Chapter 1
Introduction

Deep eutectic solvents (DESs) are a certain class of liquids at ambient conditions (that have freezing points below, say, 25 °C) that are binary compositions of two components, each of which has a melting point above that of the deep eutectic solvent, hence they are eutectics. Deep eutectic solvents are a subgroup of room temperature ionic liquids (RTILs), but are binary mixtures contrary to ordinary RTILs that are single substances. Being generally ionic in nature, deep eutectic solvents should have appreciable electrical conductivities, but nonionic deep eutectic solvents have also been described. As solvents, they should be able to dissolve a variety of solutes, be these organic substances, metal oxides, or substances of other kinds. The deep eutectic solvents also should be noninflammable, nontoxic, and friendly to the environment ('green', biodegradable) in order to be useful for industrial processes. The freezing point of 25 °C is set as an arbitrary upper limit to deep eutectic solvents to be dealt with in this book.

1.1 Solvents for Processing and in the Laboratory

Much of chemistry takes place or is carried out in a liquid solution. This is the case in nature: geochemical reactions and physiology in plants and living organisms, in industry: textile, paper, food, biomass processing, hydrometallurgy, bulk chemicals, and pharmaceuticals, and in the laboratory: synthesis, purification, and analysis. Therefore, solvents are required that have the desired properties for the processes to be carried out on the one hand and that do not have disadvantageous properties on the other.

There are several features of liquids that make them suitable as solvents. A solvent should have an appropriate liquid range, i.e., it should be liquid at ambient temperatures and pressures and over a suitable range of these conditions. It should be available at commercial quantities at the purity required for the envisaged process, or be readily purified for this purpose, and be inexpensive. It should be

recyclable (generally, but not necessarily, by distilling it out from the process mixture, after the product has been recovered) and when disposed-of should be environmentally friendly. Tunability is a desired aspect, in that by changing conditions (the temperature or pressure) or by addition of co- or anti-solvents the solubilities of the desired product and of undesired by-products and residual raw materials can be controlled. Several attributes of prospective solvents should be avoided: these include high viscosity that impedes ready flow, high volatility, flammability, and toxicity to humans and the environment.

Water is, of course, a very widely utilized solvent, because of its advantageous properties and minimal detrimental ones. It is readily available at the required purity, it is cheap, it has a convenient liquid range, it is readily recycled, and has good solvent properties for a wide variety of solutes. It is also nontoxic, non-flammable, and environmentally friendly. It may even be utilized under increased pressures at elevated temperatures, beyond its normal boiling point, and even at supercritical conditions. Water is, of course, the primary solvent for physiological processes as well as for many geochemical ones.

However, water is a poor solvent at ambient conditions for nonpolar substances, for many permanent gases, for most industrial polymers, and for those solid materials that have such large crystal energies that cannot be overcome by the solvation energies and the entropy changes involved in the dissolution. Furthermore, water is highly reactive towards many solutes and cannot be used if such solutes are required to be unchanged by the solvent itself during the process. Therefore, alternative solvents have been extensively used in industry and in the laboratory, that have better solvent properties regarding such prospective solutes for which water is inadequate as a solvent.

Organic liquids have for a long time served for this purpose, both dipolar and hydrogen bonded ones and nonpolar solvents as well, for different classes of solutes. Their main role is their ability to solvate the particles (molecules or ions) of the solutes. Their general properties have been summarized in several monographs, e.g., [1, 2], and those properties conducive to their solvating abilities have also been summarized [2]. For some applications, it has been found that aqueous/organic solvent mixtures and nonaqueous mixtures of organic solvents perform better than individual ones, for example for pharmaceutical solutes [3]. General and solvating ability properties of such mixtures have also been summarized [4]. Although such organic solvents are generally readily available commercially in high purity, their costs have to be taken into account for industrial applications. Furthermore, such solvents may be too volatile, toxic, flammable, and detrimental to the environment, so that special precautions have to be undertaken in their utilization. The present general trend in the industry is to avoid the commonly employed organic solvents and to replace them with solvents that are not volatile, nontoxic, nonflammable, and environmentally friendly.

Supercritical solvents, in particular, supercritical carbon dioxide (SCD) [5–7] and supercritical water (SCW) [8–10], but also, to a smaller extent, other super-critical fluids, have been proposed for a variety of applications. These include the sorption and separation of gases (SCD) and the total oxidation and elimination of

environmentally hazardous substances (SCW). The chemicals comprising these solvents are cheap and readily available, but appreciable costs in energy for obtaining the required elevated temperature and/or pressure as well as corrosion problems detract from the attractiveness of supercritical solvents for large-scale uses.

Ionic liquids as solvents include molten salts at elevated temperatures and have in the past been promoted for certain applications, including coolants and moderating agents for nuclear reactors, nuclear fuel reprocessing, and metallurgical applications. Their application as solvents is restricted to solutes that withstand the elevated temperatures involved, and this excludes most organic solutes. However, in the last 20 years, the class of room temperature ionic liquids (RTILs) has gained enormous interest regarding their properties [11] and uses as solvents for a host of applications [12–14]. A great variety of room temperature ionic liquids, based on imidazolium, pyrrolidinium, pyridinium, and nonsymmetrical quaternary ammonium and phosphonium cations, are now commercially available at moderate costs. They are generally used at ambient conditions, but their properties are tunable by the choice of the temperature of application and the cation/anion combination and/ or modification by inclusion of further polar and protic groups in their building stones [15] as well as by the use of cosolvents, e.g., water. Another means for production of room temperature ionic liquids is the use of large complex anions, such as chloroaluminates, $Al_2Cl_7^-$, that decrease the freezing points of the salts by diminishing their lattice energies, making them liquid at ambient conditions [16]. Room temperature ionic liquids are generally nonvolatile, but may have inconvenient viscosities unless used above ambient conditions. They still may be toxic and flammable, as well as difficult to recycle, so that their costs must be taken into account for industrial purposes.

The search for alternative solvents has not abated since the advent of the room temperature ionic liquids, and one possible candidate has been suggested by Abbott et al. [17] in 2003: the eutectic combination of choline chloride and urea. The melting points of the components are 302 °C for choline chloride ($HOC_2H_4N(CH_3)_3^+Cl^-$) and 133 °C for urea ($O=C(NH_2)_2$), whereas for the 1:2 eutectic the melting point is 12 °C, making the liquid mixture an attractive solvent. The depression of the freezing point involves hydrogen bonding, where one component urea, provides the hydrogen bond donation ability and the other component, providing the hydrogen bond accepting ability through its chloride anion. The choline chloride may be substituted by other quaternary ammonium salts or by salts with a hydrogen bond accepting moiety other than the chloride anion and the urea by other hydrogen bond donating substances. A eutectic may then be formed that melts below ambient temperature, hence constitutes a usable liquid solvent. It was found that the choline chloride/urea pair at the eutectic composition, as well as similar pairs, have large ionic conductivities and manageable viscosities, and form immiscible biphasic liquid systems with solvents that are incapable of donation of hydrogen bonds, giving rise to a host of applications [17]. This discovery opened the field of deep eutectic solvents that is the subject of this book.

1.2 Green Solvents

The concept of 'green solvents' pertains to the wider area of 'green chemistry', for which 12 principles have been established. These are as follows:

(1) Waste prevention: synthesis and processing should not leave waste materials to clean-up and dispose.
(2) Safety: no toxic materials should result from the process.
(3) Hazard prevention: avoidance of the formation of materials or processes that are hazardous.
(4) Preference for renewable feedstock: avoidance of depleting raw materials from mining or fossil fuels.
(5) Preference for catalytic reactions: catalysts are preferable to stoichiometric reagents.
(6) Avoidance of temporary modifications: derivatives require additional reagents for the regeneration of the desired products.
(7) Atom economy should be maximized: wasted atoms should be avoided.
(8) Safe solvents need to be used: minimal quantities of recyclable solvents are preferred.
(9) Energy efficiency is to be maximized: ambient temperatures and pressures should be preferred.
(10) Degradable products and reagents are preferred: the materials should not accumulate in the environment.
(11) In-time control: monitoring of reactions for the elimination of undesired by-products.
(12) Minimization of the potential for accidents: explosion, fire, and pollution possibilities of processes must be kept in mind.

In view of these principles, the chemical community is proceeding in recent years toward sustainable industrial processes, for which summit conferences are organized, annual **Green Chemistry** and Engineering Conferences take place, and Green Chemistry and Sustainable Chemistry and Engineering journals and series are published.

More than 10^7 tons of organic solvents are produced each year for industrial purposes [18], but most of these do not conform to the requirements of 'green chemistry'. Industry has, indeed, in recent years, followed the slogan "pollution prevention pays" [19] by reduction of the amounts of solvents that are used in the processes and by their recycling, so that much smaller amounts are disposed into the environment. As a consequence, the demand for 'green solvents' has proliferated, meeting the essential criteria listed above [20].

Water is the 'greenest solvent' imaginable, as mentioned in Sect. 1.1: it is readily available at the required purity, it is cheap, it is readily recycled, nontoxic, nonflammable, and environmentally friendly. However, even water, widely used as a solvent in a variety of industrial applications, should be avoided as much as possible, because of the hazard of return of contaminated water to the natural

sources: underground reservoirs, rivers, and lakes. Apart from water, there are few solvents from natural sources, and employment of these, mainly hydrocarbons from the refining of fossil fuels, contradicts principle (4) of "green chemistry". Alternative solvents may include supercritical water [8, 9] and carbon dioxide [21], ionic liquids [12–14], and fluorous phases [22]. Synthetic solvents are sought that, in addition to their desired positive properties, such as availability at low costs, dissolution abilities of the prospective solutes and the required widths of their spectroscopic and electrochemical windows, avoid the undesirable features of toxicity, flammability, loss through volatility, and environmental incompatibility.

Several metrics for the environmental health and safety properties of solvents exist that deal with process safety, human health, and the environment [23]. Several guiding specifications have been adopted by industry. The Pfizer guide provides a simple comparison of common solvents, deeming them "preferred", "usable", or "undesirable". The GSK guide focuses on small molecule organic solvents in the pharmaceutical industry and is most useful when choosing among known alternatives [24]. The Sanofi solvent selection guide provides a clear rank (recommended, problematic, hazardous, or highly hazardous) to each solvent which includes a number of bio-derived and less common solvents [25]. A further solvent selection guide is available in [26].

The process safety aspects include the flash point, the vapor pressure, explosion risk (peroxide formation potential), auto-ignition temperature, static charge formation, self-reaction potential, and corrosiveness. The health aspects include carcinogenicity, mutagenicity, reprotoxicity, skin absorption, acute toxicity, and respiratory and eye irritation, as well as prolonged occupational exposure hazard. The environmental aspects include water contamination, ozone depletion, bioaccumulation, energy demand for distillation, photoreactive potential, and non-degradability.

Room temperature ionic liquids (RTILs) have been widely promoted in recent years as 'green solvents'. A recent publication [27] shows that ∼80% of papers dealing with solvents for green technologies pertain to room temperature ionic liquids (RTILs), ∼15% pertaining to supercritical carbon dioxide, and only ∼5% pertaining to other 'green solvents'. Industrial applications of room temperature ionic liquids have been described [28, 29] and their properties have been summarized [11].

One of the main features of room temperature ionic liquids is their low volatility, so that loss to the environment and its pollution by the vapors of room temperature ionic liquids is minimized. Other hazards of room temperature ionic liquids may be minimal, but some have flashpoints below 200 °C, examples being: 1-ethyl-3-methylimidazolium ethyl sulfate (157.0 °C), 1-hexyl-3- methylimidazolium chloride (178.5 °C), 1-butyl-3-methyl-imidazolium methyl sulfate (102 °C) [30]. These temperatures are diminished when the room temperature ionic liquids are heated for a moderately prolonged time [31]. In spite of their very low vapor pressures, room temperature ionic liquids are combustible rather than nonflammable [32] and may auto-ignite at >400 °C [33].

Room temperature ionic liquids are not devoid of toxicity, as recent discussions on applications of ionic liquids in the food and bioproducts industries reveal [34, 35]. Thus, although the imidazolium-based RTILs are the most popular choice, this choice occurs despite clear indications about their toxicity. Room temperature ionic liquids with lower toxicity, such as cholinium saccharinate, were synthesized [36] and had lower eco-toxicity levels toward crustaceans, when compared to most common ionic liquids, a fact related to the natural origin of the ions. The use of renewable natural compounds for the synthesis of room temperature ionic liquids, such as amino acids, lipid-like compounds, or those involving acids from natural origin is emerging.

The low vapor pressures of room temperature ionic liquids make them much less susceptible to air pollution than common organic solvents. However, room temperature ionic liquids are not per se innocuous environmentally, and relevant issues of room temperature ionic liquids, including environmental behavior and toxicity, and routes for designing nontoxic room temperature ionic liquids and the techniques that might be adopted for the removal/recovery of room temperature ionic liquids have been discussed [37]. Of major concern are their fate, transport, and transformations in terrestrial and aquatic systems. The adsorption of room temperature ionic liquids on soils and sediments has been investigated [38]. The biodegradation of room temperature ionic liquids, including methods for its assessment, the trends observed for structurally related room temperature ionic liquids, and applications of biodegradable ionic liquids in synthetic chemistry have been reviewed [39]. Room temperature ionic liquids that are classified as readily biodegradable require a $\geq 60\%$ biodegradation level in 28 days and full biodegradation should yield completely nontoxic products.

A further issue that pertains to the use of room temperature ionic liquids as solvents is their considerable viscosity at ambient conditions. Water and common organic solvents: n-hexane, methanol, tetrahydrofuran, and acetonitrile have at 25 °C dynamic viscosities η/mPa·s < 1. On the other hand, typical room temperature ionic liquids have at 25 °C viscosities η/mPa·s of 15.0 for 1-ethyl-3-methylimidazolium hexafluorophosphate, 35.6 for 1-butyl-4-methylpyridinium dicyanamide, 30.0 for 1-butyl-1-methylpyrrolidinium trifluoromethylsulfonate, and 245 for octyl tributylphosphonium dicyanamide, and even larger viscosities for other members of these classes of room temperature ionic liquids [11].

All these considerations are relevant also to the deep eutectic solvents that are dealt with in this book, and are discussed in turn at the appropriate places.

1.3   Solid–Liquid Phase Diagrams

Solid–liquid phase diagrams present the temperatures at which crystalline solid states of aggregation of a substance or a mixture of substances are at equilibrium with liquid states, i.e., the melting/freezing points of either single substances or as a function of the composition in the case of mixtures. In the case of a binary mixture

there may occur a eutectic, that is, a composition that has a lower melting point than any other composition, including the neat components. On the other hand, a crystalline compound may be formed between the two components, and this has its own characteristic melting point. If the liquid formed on fusion of this compound crystallizes back on cooling to this same compound it is said to melt congruently, otherwise, it melts incongruently and the original compound is not reformed on cooling the liquid melt, but either of the initial components may crystallize out. A further complication that may occur is the formation of solid solutions of the components of the mixture formed on cooling the liquid melts, rich in the one component or in the other as the overall concentration changes.

Several methods are used to obtain the solid–liquid equilibrium (SLE) diagrams of binary mixtures. Commonly, the components at given molar ratios are mixed and heated above the melting point of the mixture to form a homogeneous liquid. The mixture is allowed to cool gradually and its temperature is measured until visually a solid phase appears. This procedure may be carried out by means of a hot-stage microscope [40]. A more sophisticated method is to monitor the temperature of the cooling liquid mixture with time and to note a halt in the cooling curve that indicates equilibrium crystallization of the solid phase. A possible undercooling can be noted in such cooling curves, and on nucleation of the melt, a temperature upshot is seen toward the halt at the true freezing point. A further method that is widely employed is differential scanning calorimetry (DSC) which on heating the mixture shows an endothermic peak, the onset of which indicates the melting point and the enthalpy change of fusion is obtained from integration of the DSC curve [40]. An exothermic peak is shown by DSC on cooling the molten material, indicating the freezing point.

Simple solid–liquid phase diagrams with a single eutectic are found in many binary mixtures, and the melting points of the eutectic can be a great deal below those of the constituent compounds. The distance between the eutectic melting point and the point at the composition of the eutectic on the straight line connecting the melting points of the constituents is called the eutectic distance, Δt_m, and characterizes the success with which the melting point t_m has been diminished. This is demonstrated in Fig. 1.1 for the mixtures of α-naphthol ($t_m/°C = 95.1$) with *o*-nitroaniline ($t_m/°C = 69.6$), where a eutectic occurs ($t_m/°C = 44.0$) at a mole fraction of *o*-nitroaniline of 0.5616 [41], but its t_m is above ambient temperature. In this case, the eutectic distance is $\Delta t_m/°C = 36$.

Similar situations are observed also with inorganic materials, for instance, for salt hydrates that have melting points not far from ambient temperatures, in contrast with molten salts [11] that are outside the scope of this book. The solid–liquid phase diagram of mixtures of magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$, $t_m/°C = 112$) with nickel chloride hexahydrate ($NiCl_2 \cdot 6H_2O$, $t_m/°C = 30$) [42] is shown in Fig. 1.2. The eutectic at the 1:1 composition has a melting point $t_m/°C = 4$. This binary salt hydrate system may serve as a deep eutectic solvent, but has not been so described and used so far, as much as is known, and the eutectic distance $\Delta t_m/°C = 67$ is quite appreciable.

Fig. 1.1 Solid–liquid phase diagrams of the α-naphthol with *o*-nitroaniline binary systems [41]. The lines connecting the experimental points are guides to the eye and have no further significance. The dashed line connects the melting points of the components and the vertical line represents the eutectic distance
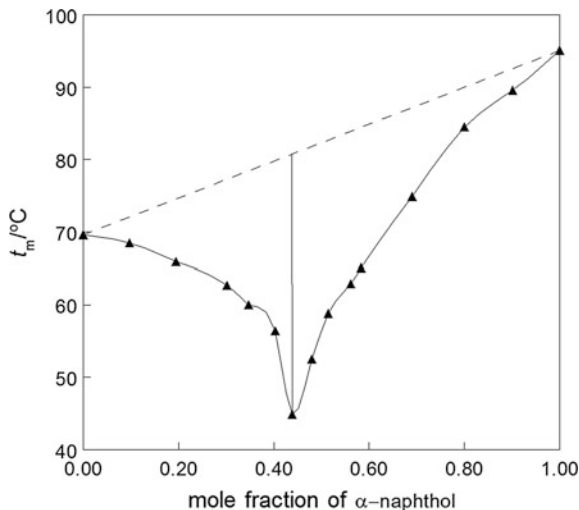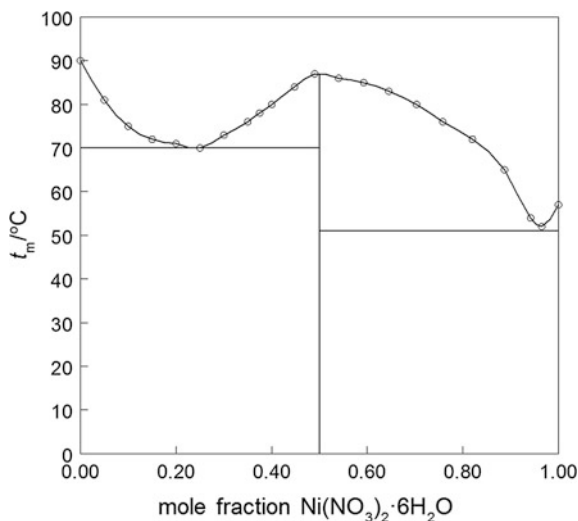

Fig. 1.2 The solid–liquid phase diagram of mixtures of MgCl$_2$·6H$_2$O and NiCl$_2$·6H$_2$O [42]. The lines connecting the experimental points are guides to the eye and have no further significance, but the eutectic distance Δt_m is indicated as a vertical solid line up to the dashed line connecting the melting points of the components
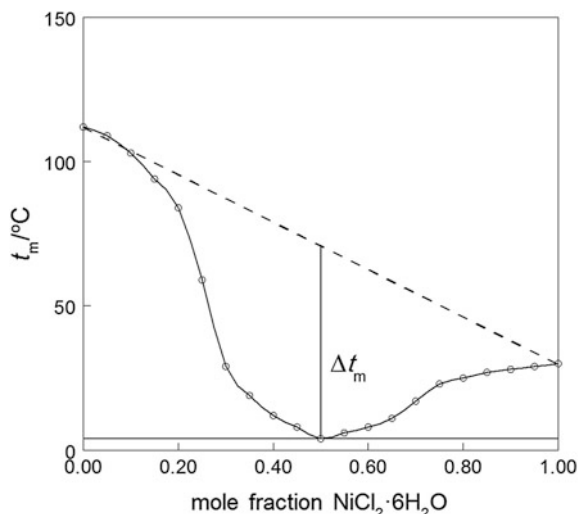
A fairly complicated phase diagram occurs for the corresponding nitrate systems: mixtures of magnesium nitrate hexahydrate (Mg(NO$_3$)$_2$·6H$_2$O, t_m/°C = 89.5) with nickel nitrate hexahydrate (Ni(NO$_3$)$_2$·6H$_2$O, t_m/°C = 56.7) [42, 43], shown in Fig. 1.3. A maximum in the diagram occurs at the 1:1 composition, at which a congruently melting compound is formed (t_m/°C = 87), surrounded by two minima (eutectics) with t_m/°C = 70 and 51.

An even more complicated phase diagram is obtained for solutions of magnesium chloride in water [44], in which a series of hydrates are successively at equilibrium with the solution, the dodecahydrate, octahydrate, hexahydrate, tetrahydrate, and dihydrate, as shown in Fig. 1.4.

Fig. 1.3 Solid–liquid phase diagram of mixtures of Mg(NO$_3$)$_2$·6H$_2$O and Ni(NO$_3$)$_2$·6H$_2$O [42, 43]

The deep eutectic solvents dealt with in this book have the much simpler form of solid–liquid phase diagram, with a single eutectic, as shown in Fig. 1.1 for the *o*-nitroaniline/α-naphthol system, and in Fig. 1.2 for the MgCl$_2$·6H$_2$O/NiCl$_2$·6H$_2$O system.
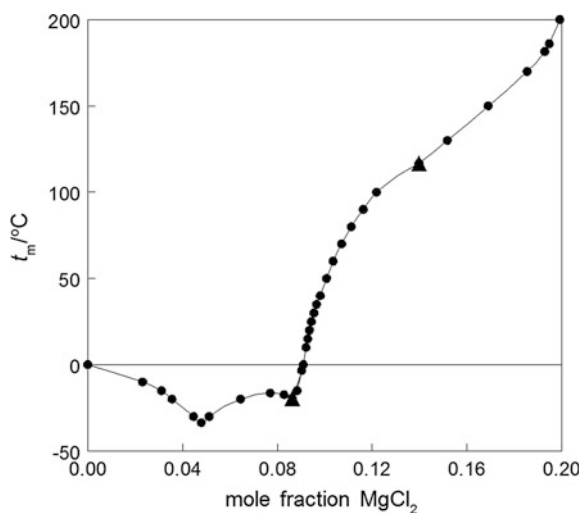
Fig. 1.4 The solid–liquid phase diagram of aqueous MgCl$_2$ [44]. The lines connecting the experimental points are guides to the eye and have no further significance. Up to the first triangle from the left, the hydrates at equilibrium with the solution are successively the dodecahydrate and the octahydrate; between the two triangles the hexahydrate is at equilibrium with the solution, and beyond the second triangle it is the tetrahydrate, that in turn reverts to the dihydrate (outside the figure)

References

1. Riddick JA, Bunger WB, Sakano TK (1986) Organic solvents, 4th edn. Wiley-Interscience, New York
2. Marcus Y (1998) Properties of solvents. Wiley, Chichester
3. Marcus Y (2017) Drugs in binary solvent mixtures—their preferential solvation. Chronicles Pharm Sci 1:170–180
4. Marcus Y (2002) Solvent mixtures. Properties and preferential solvation. M. Dekker, New York
5. Kaiser CS, Romp H, Schmidt PC (2001) Pharmaceutical applications of supercritical carbon dioxide. Pharmazie 56:907–926
6. Yuan JTC, Novak JS (2012) Industrial applications using supercritical carbon dioxide for food. Dense Phase Carbon Dioxide 227–238
7. Zhang X, Heinonen S, Levanen E (2014) Applications of supercritical carbon dioxide in materials processing and synthesis. RSC Adv 4:61137–61152
8. Fang Zh, Xu Ch (eds) (2014) Near-critical and supercritical water and their applications for biorefineries. Springer, Dordrecht
9. Marcus Y (2012) Supercritical water. Wiley, New York
10. Loppinet-Serani A, Aymonier C, Cansell F (2008) Current and foreseeable applications of supercritical water for energy and the environment. ChemSusChem 1:486–503
11. Marcus Y (2016) Ionic liquid properties. From molten salts to RTILs. Springer Intl. Publ., Switzerland
12. Pandey S (2006) Analytical applications of room temperature ionic liquids: a review of recent efforts. Anal Chim Acta 556:38–45
13. Jindal R, Sablok A (2015) Preparation and applications of room temperature ionic liquids. Curr Green Chem 2:135–155
14. Tsada T, Hussey CL (2007) Electrochemical applications of room temperature ionic liquids. Electrochem Soc Interface 16:42–49
15. Abbott AP, Capper G, Davies DL, Munro HI, Rasheed RK, Tambyrajah V (2001) Preparation of novel moisture-stable Lewis-acidic ionic liquids containing quaternary ammonium salts with functional side chains. Chem Comm 2001:2010–2011
16. Welton T (1999) Room-temperature ionic liquids. Solvents for synthesis and catalysis. Chem Rev 99:2071–2083
17. Abbott AP, Capper G, Davies DL, Rasheed RK, Tambyrajah V (2003) Novel solvent properties of choline chloride/urea mixtures. Chem Commun 2003:70–71
18. DeSimone JM (2002) Practical approaches to green solvents. Science 297:799–803
19. DeSimone L, Popoff F (2000) Eco-efficiency: the business link to sustainable development. MIT Press, Cambridge
20. Jessop PG (2011) Searching for green solvents. Green Chem 13:1391–1398
21. Michalek K, Krzysztoforski J, Henczka M, da Ponte MN, Bogel-Lukasik E (2015) Cleaning of microfiltration membranes from industrial contaminants using "greener" alternatives in a continuous mode. J Supercrit Fluids 102:115–122
22. Horvath IT, Rabai J (1994) Facile catalyst separation without water: fluorous biphase hydro-formylation of olefins. Science 266:72–75
23. Soh L, Eckelman MJ (2016) Green solvents in biomass processing. ACS Sustain Chem Eng 4:5821–5837
24. Henderson RK, Jimenez-Gonzalez C, Constable DJC, Alston SR, Inglis GGA, Fisher G, Sherwood J, Binks SP, Curzons AD (2011) Expanding GSK's solvent selection guide—embedding sustainability into solvent selection starting at medicinal chemistry. Green Chem 13:854–862
25. Prat D, Pardigon O, Flemming HW, Letestu S, Ducandas V, Isnard P, Guntrum E, Senac T, Ruisseau S, Cruciani P, Hosek P (2013) Sanofi's solvent selection guide: a step toward more sustainable processes. Org Proc Res Dev 17:1517–1525

26. Prat D, Wells A, Hayler J, Sneddon H, McElroy CR, Abou-Shehada S, Dunn PJ (2016) CHEM21 selection guide of classical and less classical-solvents. Green Chem 18:288–296
27. Bubalo MC, Vidovic S, Redfovnikovic IR, Jokic S (2015) Green solvents for green technologies. J Chem Technol Biotechnol 90:1631–1639
28. Rogers RD, Seddon KR (eds) (2002) Ionic liquids: industrial applications to green chemistry. American Chemical Society, Washington DC
29. Maase M (2008) Industrial applications of ionic liquids. In: Wasserscheid P, Welton T (eds) Ionic liquids in synthesis, vol 2, 2nd edn. Wiley, New York, pp 663–687
30. Liaw HJ, Chen CC, Chen YC, Chen JR, Huang SK, Liu SN (2012) Relationship between flashpoint of ionic liquids and their thermal decomposition. Green Chem 14:2001–2008
31. Liaw HJ, Chen CC, Chen YC, Chen JR, Liu SN (2014) Effect of heating on the flashpoint of ionic liquids. Procedia Eng 84:293–296
32. Liaw HJ, Huang SK, Chen HJ, Liu SN (2012) Reason for ionic liquids to be combustible. Procedia Eng 45:502–506
33. Chen YT, Chen CC, Su CH, Liaw HJ (2014) Auto-ignition characteristics of selected ionic liquids. Procedia Eng 84:285–292
34. Toledo Hijo QAAC, Maximo GM, Costa MC, Batista EAC, Meirelles AJA (2016) Applications of ionic liquids in the food and bioproducts industries. ACS Sustain Chem Eng 4:5347–5369
35. Prydderch H, Heise A, Gathergood N (2016) Toxicity and bio-acceptability in the context of biological processes in ionic liquid media. RSC Green Chem Ser 36:168–201
36. Nockemann P, Thijs B, Driesen K, Janssen CR, Van Hecke K, VanMeervelt L, Kossmann S, Kirchner B, Binnemans K (2007) Choline saccharinate and choline acesulfamate: ionic liquids with low toxicities. J Phys Chem B 111:5254–5263
37. Made M, Liu JF, Pang L (2015) Environmental application, fate, effects, and concerns of ionic liquids: a review. Environ Sci Technol 49:12611–12627
38. Mrozik W, Kotlowska A, Kamysz W, Stepnowski P (2012) Sorption of ionic liquids onto soils: experimental and chemometric studies. Chemosphere 88:1202–1207
39. Coleman D, Gathergood N (2010) Biodegradation studies of ionic liquids. Chem Soc Rev 39:600–637
40. Morrison HG, Sun CC, Neervannan S (2009) Characterization of thermal behavior of deep eutectic solvents and their potential as drug solubilization vehicles. Int J Pharm 378:136–139
41. Singh J, Singh NB (2015) Solidification and computational analysis of o-nitroaniline-α-naphthol eutectic system. Fluid Phase Equil 386:168–179
42. Marcus Y, Minevich A, Ben-Dor L (2005) Solid-liquid equilibrium diagrams of common ion binary salt hydrate mixtures involving nitrates and chlorides of magnesium, cobalt, nickel, manganese, and iron(III). Thermochim Acta 432:23–29
43. Mokhosoev MV, Gotanova TT (1966) Interaction of crystal hydrates of the nitrates of several elements. Russ J Inorg Chem 11:466–469
44. Linke WF, Seidell A (1965) Solubilities of inorganic and metal-organic compounds, 4th edn, vol II. K – Z, Am. Chem. Soc., Washington