



Quantum mechanical and molecular dynamic approaches to describe solvation effects by neoteric solvents

Rodrigo Ormazábal-Toledo^{1,2} and Renato Contreras²

This review deals with the problem of designing safer solvents for chemical transformation and chemical processes. These materials generically defined as neoteric solvents include the well known ionic liquids (ILs) and more recently, deep eutectic solvents (DESs). Super critical fluids also pertain to this class, but we will restrict our review to the former, IL and DES. The main object of this study is the description of properties of these solvents at a molecular level. Both IL and DES share a huge combinatorial flexibility leading to a formidable number of new solvents that can be prepared; and it is in this line that theory may help. This is because most of the binding properties to a wide variety of solutes may conveniently be described in terms of the electronic structure of matter, using quantum mechanical models, classical molecular dynamics and ab-initio molecular dynamics. The theoretical approach helps in the task of identifying and predicting optimal structures for specific applications.

Addresses

¹ Centro Integrativo de Biología y Química Aplicada (CIBQA), Universidad Bernardo OHiggins, Santiago, 8370854, Chile

² Departamento de Química, Facultad de Ciencias, Universidad de Chile, Las Palmeras 3425, Casilla 653, Santiago, Chile

Corresponding author: Contreras, Renato (rcontrer@uchile.cl)

Current Opinion in Green and Sustainable Chemistry 2020, 26:100395

This reviews comes from a themed issue on **Special Issue on South America**

Edited by **Vania Zuin** and **Rodrigo O.M.A. de Souza**

Available online 22 September 2020

For complete overview of the section, please refer the article collection - [Special Issue on South America](#)

<https://doi.org/10.1016/j.cogsc.2020.100395>

2452-2236/© 2020 Elsevier B.V. All rights reserved.

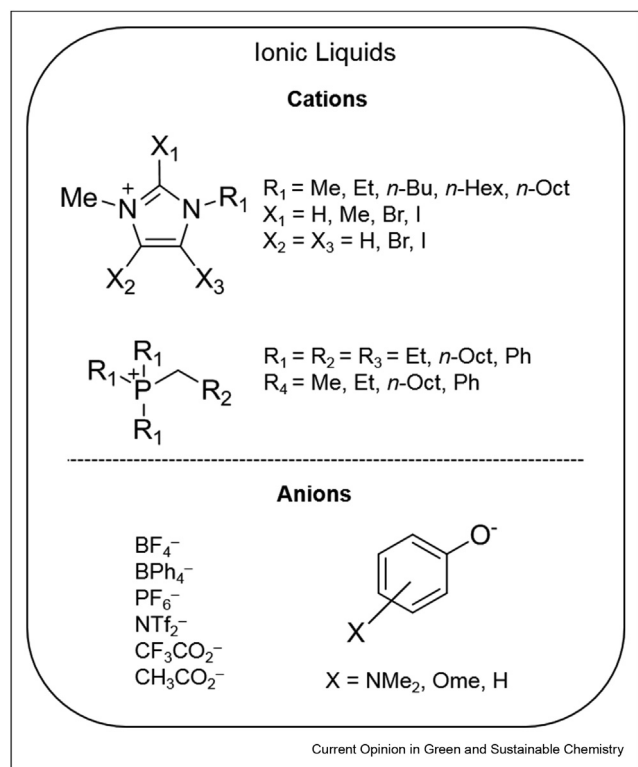
Introduction

The detailed mechanism of solvation involves the type of molecular interactions that are operative in the complex solvating process. From the early 70s, solvation effects were introduced within the quantum mechanical (QM) implementation of the reaction field theory through the polarization charge model using continuum dielectrics [1–3]. However, the application of reaction field models to describe solvation by ionic liquids (ILs)

and deep eutectic solvents (DESs) resulted in a complex challenge in the case of the former because their experimental determined dielectric constants felt in a very narrow range of variations, thereby giving a low resolution in the free energies of solvation for different IL and solutes [4,5]. A similar problem arises for DES. An alternative solution for this problem was the application of solvatochromic shift model of Kamlet and Taft which introduces empirical solvent parameters such as acidity (α), basicity (β), and polarizability (π) [6–8]. Combined dielectrics plus Kamlet–Taft parameters has been rather recently proposed with some success [9–12]. The main issue when dealing with solvation by IL is that these salts are associated to a very low extent, thereby limiting the ‘ion pair’ modelling because it is not clear how many of these ionic structures could represent more realistically a given IL. It is interesting however to consider a mixed QM and molecular dynamics (MD) approaches that can provide significant structures obtained from MD calculations, to introduce them as an “input” for a quantum chemical calculation using the supermolecule approach [13–16]. It is worth emphasizing here that DES share the same problem as IL in the sense that the application of continuum dielectric models will fail because the narrow variability of their dielectric constants. ILs are a class of organometallic salts that melt at temperatures below or near 100 °C. They received an increasing attention from the early 90s because their physicochemical properties (low vapour pressure, wide electrochemical windows, easy preparation, sometimes showing catalytic properties and other eco-friendly properties) that made the Chemistry community to increasingly use them as a first choice reaction media [17,18]. However, the presence of inorganic anions (mainly those including, for instance, phosphorus, sulphur, and cyanide-based anions), put into jeopardy their greenness because the toxicity issue. However, their extremely high combinatorial flexibility (1012 – 1014 possible combinations) rapidly led to the idea that the probability of finding the right (optimal) solvent for a specific applications was included within this huge number of combinations, leading to the concept of task-specific solvents introduced by Welton [17] (refer [Figure 1](#) for a general picture of IL).

At the same time, the quest for this task-specific solvent became a problem similar to that of finding a needle in a haystack. It is at this point that theory became as a useful tool to identify the most useful solvent suitable

Figure 1



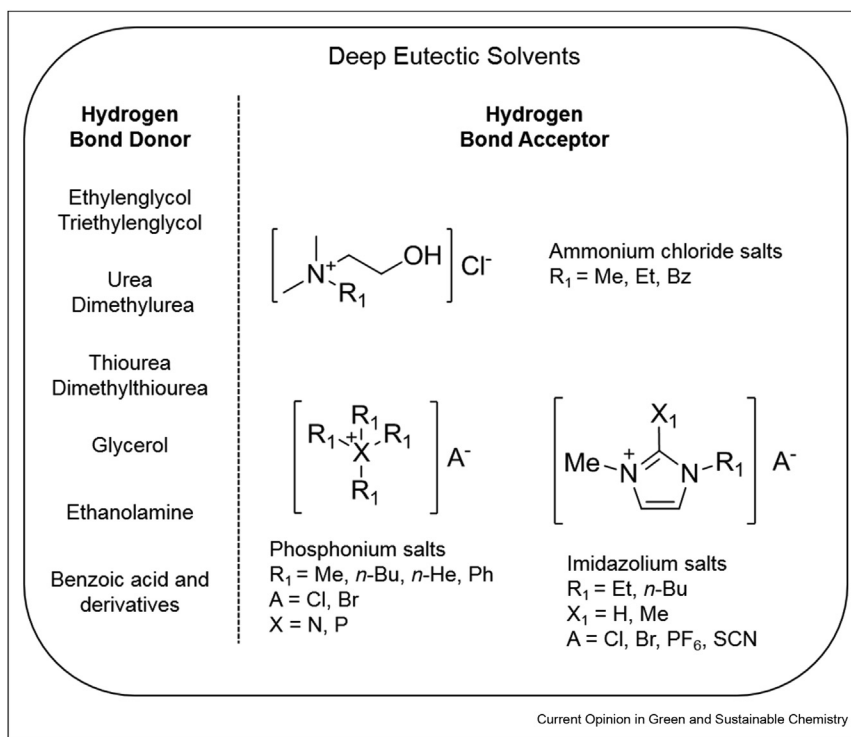
General structure of different ionic liquids.

for a specific application. The first attempt to achieve this task was the application of the current model of solvent effects based on effective polarization charges, derived from the reaction field theory, representing the solvent as a polarizable dielectric medium [1–3]. However, experimentally determined dielectric constants fell within a very narrow range, thereby producing the unusual result that any solute solvated in any IL displayed free energies of solvation with a too low resolution [9,19]. However, the combination of the reaction field model with Kamlet–Taft parameters significantly alleviated this problem. This model is still in use for some applications [20,21]. The main problem of these unspecific representation of the solvent modelled through an external electric field is certainly the poor representation of specific solute–solvent interactions (mainly hydrogen bond networks). On the other hand, the presence of organometallic moieties (mainly anions) in the IL structure strongly restricted their application in biological chemistry, biochemistry, and life sciences. Therefore, the preparation of some organic salts prompted Abbott et al. [22] to introduce the DESs that included a new class of metal-free solvents amenable to be applied in a more wide range of innocuous processes including those related to life

sciences [23,24]. DESs can be defined as the eutectic mixtures formed by two or more phase-immiscible components, which results in a new homogeneous liquid phase with lower freezing point than those observed for individual counterparts (refer Figure 2).

The forming unities of DES are Lewis or Brønsted acids and bases which can contain a variety of neutral, anionic and/or cationic species. These simplest class of DES, that can be more easily prepared does not contain metal salts, but organic species, with similar performances and physical properties than those of type 1 and 2 [22,25]. Some of them are shown in Figure 2. DES has somewhere been perceived as a new class of IL because they share many properties. However, it has been recently pointed out that IL and DES are two different types of solvents [22,24,25]. Among the main properties that DES and IL share, there is, again, their high combinatorial flexibility, suggesting that theoretical methods are clearly the suitable way to achieve their microscopic characterization. DES have been increasingly been applied in many chemical processes, namely: electrochemistry [26–31], synthesis of metal nanoparticles [32,33] and chemical engineering [34–39]. The application of DES has increasingly received attention in organic synthesis, kinetics and organocatalysis. The most relevant work describing a wide spectrum of classical organic transformations include: the review by Kumar et al. that compile about 33 types of organic reactions [40]; and a more recent review work by Punzi et al. [41] including redox reactions, esterification-type reactions, condensation reactions, multicomponent reactions, cyclization reactions and a significant number of miscellaneous reactions that focus on different carbon–carbon and carbon–heteroatom bond formation processes. However, one striking fact concerning organic reactions in DES is the scarce body of data regarding the kinetics of the huge set of organic reactions experimentally studied up to date. Among the few literature devoted to this field, we can mention some studies that are restricted to report time of reactions and product yields [40,41]. From a theoretical point of view, the description of solvation effects on the kinetics and reaction mechanism in DES is even scarcer respect to the chemistry in IL. Instead, the few efforts made in the theory of molecular interactions mainly refer to the simulation of the physical properties, such as thermodynamic properties of choline chloride-based DES using QM approach, namely evaluation of hydrogen bonding network and other noncovalent interactions in the absence of a third body (i.e. the solute) [42,43]. Another useful antecedent is related to experiments of dielectric relaxations in the acetamide/electrolyte system that provides low- and high-intensity dielectric constants that are qualitatively similar to the dielectric responses found in ILs: their dielectric constants, even though greater than those displayed by IL, fall in a narrow range of variations [44].

Figure 2



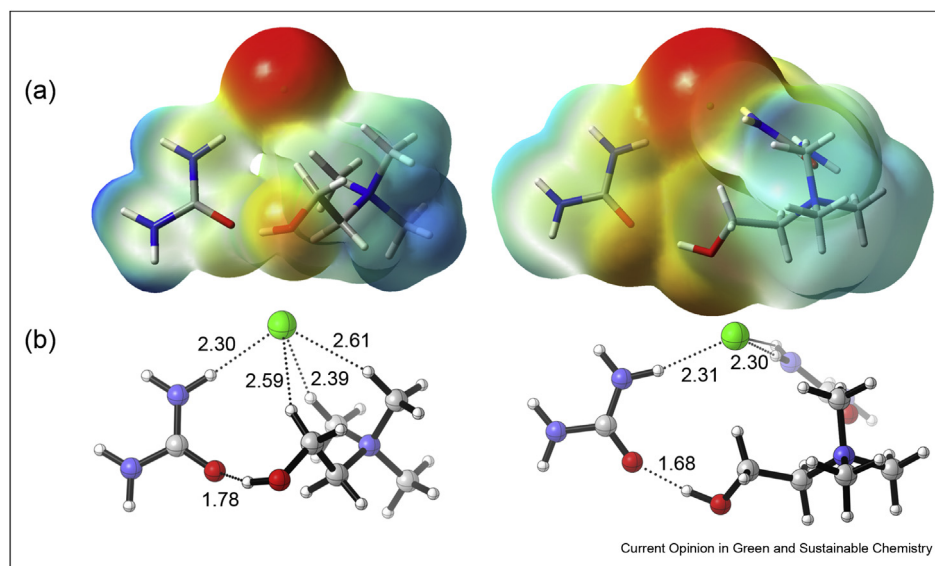
Structures of some halide salts and hydrogen bond donors used in the formation of nonmetallic DES.

QM approach to solvation effects by IL and DES

The presence of hydrogen bond donors (HBDs) moieties opens the possibility of assessing the hydrogen bond (HB) ability of IL and DES using simple tools from QM methods beyond dielectric models. As stated before ion pairs are not the best choice to mimic IL structures. Similar restrictions apply for DES, as the proportion in which (HBD) and hydrogen bond acceptor (HBA) components must be combined to achieve optimal solvation properties is a key aspect for designing task-specific DES. The way QM operates in assisting the identification of molecular regions amenable to act as HBD or HBA moieties are mainly based on regional reactivity indices, based on the concept of electronic chemical potential, derived in the context of density functional theory [45,46]. The electronic chemical potential is a suitable model to describe the direction and amount of charge transfer after a proton migrates from a donor to acceptor, or vice versa, and it is the natural descriptor of HBD and HBA abilities of molecules or fragments because charge transfer is a process that takes place in the opposite direction of proton migration [45,46]. The electronic chemical potential may be easily available from the one-electron frontier

energy levels HOMO and LUMO [45,46]. However, a more elaborated and quantitative criterium for charge transfer are the concepts of regional electrophilicity and nucleophilicity [47,48], accounting for electron density acceptance (i.e. HBA) or electron density releasing properties (i.e. HBD) abilities [47,48]. This general methodology applies for both IL and DES systems. There remains however the evaluation of the residual electrophilicity/nucleophilicity patterns of IL and DES systems. These properties allow the location of optimal sites or regions suitable for binding a third body, namely a potential solute. They have been already described as 'excess' properties [45,46]. As an illustration, consider, for instance, a super molecule model for the simplest choline chloride + urea DES in two elemental compositions. It is easy to evaluate the nucleophilic and electrophilic centres of this model aggregates by simply evaluating their molecular electrostatic potentials as shown in Figure 3. Such a simple model allows us to determine the residual nucleophilic (blue) and electrophilic (red) sites amenable to bind a solute via HB interactions. This qualitative picture may be the first step to further elaborate quantum chemical calculation leading, for instance, to assess the stabilization of reactants and transition state structures in the potential energy

Figure 3



Molecular electrostatic potentials for model DES. (a) Electrostatic potentials for 1:1 choline chloride + urea DES (left) and 1:2 choline chloride + urea DES (right) and (b) Hydrogen bonding properties for 1:1 choline chloride + urea DES (left) and 1:2 choline chloride + urea DES. The properties were evaluated at the M06–2x/6-31+G(d,p) level of theory.

surface, thereby opening the possibility of discussing possible reaction mechanisms and activation parameters.

MD approach

After considering the several restrictions imposed by using ‘ion pairs’ to model IL structures, some authors were prompted to consider the application of classical MD simulations. MD has been applied for describing solvation effects promoted by IL [49–54]. From the pioneer work by Canongia-Lopez and Padua [50,55–57] different parameterizations were introduced for a proper description of IL by using a systematic force field called CL&P [57,58], obtained from the OPLS force field introduced by Jorgensen et al. [59] and Sambasivarao and Acevedo [60]. To some extent, the description of specific cation/anion interactions and solute–cation/anion interactions allowed a cogent prediction of the task specificity of IL [53]. The use of Ab-initio MD (AIMD) allowed describing chemical reactions in IL, such as chemical fixation of gases and formation of reactive species derived from IL, as a new generation of potential catalysts [61,62]. Classical MD methods have also been reported for pure DES. An interesting point here is that the HBD ability can be related by coordination number indices, obtained from the Radial Function Distribution ($g(r)$) which is used to discuss HB interaction in pure and aqueous DES [63–68]. Similarly, the formation of amphiphilic nanostructures reminiscent to the organization in IL have been discussed by Warr and Atking by using MD [62]. A final word worth mentioning concerning MD studies on HB properties of DES is the

fact that higher aggregates containing water to diminish the high viscosity of some pure DES show that the acidity/basicity is marginally modified with reference to pure DES, resulting in an “alphabet soup” of Hydrogen bonds [69]. This result is relevant for it, viscosity may be one of the main factors on which reaction rates do depends [40,63,70–72]. Different efforts have been made for the systematic molecular description of DES. However, in contrast to IL media, the problematic ion–ion (i.e. solvent–solvent) interactions in IL, are reduced to the weaker ion-dipole ones, that are better suited for simulations. Note however, that the absence of a systematical force field, as well as the little information obtained from AIMD, makes solvation by DES to remain as an open problem [51,65,73,74].

AIMD approach

Different articles regarding AIMD studies in the field of IL and DES have been recently published. In this sense, the main goals on this techniques pointed out on structural network in IL and DES systems allowing the prediction of IR spectra [75,76]. For instance, in protic alkylammonium nitrate IL, AIMD reveals that for longer side chains, more ions can be coordinated. This result may be related to higher peaks in the RDF distributions [77]. Similarly to the results obtained by classical MD simulations in DES, in AIMD, the spatial distribution of chloride surrounding choline reveals a strong hydrogen bond network that is poorly described using static calculations using the supermolecule approach [78]. Moreover, the most promising results have been obtained in the optimization of charges along the simulation. For instance, in

DES based on choline chloride with different organic ILs, a charge spreading was observed diminishing the charge over chloride from $-1.0 e$ in the gas phase to $-0.40 e$ in the solution phase [76]. Similar results were obtained for different IL [79]. These results opens a new paradigm in the development of force field for the description of IL and DES: charge spreading might be considered for a proper description of ion–ion interactions to achieve a better description of bulk properties in a novel polarizable force field for IL and DES [80–83].

Concluding remarks and outlook

This review strongly emphasizes that solvation models based on reaction field theory for the title solvents are no longer the first choice methodology. On the other hand, empirical solvatochromic models should be better suited for DES compared to IL because the determination of Kamlet–Taft parameters is better assessed in the absence of the complex ion–ion interactions. However, MD methods seem to provide the best approach to describe solvation properties in IL and DES, because MD approaches provide a more realistic molecular picture of these solvents. Consider for instance the role of water to attenuate their high viscosity, as well as the optimal proportion of HBD and HBA components. Moreover, the use of more robust methods to unravel the catalytic properties as well as for the development of best suited polarizable force field of both IL and DES is mandatory from now on.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgements

The authors thanks to project FONDECYT 1160061.

References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest

- Constanciel R, Contreras R: **Self consistent field theory of solvent effects representation by continuum models: introduction of desolvation contribution.** *Theor Chim Acta* 1984, **65**: 1–11.
- Tomasi J, Mennucci B, Cammi R: **Quantum mechanical continuum solvation models.** *Chem Rev* 2005, **105**:2999–3093.
- Marenich AV, Cramer CJ, Truhlar DG: **Universal solvation model based on solute electron density and on a continuum model of the solvent defined by the bulk dielectric constant and atomic surface tensions.** *J Phys Chem B* 2009, **113**: 6378–6396.
- Singh T, Kumar A: **Static dielectric constant of room temperature ionic liquids: internal pressure and cohesive energy density approach.** *J Phys Chem B* 2008, **112**:12968–12972.
- Weingärtner H: **The static dielectric permittivity of ionic liquids.** *J Mol Liq* 2014, **192**:185–190.
- Dolan DA, Sherman DA, Atkin R, Warr GG: **Kamlet-taft solvation parameters of solvate ionic liquids.** *ChemPhysChem* 2016, **17**: 3096–3101.
- Lee JM, Ruckes S, Prausnitz JM: **Solvent polarities and Kamlet-Taft parameters for ionic liquids containing a pyridinium cation.** *J Phys Chem B* 2008, **112**:1473–1476.
- Crowhurst L, Mawdsley PR, Perez-Arlandis JM, Salter PA, Welton T: **Solvent-solute interactions in ionic liquids.** *Phys Chem Chem Phys* 2003, **5**:2790–2794.
- Bernales VS, Marenich AV, Contreras R, Cramer CJ, Truhlar DG: **Quantum mechanical continuum solvation models for ionic liquids.** *J Phys Chem B* 2012, **116**:9122–9129.
- Wang N, Lee JK: **Gas-phase and ionic liquid experimental and computational studies of imidazole acidity and carbon dioxide capture.** *J Org Chem* 2019, **84**:14593–14601.
- Yan H, Zhao L, Bai Y, Li F, Dong H, Wang H, Zhang X, Zeng S: **Superbase ionic liquid-based deep eutectic solvents for improving CO₂ absorption.** *ACS Sustainable Chem Eng* 2020, **8**:2523–2530.
- Yang Y, Liu Y, Zhu R, Liu C, Zhang D: **Theoretical insight into the mechanism and origin of divergent reactivity in the synthesis of benzo-heterocycles from o-alkynylbenzamides catalyzed by gold and platinum complexes.** *J Org Chem* 2019, **84**:9705–9713.
- Lodeiro L, Contreras R, Ormazábal-Toledo R: **How meaningful is the halogen bonding in 1-Ethyl-3-methyl imidazolium-based ionic liquids for CO₂ capture?** *J Phys Chem B* 2018, **122**:7907–7914.
- the article compares molecular dynamics predictions with quantum chemistry calculations in Imidazolium-based Ionic Liquids.
- Shen L, Yang W: **Molecular dynamics simulations with quantum mechanics/molecular mechanics and adaptive neural networks.** *J Chem Theor Comput* 2018, **14**:1442–1455.
- O'Connor MB, Bennie SJ, Deeks HM, Jamieson-Binnie A, Jones AJ, Shannon RJ, Walters R, Mitchell TJ, Mulholland AJ, Glowacki DR: **Interactive molecular dynamics in virtual reality from quantum chemistry to drug binding: an open-source multi-person framework.** *J Chem Phys* 2019, **150**:220901.
- Borodin O, Smith GD: **Quantum chemistry and molecular dynamics simulation study of dimethyl carbonate: ethylene carbonate electrolytes doped with LiPF₆.** *J Phys Chem B* 2009, **113**:1763–1776.
- Welton T: **Room-Temperature ionic liquids. Solvents for synthesis and catalysis.** *Chem Rev* 1999, **99**:2071–2083.
- Hallett JP, Welton T: **Room-temperature ionic liquids: solvents for synthesis and catalysis. 2.** *Chem Rev* 2011, **111**: 3508–3576.
- Filippi C, Zaccheddu M, Buda F: **Absorption spectrum of the green fluorescent protein chromophore: a difficult case for ab initio methods?** *J Chem Theor Comput* 2009, **5**:2074–2087.
- Dai C, Zhang J, Huang C, Lei Z: **Ionic liquids in selective oxidation: catalysts and solvents.** *Chem Rev* 2017, **117**:6929–6983.
- Cláudio AFM, Swift L, Hallett JP, Welton T, Coutinho JA, Freire MG: **Extended scale for the hydrogen-bond basicity of ionic liquids.** *Phys Chem Chem Phys* 2014, **16**:6593–6601.
- Abbott AP, Capper G, Davies DL, Munro HL, Rasheed RK, Tambyrajah V: **Preparation of novel, moisture-stable, lewis-acidic ionic liquids containing quaternary ammonium salts with functional side chains.** *Chem Commun* 2001, **1**: 2010–2011.
- Rogers R, Gurau G: **Is "choline and geranate" an ionic liquid or deep eutectic solvent system?** *Proc Natl Acad Sci USA* 2018, **115**:E10999.
- Banerjee A, Ibsen K, Brown T, Chen R, Agatemor C, Mitragotri S: **Definitions of ionic liquids and deep eutectic solvents.** *Proc Natl Acad Sci USA* 2018, **115**:E11000–E11001.
- the article gives a concise definition and discuss differences between Ionic Liquids and Deep Eutectic Solvents.

25. Longo LS, Craveiro MV: **Deep eutectic solvents as unconventional media for multicomponent reactions.** *J Braz Chem Soc* 2018, **29**.
26. Alesary HF, Cihangir S, Ballantyne AD, Harris RC, Weston DP, Abbott AP, Ryder KS: **Influence of additives on the electro-deposition of zinc from a deep eutectic solvent.** *Electrochim Acta* 2019, **304**:118–130.
27. Bernasconi R, Lucotti A, Nobili L, Magagnin L: **Ruthenium electrodeposition from deep eutectic solvents.** *J Electrochem Soc* 2018, **165**:D620–D627.
28. Manolova M, Böck R: **Electrodeposition of Pd from a deep eutectic solvent system: effect of additives and hydrodynamic conditions.** *Trans Inst Met Finish* 2019, **97**:161–168.
29. Huang P, Zhang Y: **Electrodeposition of nickel coating in choline chloride-urea deep eutectic solvent.** *Int. J. Electrochem. Sci.* 2018, **13**:10798–10808.
30. Kopczyński K, Lota G: **Electrocatalytic properties of a cerium/nickel coating deposited using a deep eutectic solvent.** *Electrochem Commun* 2019, **107**:106538.
31. Li R, Dong Q, Xia J, Luo C, Sheng L, Cheng F, Liang J: **Electrodeposition of composition controllable Zn–Ni coating from water modified deep eutectic solvent.** *Surf Coating Technol* 2019, **366**:138–145.
32. Adhikari L, Larm NE, Bhawawet N, Baker GA: **Rapid microwave-assisted synthesis of silver nanoparticles in a halide-free deep eutectic solvent.** *ACS Sustain Chem Eng* 2018, **6**: 5725–5731.
33. Li A, Duan W, Liu J, Zhuo K, Chen Y, Wang J: **Electrochemical synthesis of AuPt nanoflowers in deep eutectic solvent at low temperature and their application in organic electro-oxidation.** *Sci Rep* 2018, **8**:1–9.
34. Anggara S, Bevan F, Harris RC, Hartley JM, Frisch G, Jenkin GR, Abbott AP: **Direct extraction of copper from copper sulfide minerals using deep eutectic solvents.** *Green Chem* 2019, **21**: 6502–6512.
35. Söldner A, Zach J, König B: **Deep eutectic solvents as extraction media for metal salts and oxides exemplarily shown for phosphates from incinerated sewage sludge ash.** *Green Chem* 2019, **21**:321–328.
36. Cui G, Lv M, Yang D: **Efficient CO₂ absorption by azolide-based deep eutectic solvents.** *Chem Commun* 2019, **55**: 1426–1429.
37. Mukesh C, Khokarale SG, Virtanen P, Mikkola JP: **Rapid desorption of CO₂ from deep eutectic solvents based on polyamines at lower temperatures: an alternative technology with industrial potential.** *Sustain. Energy Fuels* 2019, **3**: 2125–2134.
38. Trotter DZ, Todorović ZB, Dokić-Stojanović DR, Stamenković OS, Veljković VB: **Application of ionic liquids and deep eutectic solvents in biodiesel production: a review.** *Renew Sustain Energy Rev* 2016, **61**:473–500.
39. Zhao H, Baker GA: **Ionic liquids and deep eutectic solvents for biodiesel synthesis: a review.** *J Chem Technol Biotechnol* 2013, **88**:3–12.
40. Khandelwal S, Tailor YK, Kumar M: **Deep eutectic solvents (DESs) as eco-friendly and sustainable solvent/catalyst systems in organic transformations.** *J Mol Liq* 2016, **215**:345–386.
- this review presents a general picture about Deep Eutectic Solvent as synthesis, physicochemical properties and catalytic properties in industrial applications.
41. Punzi A, Coppi DI, Matera S, Capozzi MA, Operamolla A, Ragni R, Babudri F, Farinola GM: **Pd-catalyzed thiophene-aryl coupling reaction via C–H bond activation in deep eutectic solvents.** *Org Lett* 2017, **19**:4754–4757.
- the works presents a C–H bond activation method in Deep Eutectic Solvents.
42. Wagle DV, Zhao H, Deakynne CA, Baker GA: **Quantum chemical evaluation of deep eutectic solvents for the extractive desulfurization of fuel.** *ACS Sustain Chem Eng* 2018, **6**: 7525–7531.
43. Atilhan M, Altamash T, Aparicio S: **Quantum chemistry insight into the interactions between deep eutectic solvents and SO₂.** *Molecules* 2019, **24**:2963.
44. Mukherjee K, Das A, Choudhury S, Barman A, Biswas R: **Dielectric Relaxations of (Acetamide + electrolyte) deep eutectic solvents in the frequency window, 0.2 ≤ ν/GHz ≤ 50: anionic and cation dependence.** *J Phys Chem B* 2015, **119**: 8063–8071.
45. Cerda-Monje A, Aizman A, Tapia RA, Chiappe C, Contreras R: **Solvent effects in ionic liquids: empirical linear energy–density relationships.** *Phys Chem Chem Phys* 2012, **14**:10041–10049.
46. Contreras R, Aizman A, Tapia RA, Cerda-Monje A: **Lewis molecular acidity of ionic liquids from empirical energy–density models.** *J Phys Chem B* 2013, **117**:1911–1920.
47. Domingo LR, Aurell MJ, Pérez P, Contreras R: **Quantitative characterization of the local electrophilicity of organic molecules. understanding the regioselectivity on dielsalder reactions.** *J Phys Chem A* 2002, **106**:6871–6875.
48. Ormazábal-Toledo R, Campodónico PR, Contreras R: **Are electrophilicity and electrofugality related concepts? a density functional theory study.** *Org Lett* 2011, **13**:822–824.
49. Hayes R, Warr G, Atkin R: **Structure and nanostructure in ionic liquids.** *Chem Rev* 2015, **115**:6357–6426.
50. Canongia Lopes J, Pádua A: **Nanostructural organization in ionic liquids.** *J Phys Chem B* 2006, **110**:3330–3335.
51. Bedrov D, Piquemal J-P, Borodin O, MacKerell A, Roux B, Schröder C: **Molecular dynamics simulations of ionic liquids and electrolytes using polarizable force fields.** *Chem Rev* 2019, **119**:7940–7995.
- this review presents different studies about the simulation of Ionic Liquids by using Molecular Dynamics, discussing different Force Fields.
52. O. Russina, F. Lo Celso, N. Plechkova, C. Jafta, G. Appetecchi, A. Triolo, Mesoscopic organization in ionic liquids, *Top. Curr. Chem.* 375.
53. Dong K, Liu X, Dong H, Zhang X, Zhang S: **Multiscale studies on ionic liquids.** *Chem Rev* 2017, **117**:6636–6695.
54. Gehrke S, Von Domaros M, Clark R, Hollóczki O, Brehm M, Welton T, Luzar A, Kirchner B: **Structure and lifetimes in ionic liquids and their mixtures.** *Faraday Discuss* 2018, **206**: 219–245.
55. Canongia Lopes J, Deschamps J, Pádua A: **Modeling ionic liquids using a systematic all-atom force field.** *J Phys Chem B* 2004, **108**:2038–2047.
56. Freire M, Cláudio A, Araújo J, Coutinho J, Marrucho I, Lopes J, Rebelo L: **Aqueous biphasic systems: a boost brought about by using ionic liquids.** *Chem Soc Rev* 2012, **41**:4966–4995.
57. Pádua A, Costa Gomes M, Canongia Lopes J: **Molecular solutes in ionic liquids: a structural perspective.** *Acc Chem Res* 2007, **40**:1087–1096.
58. Bernardes C, Canongia Lopes J: **Modeling halogen bonds in ionic liquids: a force field for imidazolium and haloimidazolium derivatives.** *J Chem Theor Comput* 2017, **13**: 6167–6176.
59. Jorgensen W, Maxwell D, Tirado-Rives J: **Development and testing of the opls all-atom force field on conformational energetics and properties of organic liquids.** *J Am Chem Soc* 1996, **118**:11225–11236.
60. Sambasivarao S, Acevedo O: **Development of opls-aa force field parameters for 68 unique ionic liquids.** *J Chem Theor Comput* 2009, **5**:1038–1050.
61. Clarke C, Tu W-C, Levers O, Bröhl A, Hallett J: **Green and sustainable solvents in chemical processes.** *Chem Rev* 2018, **118**:747–800.
- this review presents relevant information about using Green Solvents in Chemical Industries.
62. Warr G, Atkin R: **Solvophobicity and amphiphilic self-assembly in neoteric and nanostructured solvents.** *Curr Opin Colloid Interface Sci* 2020, **45**:83–96.

this review discuss the knowledge on the nanostructure and 3D networks in DES and IL.

63. Hossain S, Paul S, Samanta A: **Liquid structure and dynamics of tetraalkylammonium bromide-based deep eutectic solvents: effect of cation chain length.** *J Phys Chem B* 2019, **123**: 6842–6850.
64. Korotkevich A, Firaha D, Padua A, Kirchner B: **Ab initio molecular dynamics simulations of SO₂ solvation in choline chloride/glycerol deep eutectic solvent.** *Fluid Phase Equil* 2017, **448**:59–68.
65. Doherty B, Acevedo O: **OPLS force field for choline chloride-based deep eutectic solvents.** *J Phys Chem B* 2018, **122**: 9982–9993.
66. Migliorati V, Sessa F, D'Angelo P: **Deep eutectic solvents: a structural point of view on the role of the cation.** *Chem Phys Lett: X* 2019, **2**:100001.
67. Perkins S, Painter P, Colina C: **Experimental and computational studies of choline chloride-based deep eutectic solvents.** *J Chem Eng Data* 2014, **59**:3652–3662.
68. Stefanovic R, Ludwig M, Webber G, Atkin R, Page A: **Nanostructure, hydrogen bonding and rheology in choline chloride deep eutectic solvents as a function of the hydrogen bond donor.** *Phys Chem Chem Phys* 2017, **19**:3297–3306.
69. Ashworth CR, Matthews RP, Welton T, Hunt PA: **Doubly ionic hydrogen bond interactions within the choline chloride–urea deep eutectic solvent.** *Phys Chem Chem Phys* 2016, **18**: 18145–18160.
70. Abbott A, Boothby D, Capper G, Davies D, Rasheed R: **Deep eutectic solvents formed between choline chloride and carboxylic acids: versatile alternatives to ionic liquids.** *J Am Chem Soc* 2004, **126**:9142–9147.
71. Zhekenov T, Toksanbayev N, Kazakbayeva Z, Shah D, Mjalli F: **Formation of type III Deep Eutectic Solvents and effect of water on their intermolecular interactions.** *Fluid Phase Equil* 2017, **441**:43–48.
72. Meng X, Ballerat-Busserolles K, Husson P, Andanson J-M: **Impact of water on the melting temperature of urea + choline chloride deep eutectic solvent.** *New J Chem* 2016, **40**: 4492–4499.
73. Pham T: **Ab initio simulations of liquid electrolytes for energy conversion and storage.** *Int J Quant Chem* 2019, **119**.
74. Fetisov E, Harwood D, Kuo I-F, Warrag S, Kroon M, Peters C, Siepmann J: **First-principles molecular dynamics study of a deep eutectic solvent: choline chloride/urea and its mixture with water.** *J Phys Chem B* 2018, **122**:1245–1254.
75. Lassègues J-C, Grondin J, Cavagnat D, Johansson P: **New interpretation of the ch stretching vibrations in imidazolium-based ionic liquids.** *J Phys Chem A* 2009, **113**:6419–6421.
76. Zahn S, Kirchner B, Mollenhauer D: **Charge spreading in deep eutectic solvents.** *ChemPhysChem* 2016, **17**:3354–3358.
77. Campetella M, Macchiagodena M, Gontrani L, Kirchner B: **Effect of alkyl chain length in protic ionic liquids: an aimed perspective.** *Mol Phys* 2017, **115**:1582–1589.
78. Zahn S: **Deep eutectic solvents: similia similibus solvuntur?** *Phys Chem Chem Phys* 2017, **19**:4041–4047.
79. Jiang K, Liu X, Huo F, Dong K, Zhang X, Yao X: **Viscosity calculation of 1-ethyl-3-methylimidazolium chloride ionic liquids based on three-body potential hydrogen bond model.** *J Mol Liq* 2018, **271**:550–556.
80. García G, Atilhan M, Aparicio S: **The impact of charges in force field parameterization for molecular dynamics simulations of deep eutectic solvents.** *J Mol Liq* 2015, **211**:506–514.
81. Goloviznina K, Canongia Lopes JN, Costa Gomes M, Pádua AAH: **Transferable, polarizable force field for ionic liquids.** *J Chem Theor Comput* 2019, **15**:5858–5871.
82. Bernardino K, Goloviznina K, Gomes MC, Pádua AAH, Ribeiro MCC: **Ion pair free energy surface as a probe of ionic liquid structure.** *J Chem Phys* 2020, **152**, 014103.
83. Koverga V, Kalugin ON, Miannay F-A, Smortsova Y, Goloviznina K, Marekha B, Jedlovszky P, Idrissi A: **The local structure in the bmimpf6/acetonitrile mixture: the charge distribution effect.** *Phys Chem Chem Phys* 2018, **20**: 21890–21902.