, S. Fourmentin, H. Greige-Gerges, Deep eutectic solvents: An overview on their interactions with water and biochemical compounds, J. Mol. Liq. 288 (2019).
[17] A. Paiva, R. Craveiro, I. Aroso, M. Martins, R.L. Reis, A.R.C. Duarte, Natural deep eutectic solvents - Solvents for the 21st century, ACS Sustain. Chem. Eng. 2(5) (2014) 1063-1071.
[18] V. Migliorati, F. Sessa, P. D’Angelo, Deep eutectic solvents: A structural point of view on the role of the cation, Chem. Phys. Lett. X 2 (2019) 100001.
[19] R. Ratti, Ionic Liquids: Synthesis and Applications in Catalysis, Adv. Chem. Ser. (2014) 729842.
[20] C. Florindo, F.S. Oliveira, L.P.N. Rebelo, A.M. Fernandes, I.M. Marrucho, Insights into the synthesis and properties of deep eutectic solvents based on cholinium chloride and carboxylic acids, ACS Sustain. Chem. Eng. 2(10) (2014) 2416-2425.
[21] M.C. Gutiérrez, M.L. Ferrer, C.R. Mateo, F.D. Monte, Freeze-drying of aqueous solutions of deep eutectic solvents: A suitable approach to deep eutectic suspensions of self-assembled structures, Langmuir 25(10) (2009) 5509-5515.
[22] S.P. Kelley, A. Narita, J.D. Holbrey, K.D. Green, W.M. Reichert, R.D. Rogers, Understanding the Effects of Ionicity in Salts, Solvates, Co-Crystals, Ionic Co-Crystals, and Ionic Liquids, Rather than Nomenclature, Is Critical to Understanding Their Behavior, Cryst. Growth Des. 13(3) (2013) 965-975.
[23] B.D. Ribeiro, C. Florindo, L.C. Iff, M.A.Z. Coelho, I.M. Marrucho, Menthol-based Eutectic Mixtures: Hydrophobic Low Viscosity Solvents, ACS Sustain. Chem. Eng. 3(10) (2015) 2469-2477.
[24] M. Królikowska, M. Zawadzki, U. Domańska, D. Ramjugernath, P. Naidoo, The influence of temperature and composition on the density, viscosity and excess properties of aqueous mixtures of carboxylic-based ionic liquids, J. Chem. Thermodyn. 109 (2017) 71-81.
[25] M. Moghimi, A. Roosta, Physical properties of aqueous mixtures of (choline chloride + glucose) deep eutectic solvents, J. Chem. Thermodyn. 129 (2019) 159-165.
[26] M. Vilková, J. Płotka-Wasylka, V. Andruch, The role of water in deep eutectic solvent-base extraction, J. Mol. Liq. 304 (2020).
[27] R. Germani, M. Orlandini, M. Tiecco, T. Del Giacco, Novel low viscous, green and amphiphilic N-oxides/phenylacetic acid based Deep Eutectic Solvents, J. Mol. Liq. 240 (2017) 233-239.
[28] Q.B. Cheng, L.W. Zhang, Highly efficient enzymatic preparation of daidzein in deep eutectic solvents, Molecules 22(1) (2017).
[29] A. Shishov, A. Bulatov, M. Locatelli, S. Carradori, V. Andruch, Application of deep eutectic solvents in analytical chemistry. A review, Microchem. J. 135 (2017) 33-38.

[30] M. Opallo, A. Leśniewski, A review on electrodes modified with ionic liquids, J. Electroanal. Chem. 656 (2011) 2-16.

[31] M. Hayyan, M.A. Hashim, A. Hayyan, M.A. Al-Saadi, I.M. AlNashef, M.E.S. Mirghani, O.K. Saheed, Are deep eutectic solvents benign or toxic?, Chemosphere 90(7) (2013) 2193-2195.