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Review Article

DEEP EUTECTIC SOLVENTS: AN OVERVIEW OF ITS BASICS AND PROPERTIES

KHUSHBOO BHAKER*
Department of Chemistry, BLJS College, Tosham
Email: khushboobhaker@gmail.com

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ABSTRACT

Deep eutectic solvents (DESs) are a rising elegance of combos characterized by using sizeable depressions in melting factors as compared to the ones of the neat constituent additives. These substances are promising for programs as cheaper "designer" solvents showing a bunch of tunable physicochemical properties. An in-depth review of the modern-day literature reveals the lack of predictive knowledge of the microscopic mechanisms that govern the shape–property relationships in this elegance of solvents. complicated hydrogen bonding is postulated as the foundation motive of their melting point depressions and physicochemical residences; to apprehend these hydrogen-bonded networks, it is imperative to look at these structures as dynamic entities using both simulations and experiments. This review emphasizes the current study's efforts to elucidate the next steps needed to increase a fundamental framework wished for a deeper understanding of DESs. It covers recent trends in DES studies, frames terrific medical questions, and identifies promising research thrusts aligned with the advancement of the sphere closer to predictive fashions and a fundamental understanding of those solvents

Keywords: *Choline chloride Deep eutectic solvents, Eutectic factor, Herbal deep eutectic solvents, Physicochemical home, Supramolecular community*

INTRODUCTION

DESs are a category of ionic liquids that have gained growing attention in modern years due to their particular houses and potential packages in various fields. DESs are composed of or more components, normally a hydrogen bond acceptor (HBA) and a hydrogen bond donor (HBD), that form a eutectic mixture with a melting point considerably decreased than that of

the person components. Not like traditional ionic liquids, which are normally synthesized from complicated and high-priced starting materials, DESs can be without problems organized from easy-to-be-had and cheaper compounds, along with choline chloride, urea, and glycerol. DESs are also considered to be greater environmentally pleasant than conventional organic solvents, as they are commonly biodegradable and have low toxicity.

DESs have shown promise in an extensive variety of packages, as solvents for chemical reactions and separations, as electrolytes in batteries and supercapacitors, as lubricants, and as media for biocatalysis. Some over, DESs were investigated for their capacity use in drug delivery, as they can solubilize a huge range of compounds and have low toxicity. Notwithstanding their potential blessings, there are nevertheless some challenges associated with the use of DESs, including their relatively excessive viscosity and occasional conductivity compared to standard solvents. but, ongoing research is centered on addressing those issues and similarly exploring the ability programs of those fascinating substances.

Deep Eutectic solvents

DESs include big, non-symmetric ions that have low lattice power and occasional melting factor. they're typically acquired with the aid of the complexation of a quaternary ammonium salt with a steel salt or hydrogen bond donor. The fee delocalization occurring via hydrogen bonding among as an instance halide ion and the hydrogen fonormoirty is answerable for lower in the melting point of the combination relative to the melting point of the individual components. Quite some beverages fashioned from eutectic combos of salts and hydrogen bond donors have now been developed. Those liquids have been named deep eutectic solvents to differentiate them from ionic liquids which comprise the simplest discrete anions The term DES refers to drinks close to the

eutectic composition which offers the lowest melting factor.

Deep eutectic solvents can be described by way of the well-known system Cat+X-zY, in which Cat+ is in principle any ammonium phosphonium or sulfonium cation, and X is a Lewis base, normally a halide anion. The complicated anionic species are formed among X- and either a Lewis or bronsted acid Y,z refers back to the number of Y molecules that have interaction with anion. The foremost research has centered on quaternary ammonium and imidazolium captions with the precise emphasis being placed on a greater practical device using choline chloride, [ChCl, HOC2H4N+(CH3)3Cl-]. DESs are largely labeled relying on the nature of the complex dealers used (Figure 1).

DES formed from MClx and quaternary ammonium salts, type 1, may be classified to be of an identical kind to the properly-studied metallic halide/ imidazolium salts gadget. An instance of type 1 eutectics encompasses the nicely-studied chloroaluminate/imidazolium salt melts and less common ionic liquids shaped with imidazolium salts and diverse metallic halides including FeCl2, AgCl, CuCl, LiCl, CdCl, CuCl2, SnCl2, ZnCl2, LaCl3, YCl3, SnCl4.

The range of non-hydrated metallic halides which have a suitably low melting factor to form kind 1 DESs is limited; but, the scope of deep eutectic solvents may be expanded by using. Hydrated steel halides and choline chloride (type 2 DESs). The enormously low fee of many hydrated metal salts coupled with their inherent air/ moisture insensitivity makes their use in large-scale commercial strategies feasible. Type 3 eutectics, shaped from choline chloride and hydrogen bond donors, had been of hobby due to their capacity to solvate a wide range of transition metal species, consisting of chlorides and oxides. A range of hydrogen bond donors were studied so far, with deep eutectic solvents formed by the use of amides, carboxylic

acids, and alcohols. These liquids are easy to put together, and relatively unreactive with water; many are biodegradable and are enormously low priced.

The extensive range of hydrogen bond donors to be had method that this class of deep eutectic solvents is specifically adaptable. The bodily houses of the liquid are dependent upon the hydrogen bond donor and can be without difficulty tailor-made for precise packages. although the electrochemical home windows are drastically smaller than the ones for a number of the imidazolium salt–discrete anions. Ionic beverages, they're sufficiently wife to allow the deposition of metals which include Zn with high modern-day efficiencies. This magnificence of deep eutectic solvents was especially flexible, with an extensive range of viable programs investigated together with the removal of glycerol from biodiesel, processing of metal oxides, and the synthesis of cellulose derivatives. A majority of ionic drinks that are fluids at ambient temperature are fashioned with the usage of a natural cation, primarily based on ammonium, phosphonium, and sulfonium moieties. Inorganic captions no longer shape low melting factor eutectics due to their excessive charge densities.

Ionic Liquids

Ionic beverages (ILs) had been one of the most extensively studied regions in science in the decade and are in all likelihood subject to greater opinions according to research papers than every other modern subject matter. The arbitrary definition that an ionic liquid is a category of fluid that consists of ions and is liquid at temperatures <100 °C become used historically to distinguish between ionic drinks and classical molten salts, which soften at higher temperatures; however, ionic drinks at moment are usually called solvent which consists totally of ions. The conventional definition changes into first used to explain chloroaluminate-based ionic fluids. A major hindrance of the chloroaluminate ionic liquids is their

inherent air and moisture sensitivity, due to the rapid hydrolysis of AlCl3 upon contact with moisture. The moisture sensitivity of these systems may be incredibly decreased via the replacement of AlCl3 with greater solid metal halides consisting of ZnCl2 to form eutectic-based ionic beverages. The ionic drinks formed from organizations with AlCl3 and ZnCl2 are frequently termed first-generation ionic liquids. This magnificence of ionic liquids is fluid at low temperatures because of the formation of bulky chloroaluminate or chlorinate ions at the eutectic compositions of the mixture. This reduces the rate density of the ions, which in flip reduces the lattice energy of the machine main to a discount in the freezing point of the mixture.

The second generation of ionic drinks is those that are entirely composed of discrete ions, in place of the eutectic mixture of complicated ions visible within the first generation ionic drinks. The air and moisture-strong drinks may want to be synthesized by replacing the AlCl3 used within the eutectic ionic drinks with discrete anions which include the tetrafluoroborate and acetate moieties. Even though generally air and moisture are strong, some research has determined that exposure to moisture influences their chemical and bodily residences, with the development of a water content material increases. the stability of this elegance of ionic liquids can be improved through the usage of extra hydrophobic anions such as tri fluoro methanesulfonate (CF 3 S O3-), bis-(trifluoromethane sulphonyl)imide [(CF3SO2)2N−], and tris-(trifluoromethane sulphonyl)methide [(CF3SO2)C−]. These structures have the extra benefit of huge electro-chemical home windows, permitting less noble metals, inaccessible from the chloroaluminate drinks, to be electrodeposited

In precise, the maximum broadly used ionic drinks may be split into two awesome classes, those formed from eutectic mixtures of metallic halides

(which includes AlCl3) and natural salts (commonly nitrogen primarily based and predominantly with halide anions), and those containing discrete anions which include PF6 or bis- (trifluoromethane sulphonyl) imide. Its miles envisioned that the whole quantity of viable ionic beverages could be inside the variety of 106 distinct systems. Genuine ionic beverages can be highly flexible solvents, with residences that can be without difficulty tuned for unique make use but, if ionic drinks are to achieve success as possible options for aqueous electrolytes, they must also be simple and economical to synthesize.

Methods of preparations

Researchers generally use one of the major techniques to put together deep eutectic solvents: the heating technique and the grinding approach. The heating method consists of blending and heating the compounds, under regular stirring, until a homogeneous liquid is shaped. The heating temperature generally levels between 50 and one hundred °C. however, a high temperature may additionally potentially result in a degradation of the deep eutectic solvent because of an esterification reaction irrespective of the training approach, as tested by way of Rodriguez et al. for solvents primarily based on choline chloride and carboxylic acids. The grinding method is primarily based on mixing the compounds at room temperature and crushing them in a mortar with a pestle till a clear liquid is fashioned. Some other methods based totally on the freeze-drying of the aqueous answers of the components of deep eutectic solvents become also been discovered by Gautier-et al. (Gutiérrez et al. 2009). An evaporation method become also pronounced by using Dai et al. consists of dissolving the additives of deep eutectic solvents in water, accompanied using evaporation at 50 °C. The resulting liquid is then placed in a desiccator in the presence of silica gel (Dai et al. 2013). considering the optimization of time and strength consumption, a

greener microwave-assisted method become proposed for the training of natural deep eutectic solvents within seconds. ultimately, an ultrasound-assisted synthesis of herbal deep eutectic solvents was recently added.

Properties of DESs

A. ***Physico Chemical Properties***

while DESs and traditional ILs have specific chemical residences, they have got comparable bodily properties, in particular, the ability as tunable solvents that may be custom designed to a particular kind of chemistry; in addition, they show off a low vapour pressure, highly huge liquid-range, and nonflammability. DESsHave numerous advantages over conventional ILs which include their ease of preparation, and easy availability from distinctly inexpensive components (the additives themselves are toxicologicallyWell-characterised, so they can be easily shipped for big-scale processing); they may be, however, in standard less chemically inert. The manufacturing of DESs entails the easy blending of the two components, commonly with moderate heating. This keeps a comparatively low manufacturing fee with recognise of standard ILs (together with imidazolium-based total liquids) and permits massive-scale applications. Whilst the man or woman components of DESs tend to be personally well toxicologically characterized, there are very few records about the toxicological houses of the eutectic solvents themselves, and this needs to be further investigated using the clinical community. The statistics from the few publications addressing this trouble are supplied in phase. The term deep eutectic solvent turned into coined to start with to describe kind III eutectics but has subsequently been used to explain all of the eutectic combos defined above. That is a logical method, and although this includes all the early work on halo aluminates, this is already the subject of several reviews and will now not be dealt with right here other than in comparative phrases

Phase Behaviour

The difference in the freezing factor at the eutectic composition of a binary combination of A + B as compared to that of a theoretical perfect combination, ΔTf, is associated with the importance of the interaction between A and B. The larger the interplay; the larger may be ΔTf. that is proven schematically in discern 2. Thinking about Figure 2. Schematic representation of a eutectic point on a two-component phase diagram.

Type I eutectics: the interactions between special steel halides and the halide anion from the quaternary ammonium salt will all produce similar halometallate species with similar Enthalpies of formation. This indicates that ΔTf values have to be between 2 hundred and 300 °C. It has been located to provide a eutectic at about the ambient temperature of the metal halide. normally needs to have a melting point of about three hundred °COr much less. it is glaring therefore why metal halides which include AlCl3 (mp = 193 °C), FeCl3 (308), SnCl2 (247), ZnCl2 (290), InCl3 (586), CuCl (423), and GaCl3 (seventy-eight) all produce ambient temperature eutectics. while unstudied so far, it could also be predicted that steel salts such as SbCl3 (mp = seventy-three °C), BeCl2 (415), BiCl3 (315), PbBr2 (371), HgCl2 (277), and TeCl2 (208) ought to additionally shape ambient temperature eutectics. The same is genuine of the quaternary ammonium salts wherein it's miles the less symmetrical cations that have a lower melting point and therefore lead to decrease melting point eutectics. This explains whyImidazolium halides C2mimCl (mp = 87 °C) and C4mimCl (65°C) have superior phase conduct and mass delivery to ChCl(301 °C).

Kind II eutectics were developed in a try to encompass different metals into the DES formulations. It becomes located that steel halide hydrates have lower melting factors than the corresponding anhydrous salt. Truly the waters of hydration decrease the melting point of metallic salts because they

decrease the lattice strength. As discern 1 suggests, a decreased melting point of the pure metallic salt will produce a smaller melancholy of freezing factor ΔTf.

This correlation can be seen in the literature and arises because salts with lower lattice energy will generally tend to have smaller interactions with the chloride anion. The most effective system completely defined to date is that of CrCl3•6H2O,11 even though others such as CaCl2•6H2O, MgCl2•6H2O, CoCl2•6H2O, LaCl3•6H2O, and CuCl2•2H2O are defined inside the patent literature.[2] Small wide variety of systems containing AlCl3, FeCl3, and SnCl2 have every proven eutectic point while blended with imidazolium chlorides at approximately 33% and 66% metal halide.

The type III eutectic combinations rely on the formation of hydrogen bonds between the halide anion of the salt and the HBD; where these HBDs are multifunctional, the eutectic point tends to be toward a 1:1 molar ratio of salt and HBD. In the same look at the depression of freezing factor turned into shown to be related to the mass fraction of HBD within the combination.

Density, viscosity, surface tension, and conductivity.

Mjalli et al. proposed a method for predicting the density of DESs at distinctive temperatures. The values of measured and predicted densities had been in comparison and the average of absolute relative per cent error (ARPE) for all of the DESs tested was observed to be 1.9%. The effect of salt to HBD molar ratio on ARPE in predicted DES densities become also investigated. The identical institution has additionally studied DESs fashioned from phosphonium-based total salts with specific hydrogen bond donors. Melting temperature, density, viscosity, pH, conductivity, and dissolved oxygen content material had been measured as a feature of temperature. The authors found that the sort of salt and HBD and the mole ratio of both compounds had a great impact at the research residences. Figure 3 decided on

traditional physical properties for the diffusion of DESs on the eutectic composition at 298 OKs and compares this with ionic liquids with discrete anions and some molecular solvents. DESs are quite high in phrases of their viscosity and lower in terms of their conductivity than different ionic drinks and molecular solvents. The starting place of this disparity is proposed to be due to the large size of the ions and comparatively loose volume within the ionic structures. The viscosity of the ionic liquids is a great deal higher than the maximum commonplace molecular solvents, and the exchange in viscosity with temperature is discovered to adjust in an Arrhenius way with huge values for the activation electricity for viscous go-with-the-flow. This turned into shown to empirically correlates to the ratio of the ion size and the average radius of the voids in the liquid.

It is usually observed that there is a superb linear correlation between the molar conductivity, Λ, of an ionic liquid and the fluidity (reciprocal of viscosity, η).23 The equal correlation is found with DESs. This has previously been mistakenly attributed to the validity of the Walden rule, Λη = constant. This is valid for a given electrolyte at limitless dilution in several solvents. Abbott showed that due to the hole idea, it isn't the ions that limit charge transport however alternatively the holes which might be at endless dilution. Through the use of this model, it could be shown that the Nernst−Einstein equation is valid. The refractive index of choline chloride-based drinks with the hydrogen bond donors Glycerol, ethylene glycol, and 1,4-butanediol were measured and in comparison to the anticipated values the use of an atomic contribution method. It become discovered that it became feasible to predict the refractive indexes of these beverages with the use of the method selected, where it become found that the refractive index lay among the values for the salt and the HBD. Unsurprisingly, with the relationship among viscosity and

temperature, it has been shown that the electric conductivity of DESs is temperature based. The effective polarity of choline chloride mixed with four HBDs, 1,2-ethanediol, glycerol, urea, and malonic acid, has been anticipated, and all 4 drinks were discovered to be fairly dipolar.

Polarity

Polarity is a key property because it reflects the overall solvation capability of solvents. Despite its significance, the polarity of the deep eutectic solvents changed into not drastically studied and turned into now not addressed till these days. This property is often estimated via the solvatochromic parameters which bear in mind the hypsochromic (blue) shift or bathochromic (purple) shift of UV−vis bands for the negatively solvatochromic dyes (e.g., Reichardt'sbetaine dye) or the positively. solvatochromic dyes (e.g., Nile crimson), respectively, as a characteristic of the solvent's polarity. The maximum regularly used scales are the polarity scales of Dimrothand Reichardt (ET and ETN) (Reichardt 1994) and the multiparameter scale of Kamlet and Taft (the hydrogen bond donating capacity α, the hydrogen bond accepting ability β and polarity/polarizability π*) (Kamlet et al. 1977; Kamlet and Taft, 1976). However, it's miles worth mentioning that the polarity scales aren't universal and are probe dependent because of this that we can't examine polarity parameters obtained through different solvatochromic probes.

Effect of water

Given the omnipresence of water and the hygroscopic individual of some deep eutectic solvents and their forming compounds, water uptake by way of the eutectic solvents is inevitable. At the same time as traces of water in deep eutectic solvents are usually taken into consideration as impurities, a plethora of papers intentionally brought water to their solvents if you want to excellent-tune their residences so they can respond to the requirements of some desired utility and water allowed, in lots of instances, to

enhance the overall performance of deep eutectic solvents. then again, the presence of water not best impacts the physicochemical properties but might also jeopardize the integrity of deep eutectic solvents (El Achkar et al. 2019), and this is the reason the inconsistency inside the literature given that deep eutectic solvents are prepared in exclusive running conditions. Consequently, analyzing the impact of water on the eutectic systems is of maximum importance. This phase highlights the impact of water on the physicochemical properties of deep eutectic solvents and the traits of their supramolecular organizations.

Electrochemical Behavior

In electrochemical programs, the conduct of electrolytes at an electrified interface is a vital asset; Scientists have investigated the electrochemical homes of ChCl primarily based DESs. The residences of the interfaces among platinum, gold, and glassy carbon electrodes and a ChCl: glycerol DES have been assessed with the use of cyclic voltammetry and electrochemical impedance spectroscopy. The double layer differential capacitance, acquired from electrochemical impedance, discovered that the capacitance curve of the ChCl: glycerol DES relies upon the material of the working electrode. The values of capacitance have been in the variety of values said for RTILs and have a comparable form dependence on the carried-out ability. The work revealed that differential capacitance expanded with temperature in evaluation to excessive temperature molten salts for all the electrodes examined excluding Au, wherein a crossing point in the capacitance curves becomes located. the electric interfaces of six one-of-a-kind DESs based totally on choline chloride with 1,2-ethanediol,1,2-propanediol, 1,3-propanediol, urea, and thiourea or acetylcholine chloride with urea had been studied at a Hg electrode. The CVs (determine four) show any contemporary peaks which may be attributed to price

transfer tactics within the capability limits selected. inside the ChCl: urea DES a couple of sharp peaks become observed around zero V, similar to the ones observed for aqueous thiourea solution on Hg. The negative limit of polarization turned into located to be dependent on the hydrogen bond donor with the limit increasing inside the following order: 1,3-propanediol < urea ethylene glycol <1,2-propanediol. The growing temperature of the DES extended the found capacitive modern-day and decreased the electrochemical window. At the same time, the electrochemical windows of these liquids are not as big as in some traditional ionic liquids, they're wider than one may expect from a protic solvent (which these are). Even though the concentration of protons may be pretty excessive in these beverages, the reduction of protons isn't always observed which is constant with the idea that the protons are strongly sure to the chloride ions. The differential capacitance curves for ethylene (1 ChCl:2ethylene glycol), 1,2-pipeline (1 ChCl:2 1,2-propanediol), 1,3-pipeline (1 ChCl:2 1,3-propanediol), and reline (1 ChCl:2 urea) were almost equal (parent five) The capacitance is constant at potentials poor of the point of zero price (p.c). changing the diol hydrogen bond donor with urea most effectively brought on a change in the differential capacitance curves at an ability near zero V. Much like aqueous or organic electrolytes, at large bad potentials, the shape of the interface accommodates a layer of choline cations separated from the electrode surface by way of a layer of HBD molecules. because the potential becomes much less bad the capacitance rises steeply suggesting the replacement of choline cations by way of the adsorption of anions. The minor effect of the HBD on the differential capacitance suggests the anion absorbed is mainly the chloride anion which is uncoordinated with the HBD. replacing the choline with the acetylcholine cation (or changing urea with the HBD thiourea) no longer motivates any alternate in the capacitance at big negative

potential. Those results had been taken by way of the authors as further support for a Helmholtz-type layer version of the double layer at large bad potentials, comprising choline cations separated from the electrode floor by way of a layer of HBD molecules. One of the essential problems is at which composition do DESs start to lose their ionic person and come to be predominantly a salt dissolved in an HBD.

Speciation

The ionic nature and comparatively high polarity of DESs suggest that many ionic species, inclusive of metallic salts, display excessive solubility. One of the key questions when thinking about the reactivity of steel in a DES is the species that form upon dissolution. Metal ions being generally Lewis acidic will complicate with Lewis or Brønsted base to form a spread of complexes. In aqueous solvents, the chemistry of H+ and OH− dominates the species formed in solution, the redox houses, and the solubility of metals. The study of steel ion speciation in DESs has been best started currently; sadly, the systems are extra complicated than aqueous solutions because of the differing Lewis basicities of the anions and composition of the eutectic. It's miles important to understand the speciation of DESs while trying to determine the mechanisms of nucleation and growth of metallic coatings because the number and binding constants of the ligands determine the detailed mechanistic steps related to electrochemical reduction. One of the reasons speciation is poorly understood is the difficulty in acquiring quantitative structural information. Most metals form ionic complexes that are tough or impossible to crystallize from the answer, and path evaporation of the solvent is not viable. a chain of in situ strategies is required to assimilate metal ligation in solution.

X-ray absorption pleasant shape (EXAFS) arises from a modulation in the intensity of the X-ray absorption side using interference with photoelectrons

backscattered from neighbouring atoms. Fourier transformation gives a radial distribution feature in the actual area inside a radius of approximately 600 pm. EXAFS is detailed and unique and indicates the neighbourhood arrangement across the excited detail, even for low concentrations. To date, EXAFS has been used to look at ZnCl2, CuCl2, and AgCl in each ChCl:EG and ChCl:urea DESs. It was discovered that ZnCl42− and CuCl42− were present within the former solutions while the last liquid contained a combination of AgCl2− and AgCl32−. while those outcomes are intuitively steady with the excessive Cl− ion attention (ca. four. eight M) in both of these liquids, it indicates that the coordination chemistry of the zinc ions on the electrode surface controls the deposition mechanism and further complicates the elucidation of these tactics. An observation through do Nacimeno et al. used tender X-ray absorption spectroscopy to probe solute−solvent interactions in ChCl: urea combos with a nitrate salt. The authors experienced giant troubles with the signal of the solvent but were able to stumble on solute alerts and notice spectral modifications attributed to solvent−solute interactions. The differential spectrum obtained from the subtraction of the spectra of sodium nitrate dissolved in DES with pure DES was almost identical to that of pure nitrate indicating no sturdy interplay among the choline cation and nitrate anion

Rm = ((nD2 -1)/(nD2+2)V

The refractive index of DESs, though underutilized or ignored in most cases, can therefore be a useful tool to supplement physical property measurements as additional evidence to H-bond formation.

(B) Experimental Techniques

To represent and understand DESs, especially within the ongoing effort to broaden essential knowledge, a wealth of information is needed as a way to map the portions and behaviours of DES structures. The following sections spotlight the principal experimental strategies used in the study of DES systems.

Nuclear Magnetic Resonance

Nuclear Magnetic Resonance Spectroscopy (NMR) permits researchers to examine the cumulative outcomes of local magnetic fields in the place of atomic nuclei. Because it alternatives up signals originating from dipoles that arise at the nuclear stage (additionally referred to as electric polarization), it is predominantly used to decide the presence and/or contributions from numerous purposeful organizations in a sample for purposes ranging from verification of purity to identification of new useful companies. because of its potential to pick out an extensive range of additives thru 'snapshots' from numerous degrees of a procedure, it's miles of splendid application to gain a baseline knowledge as to what functional corporations are a gift, how they rearrange, and how the interaction. amongst DES studies, therefore, NMR predominantly unearths software in analyzing shipping phenomena and composition evaluation. The top-notch majority of NMR usage in DES studies, but, lends itself to composition analysis. The usage of NMR permits researchers to quantify/verify what's present in their gadget before acting different analytical strategies, allowing researchers to draw conclusions primarily based on facts approximately impurities, water content, and subtle shifts in useful group NMR alerts while used in tandem with other characterization techniques.

Broadband Dielectric Spectroscopy

Broadband Dielectric Spectroscopy (BDS), by contrast, provides a compact toolkit to look at many aspects of the dynamics of DES. Where techniques like NMR let researchers "see" silhouettes of each piece present in the sample, BDS reveals less about individual pieces, providing instead information on the movements of the silhouetted, "assembled" whole. The types of dynamics observable using BDS result from atomic polarization, which occurs when the entire nucleus of an atom is displaced by a magnetic or electric field

and is subject to the degrees of freedom afforded by the existing bond structure. This technique gives insight into the characteristic molecular behavior by a measured relaxation response to an applied perturbation in the form of an alternating electric field, which in turn allows researchers to gain an understanding of how various functional groups behave over a range of temperatures. Since many different kinds of movement in the form of stretching, vibration, rotation, and translation are possible, and since each of these fundamental movements has an associated timescale in which they can progress from an initial position to a final position, looking for resonance at different timescales enables researchers to determine what kinds of motion are present. By correlating this information back to information about what kinds of functional groups are present, a more complete understanding of the system can be obtained. This information allows for microscopic connections to macroscopic physical properties such as viscosity, conductivity, eutectic composition, and surface tension, insights that are likely essential to the development of a general model. This aspect of measuring motion enables BDS to be perfectly suited for studying the dynamics of molecular interaction to better grasp how and why deep DESs are more than just the sum of their parts. The transient aspect of hydrogen bonding is thought to be responsible for the high viscosities in DES, which makes it a perfect candidate for study through BDS measurements. Since viscosity is a measure of how easily molecules in a fluid can "slide" past each other when exposed to shear stresses, the timescales at which that operation can be completed will vary drastically with both substance and temperature. This makes BDS an ideal tool to connect dynamics to observed physical properties (e.g. viscosity). Furthermore, this technique is not limited to solid-liquid transitions. As it studies dynamics directly, BDS is a mature

analytical tool that can be applied profitably to study supercooled liquids and glasses as well, which is ideal given the supercooling tendency of DES systems.

Rheology

Rheology is the examination of substances that showcase both stable and fluid traits and allows us to discover while substances undergo plastic deformation vs elastic deformation, principally yielding records of approximately a material's viscosity. Correspondingly, rheometric checks come in many specific forms, may be used on Newtonian and non-Newtonian materials, and can offer data about viscosity in non-regular nation systems in addition to equilibrium states. This huge variety of records affords a wide picture of ways a substance flows below given conditions or states and using an extension, permits researchers to make predictions approximately the underlying molecular interactions that in the end dictate such observed behavior. Studies have been completed on DES structures so one can more completely apprehend how rheology is tormented by changes in testing parameters. thirteen, a look at mainly by Aroso et al. analyzed specific natural deep eutectic solvents (NADESs) shaped from choline chloride or betaine with distinct sugar molecules at exclusive molar ratios. After samples were organized, a KinexusProtRheometer turned into used to signify the rheological properties. Glide curves were acquired using applying a shear fee ramp from 0.1 to one hundred s-1 inside the temperature range of 283 to 373K on steps of 10. All NADESs analyzed displayed Newtonian conduct, as could be visible with the aid of staring at the regular viscosity at growing shear costs, so the Arrhenius equation becomes used to explain the glide of the samples. A similar examination analyzed numerous residences of benzyltripropylammonium-based DESs, however rather than the use of simply the Arrhenius equation to shape the viscoelastic information, the Vogel-Fulcher-Talmann equation, just like the

Arrhenius equation in that it describes Newtonian fluids, become extensively utilized and supplied a more accurate suit of the information. A study also analyzed rheological homes of NADESs, but as opposed to the usage of the Arrhenius or VFT equations to version the statistics, the Bingham equation became used rather than describe the non-Newtonian conduct of those systems. Those equations, or rheological fashions, assist perceive the shear strain conduct of DESs and analyze the impact of temperature on rheological drift curves. In trendy, it could be visible that there is a decrease in viscosity with growing temperature, and with the use of the model, there may be also a lower in yield stresses with temperature growth. A similar look at analyzed rheological properties of natural DESs characterized these houses as capabilities of temperature at constant shear fees and found comparable consequences. Given the commonly high viscosity of many DESs, know-how the effects of diffusion of variables on the ensuing viscosity is paramount. Moreover, given the robust tendency toward glass formation in many DESs, viscosity information is generally paramount in characterizing behaviours in any given system.

Raman Spectroscopy

Raman spectroscopy is used to observe molecular rotations, vibrations, and different low-frequency modes in a machine. It operates by passing monochromatic wavelengths of light through a sample and staring at the differences among elastic and inelastic scattering that occurs for given wavelengths, bearing in mind the high-quality identity of diverse molecules. These particular 'fingerprints' are exploited via a massive form of various techniques to determine what is present in a sample of DES and, to some degree, how its miles are present. Due to these assets, NMR, Fourier rework Infrared Spectroscopy (FTIR), and Raman spectroscopy are often used in conjunction to confirm the composition

and purity of the studied substances. The conjunction of techniques allows for greater accuracy and concerning information that is difficult to deconvolve for sure frequency degrees in a single or any other spectra. Frequently instances, but, they're used as a way of not directly verifying the life of hydrogen-bond-donor supramolecular complexes, as they provide clues approximately chemical shifts tied to the bond formation and dissolution of this type. One specific take look demonstrates the extent of detail that can be received from Raman measurements. In an examination they finished investigating phenylacetic acid and mandelic (2-hydroxy-2-phenylacetic) acid, they were capable of attaining exhaustive measurements of bond attitude deformations within the condensed nation of the combination. via consisting of effects obtained using infrared spectroscopy (IR), they have been capable of affirming results among the 2 strategies, which showed replicate parameters, widened the general variety of gadgets studied, and furnished finer resolutions. Those measurements together were sufficiently comprehensive and accurately sufficiently using themselves to make definite conclusions approximately the resting state of the phenylacetic and mandelic acid eutectic combination.

Fourier Transform Infrared Spectroscopy

FTIR is a technique used to verify the systems of various molecules with the aid of obtaining a pattern's infrared spectrum of emissions over a huge range of wavelengths. Because obtaining accurate data approximately the structure of DES compounds is crucial to expertise why they exhibit such precise residences, FTIR is a useful device while trying to and is one of the first techniques that researchers will flip to whilst trying to pick out what might be present in a sample. That is a beneficial way to perceive impurities that may be present in a sample, but it's far mainly used to pick out how the molecular systems shift and alter while each DES constituent is

mixed at diverse compositions. As an example, it has been used to determine the shape of solvent formation among choline chloride and citric acid, and work by Using Ibrahim et. at. used FTIR to affirm the existence of new purposeful groups in DES systems made from ethylene glycol and various salts. Moreover, FTIR has been used to confirm the presence of eutectic combos among choline and diverse compounds and to elucidate structural adjustments that arise at distinct temperatures inside the DES.

Neutron Scattering

Neutron scattering gives perception into the shape and dynamics of substances over length scales that vary from angstroms to hundreds of nanometers. It is particularly useful for reading natural substances, as the usage of evaluation variants gives a mechanism to highlight quantities of the material for inspection. This is possible due to the fact the scatter duration density of hydrogen and deuterium are appreciably one of a kind, and accordingly, the replacement of select protons with deuterium affords pathways to monitor their various portions of natural combinations without essentially altering their structure or thermodynamics. This technique consequently provides a unique method to decide the complex shape and dynamics of organic mixtures consisting of DESs. Taking benefit of this comparison control, some organizations have used neutron scattering to clarify the meeting, structure, and dynamics of several DESs. Researchers have provided some of the earliest neutron-based studies of DESs, wherein they examined the sub-diffusive motions of glycerine. The research showed that the movement of the glycerol and choline chloride range as the length scale changes from a few angstroms to many nanometers. In glycerine, the lengthy-variety translational diffusion is quicker for glycerol than choline, while at smaller length scales, the localized diffusive displacements are greater for choline than glycerol. The authors ascribe this counter-

intuitive result to the extra spatial constraint of the glycerol at the local level due to the inherent hydrogen bonding network of the DES. This take look at, therefore, emphasizes the need to apprehend dynamics over a variety of period scales while trying to correlate overall performance to local dynamics. Inelastic neutron scattering and wide-perspective neutron scattering have also provided critical details of the dynamics and structure of reline, an iconic deep eutectic solvent that consists of urea and choline chloride. wide perspective neutron scattering offers a perception into the connectivity of the complicated hydrogen bonding, in which the aggregate of neutron and computational research display that the large hydrogen bonding network includes interactions between all additives. mainly, the choline is found to contribute strongly to the hydrogen bonding network via the hydroxyl group, ensuing in a radially layered shape. Additional research by way of the identical institution shows that the DES nanostructure of the hydrogen bonding community in reline is enormously resilient to hydration, changing very little with the addition of as much as ≈ 42% water. The authors ascribe this result to the sequestration of the water to domains close to the the cholinium cation. At better degrees of water, the network shape of the reline DES is disrupted and is excellent described as an aqueous solution of urea and choline chloride. Inelastic neutron studies of reline provide the complementary perception that reveals that the torsional motion of the choline is much less hindered within the DES than in its natural state and that the urea attains a non-planar shape in reline. The sort of hydrogen bonds that exist in the reline DES outcomes in intermolecular, non-covalent interactions with urea that range from smooth to strong, which imparts flexibility to the device and allows the system to stay as a liquid at room temperature. Interestingly, comparable studies on glycerine show that the structure

of the hydrogen bonding community inside the DES consists nearly exclusively of glycerol, with the choline ions residing in voids of a few of the distinctly correlated hydrogen bonding communities. For that reason, the choice of hydrogen bonding issue within the DES will have a dramatic impact on the nature of the complicated hydrogen-bonded network that paperwork inside the eutectic liquid. The glycerol in glycerine does showcase complex dynamics, related to the complicated hydrogen bonding community of the DES. Comparable neutron scattering research for medicine shows that the malic acid and choline sandwich the chloride ion in this DES, forming greater well-described ionic domains than in reline. Those researches additionally verifies the robustness of the medicine network structure, displaying full-size retention of the DES structure as much as ≈ 50% hydration, with the water becoming a member of the network formation as an additional HBD. Thus, static and dynamic neutron scattering gives a remarkable perception of the structure and dynamics of the hydrogen bonding community and ionic clustering in a range of DESs. Those research elucidates the version in assembly and dynamics with hydrogen bonding donor, but also screens similarities of resiliency and retention of structure with hydration. Those foundational studies exemplify the significance of neutron scattering in figuring out DES meeting and dynamics, intending to be critical in their rational design as novel electrolytes.

Thermogravimetric Analysis

Thermogravimetric analysis (TGA) is another form of thermal evaluation that measures modifications in physical mass as a feature of temperature and/or time, considering sure inferences about physical and chemical residences to be made. However, because thermal conduct and physical houses are usually carefully correlated, it is also a useful device for detecting marked deviations and adjustments in behaviour because of

activities along with segment adjustments. Many editions allow for this approach to be leveraged to have a look at many exclusive physicochemical houses, and it's miles consequently applied often in determining how traits alternate because of myriad thermal activities which include absorption, desorption, sublimation, vaporization, decomposition, oxidation, and reduction. This feature makes it, in particular, useful in the analysis of volatile and/or gaseous products. It is utilized in DES to recognize factors in which and how behaviours change, and therefore presents rudimentary facts approximately thermal conduct in both crystals- and glass-forming transitions. Due to the maturity of the technique and the brilliant kind of 'basic' information that can be won from pretty trustworthy checking out, it's miles used regularly as a preliminary step to speedy benefit baseline information on completely alien DES mixtures, particularly if data concerning volatility isn't regarded beforehand. even as this makes it a supplementary method to others that give extra direct seems into physicochemical homes, companies which include Shahbaz et al. made sizeable use of entirely TGA to fast advantage such baseline statistics on mixtures of Choline Chloride, N, N-Diethylethanolammonium chloride, Methyltriphynlphosphonium bromide (HBAs) with glycerol and urea (HBDs). Through measuring the evaporation charges of each DES with TGA, correct tendencies inside the vapour pressure of every pattern may be decided. The consequences validated adjustments in vapour stress which had been attributed to the advent of recent hydrogen bonds within the combinations; greater intriguingly, the consequences tested that the vapour pressure of DES in this regard became considerably better than that exhibited by way of comparable ILs. As one of the few techniques on this list to provide definitive classification on the vapour strain, TGA is a reasonably easy and beneficial characterization tool to consist of in any

regime of checks when performing analysis on DES, irrespective of the primary objective beneath attention (particularly considering the relative loss of this kind of records for lots common DES).

Differential Scanning Calorimetry

Differential Scanning Calorimetry (DSC) is a thermoanalytical method that measures the amount of heat required to provide a found exchange in temperature in a sample and is especially beneficial in analyzing latent heat in the course of transformation events inclusive of section adjustments or, to a sure extent, glass transitions. it's miles usually used in DES research to find critical statistics figuring out melting factors, enthalpies of formation and fusion, warmness capacity data, and thermal balance of each natural component and ensuing combos. The potential to capture segment exchange occasions makes DSC, in particular, beneficial for detecting anomalous behaviour in DES. A DSC curve gathered for the 1:1 molar ratio of ChCl to malonic acid confirmed no peaks related to melting, crystallization, or glass transition, demonstrating as an alternative a baseline shift, a characteristic that was attributed to the incapacity of the DES to nucleate. Moreover, it became located that the solubility of numerous pharmaceutical precursors that are poorly soluble in ordinary solvents which include water has been as a lot as 22,000 times more soluble within the DESs tested than in water. Some other studies by Francisco et al. provided several DES composed of herbal compounds (NADES) that exhibited the most effective glass transition. This data has traditionally been vital for everyday answer theory to make accurate predictions about normal answers. It seems obvious, consequently, that these facts at a minimum may be needed for potential future models that can predictively describe the behavior of DESs.

Dynamic Light Scattering

Dynamic light Scattering (DLS) is an analytical method used by and large to

determine a size distribution profile of debris in suspension, including micelles in answer. A beam of light transmitted via the answer hits the suspended particles and is then scattered in all directions. The scattered mild undergoes both constructive or unfavourable interference by different debris, which may then be used to analyze the time scale of the motion of the scatterers, and need to be completed with optically translucent answers freed from dust and other particles. Many organizations have utilized DLS to affirm the formation of micelles and different merchandise in DES. Others have applied DLS so that you can advantage of better know-how of molecular shape of materials. Banjare et al. applied DLS to be able to degree the size of ionic liquid amphiphilic micelles shaped in DES. A comparable effort by way of employed DLS to evaluate the dimensions distribution (with the aid of intensities) of a DES-wealthy section in various protein-rich environments, while an examination through Griffin et al. concerning a lidocaine-decanoic acid (LID-DA) DES utilized DLS to decide structural reorientation costs over a huge temperature range.

X-ray Scattering

wide- and Small-attitude X-ray Scattering (WAXS and SAXS) are additional strategies utilized in determining the shape of materials, and both essentially bombard a material with X-rays to determine what's a gift. The most important difference between huge- and Small- perspective X-Ray Scattering (WAXS and SAXS) has to do with the angles at which diffraction maxima are analyzed. The change in angles of the scattering is attributed to the distinction within the period between the detector and the pattern; for a wide-attitude scattering, the space is shorter, hence the angle among diffraction maxima is wider. In trendy, WAXS is applied to take a look at brief-variety ordering in crystalline materials (along with a few polymers), at the same time as SAXS is applied to look for longer-variety ordering (including in

some amorphous or semi-crystalline substances). Since the ordering that DES show off inside the liquid section may be very quick-variety, WAXS is utilized often in analyzing DES sample. Bryant et al. utilized WAXS and SAXS to have a look at DES samples with glycerol and ethylene glycol HBDs. different studies have applied SAXS so that you can affirm the presence of micelle aggregates in DES. One study performed by way of Sakuragi et al. incorporated SAXS so that it will look at the trade-in structure of microemulsions in DESs due to variations within the ratio of surfactants used in the technique and solvents (DES and water).

Fluorescence Spectroscopy

Multi-dimensional in nature, fluorescence is characterized by several parameters, most notably the excitation and emission wavelengths, the constant nation polarization or anisotropy, the quantum yield, the excited-kingdom lifetime, and the rotational reorientation time. 359 The latter two replicate the time course of the emission procedure (rates of 107–1012 S–1) and, as a result, any procedure which occurs on a comparable timescale can potentially perturb the fluorescence (e.g., collisional quenching, power switch, solvent relaxation, rotational reorientation). Consequently, an excited-country fluorophore can be used to file on its nearby surroundings including temporal modifications in that environment, imparting insight into essential techniques occurring on the nanosecond and sub-nanosecond timescales. Fluorescence spectroscopy has come to be a crucial device for knowledge of the microenvironmental polarity, shape, interactions, and solvation inside DESs. The Pandey organization has contributed significantly to our understanding of the nearby microenvironment or cybotactic location surrounding solvatochromic fluorescent probes dissolved in DES structures. In their preliminary contribution, Pandey and co-employees assessed the effective polarity within

reline, ethylene, glycerine, and malo line based on a collection of polarity-sensitive fluorescent journalists (pyrene, pyrene-1-carboxaldehyde, 1-aniline-eight-naphthalene sulfonate, p-toluidine-6-naphthalene sulfonate, 6-propionyl-2-(dimethylaminonaphthalene), coumarin. In subsequent work, the Pandey institution explored the results of co-solvent (e.g., water, tetramethylene glycol, 2,2,2-trifluoroethanol, hexamethylphosphoramide,17hydrogen or solute (e.g., LiCl/citedhingra2019pyrene) change on DES structures. The same organization has additionally hired fluorescence spectroscopy to interrogate different molecular-degree procedures inside choline chloride-primarily based DESs to advantage additional perception into the nature of these trade media, which include the quenching of polycyclic aromatic hydrocarbons (PAHs) and L-tryptophan, the protolytic equilibrium of norharmane (β-carboline), the J- and H-aggregation of carbocyanine dyes, and the self-aggregation of the anionic surfactant sodium dodecyl sulfate (SDS) within DES-containing media. Time-resolved fluorescence measurements which include time-resolved depth and anisotropy decays offer a specially flexible way by way of which to examine the dynamics, structure, company, and reactivity inside complex systems. A growing quantity of studies organizations have begun to appoint time-resolved fluorescence techniques to look at solute solvation dynamics and solute rotational and translational mobility within DESs. Solvent reorganization within the region of a photoexcited fluorescence probe offers an upward push to a time-established spectral rest. This dipolar solvation reaction, or time-structured stokes shift, contributes to microscopic expertise of solvent reorganization procedures and solute–medium coupling in those crucial media. essential experts, the Biswas group has suggested widely the usage of time-resolved fluorescence to probe numerous DES systems, along with

structures composed of (acetamide + calcium nitrate), (acetamide + LiBr/LiNO3), (acetamide +NaSCN /KSCN), and (choline chloride + urea). In a maximum of these structures, signatures of both spatial and temporal heterogeneity had been located. Spatial heterogeneity is usually discovered with the aid of the excitation wavelength dependence of solute emission height frequency using molecular probes having broadly one-of-a-kind fluorescence lifetimes. then again, a robust fractional viscosity (η) dependence of common rotation and solvation instances (i.e., hτxi∝ (η/T)p for deviation from p = 1, T is the temperature) shows temporal heterogeneity in the rotational and relaxation dynamics. This deviation from hydrodynamics denotes a decoupling of probe rotation and solvation from medium viscosity. Intriguingly, however, Biswas and co-people discovered that nonionic DESs comprising acetamide + urea were spatially and temporally homogeneous, suggesting an essential difference between ionic and non-ionic DESs. Interestingly, the addition of polyethylene glycol (PEG) to the previous device introduced temporal heterogeneity, however nonetheless no evidence for spatial heterogeneity. A similar scenario of clear temporal heterogeneity without a strong signature for spatial heterogeneity was discovered for (glucose + urea + water) and (betaine + urea + water) DESs. In most paintings so far, the early part of the solvation dynamics for time-established Stokes shifts couldn't be captured due to the fact the sub-picosecond rest components have been too fast relative to the restrained time-decision (normal FWHM for the device reaction function is 25–85 play station), resulting in "missing" components where the envisioned missing amplitudes may without problems be as huge as Using an approach similar to that previously hired to have a look at ILs, the Biswas and Samanta agencies have recently coupled time-correlated unmarried-photon counting with

fluorescence-conversion measurements to capture the whole solvent dynamics of acetamide + LiX (X = Br -, NO3, ClO4-) and 1:three tetraalkylammonium bromide: ethylene glycol DESs, respectively. In both cases, a big ultrafast (sub-picosecond) solvation response became detected. In any other key observation of commonplace DESs (reline, ethylene, glycerine, monoline), Turner and Kim said "red-part consequences attributed to spatial heterogeneity, common solvation times shorter than those discovered in ILs of comparable viscosity, and more "slip"-like conduct for rotational coupling of the probe coumarin 153 in DESs compared to ILs. The Seth institution has also explored the microenvironment and structural heterogeneity within Reline on the premise of the photophysics of thioflavin T and several coumarin-based probes. the use of the powerful aggregate of ensemble (time-resolved anisotropy) and single-molecule (fluorescence correlation spectroscopy, FCS) measurements to examine solute rotational and translational dynamics in DESs, Samanta and co-workers discovered an increase in both the spatial (static) and the dynamic (temporal) heterogeneity for growing diol chain duration in choline chloride: diol DESs and increasing alkyl chain duration in 1:three tetraalkylammonium bromide: ethylene glycol DESs.This shows that the spatial and dynamic heterogeneity may be drastically modified by using altering the hydrocarbon chain length of both the HBD and HBA aspect of an ionic DES. interestingly, the identical researcher found clear proof for dynamic heterogeneity (i.e., departure of solute reorientation times from hydrodynamic conduct and anomalous diffusion in FCS) in ethylene, however, no static heterogeneity of the medium might be detected.

Conclusion

This review has revealed that interest in DESs has grown significantly in the 10 years since their first description. The similarity in physical properties between

DESs and ILs suggests that they belong in the same class of liquid which is distinct from molecular liquids; yet, the disparity in chemical properties between the liquids means that to date DESs have found very different application fields to ILs. The metal finishing industry is being restricted by legislation, toxicity issues, and cost; DESs offer a viable alternative to existing technologies, and hence, the application and scale-up of these processes have received considerable attention. While research into DESs has mainly focused on their application in metal finishing, DESs are beginning to be used in various synthetic applications; the limited reactions that have been investigated prove the potential of DESs in this area. Thus far, only a narrow range of DESs have been utilized: the future offers significant potential to expand the types of salts and hydrogen bond donors which are used and hence further increase the applications of these solvents.

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Figure 1. General formula for the classification of DESs.

type	general formula	terms
Type I	$Cat^+X^- + zMCl_x$	M = Zn, Sn, Fe, Al, Ga, In
Type II	$Cat^+X^- + zMCl_x.yH_2O$	M = Cr, Co, Cu, Ni, Fe
Type III	$Cat^+X^- + zRZ$	$Z = CONH_2$, COOH, OH
Type IV	$MCl_x + RZ$	M = Al, Zn; $Z = CONH_2$, OH
Type V	$RZ_1 + RZ_2$	$Z_{1,2}$ = OH, COOH

Figure 2. Freezing Point Temperatures of a Selection of DESs

halide salt	mp/°C	hydrogen bond donor (HBD)	mp/°C	salt:HBD (molar ratio)	DES T_f/°C	ref
ChCl	303	urea	134	1:2	12	13
ChCl	303	thiourea	175	1:2	69	12
ChCl	303	1-methyl urea	93	1:2	29	12
ChCl	303	1,3-dimethyl urea	102	1:2	70	12
ChCl	303	1,1-dimethyl urea	180	1:2	149	12
ChCl	303	acetamide	80	1:2	51	12
ChCl	303	banzamide	129	1:2	92	12
ChCl	303	ethylene glycol	−12.9	1:2		
ChCl	303	glycerol	17.8			
ChCl	303	adipic acid	153	1:1	85	13
ChCl	303	benzoic acid	122	1:1	95	13
ChCl	303	citric acid	149	1:1	69	13
ChCl	303	malonic acid	134	1:1	10	13
ChCl	303	oxalic acid	190	1:1	34	13
ChCl	303	phenylacetic acid	77	1:1	25	13
ChCl	303	phenylpropionic acid	48	1:1	20	13
ChCl	303	succinic acid	185	1:1	71	13
ChCl	303	tricarballylic acid	159	1:1	90	13
ChCl	303	$MgCl_2{\cdot}6H_2O$	116	1:1	16	42
methyltriphenylphosphonium bromide	231−233	glycerol	17.8		−4.03	44
methyltriphenylphosphonium bromide	231−233	ethylene glycol	−12.9		−49.34	44
methyltriphenylphosphonium bromide	231−233	2,2,2-trifluoroacetamide	73−75		−69.29	44
benzyltriphenylphosphonium chloride	345−347	glycerol	17.8		50.36	44
benzyltriphenylphosphonium chloride	345−347	ethylene glycol	−12.9		47.91	44
benzyltriphenylphosphonium chloride	345−347	2,2,2-trifluoroacetamide	73−75		99.72	44
$ZnCl_2$	293	urea	134		9	21
$ZnCl_2$	293	acetamide	81		−16	21
$ZnCl_2$	293	ethylene glycol	−12.9		−30	21
$ZnCl_2$	293	hexanediol	42		−23	21

Figure 3. Physical properties of DESs

Table 3. Physical Properties of DESs, Ionic Liquids, and Molecular Solvents at 298 K[a]

salt (mol equiv)	HBD (mol equiv)	viscosity/cP	conductivity/mS cm^{-1}	density/g cm^{-3}	surface tension/mN m^{-1}
ChCl (1)	urea (2)	632	0.75	1.24	52
ChCl (1)	ethylene glycol (2)	36	7.61	1.12	49
ChCl (1)	glycerol (2)	376	1.05	1.18	55.8
ChCl (1)	malonic acid (1)	721	0.55		65.7
C_4mimCl	$AlCl_3$	19	9.2	1.33	
ChCl (1)	$CrCl_3 \cdot 6H_2O$	2346	0.37		77.3
C_4mimBF_4		115	3.5	1.14	46.6
C_4mim$(CF_3CO_2)_2N$		69	3.9	1.43	37.5
	ethanol	1.04		0.785	22.39

Abbreviations

DES.	Deep eutectic solvents
NADES	natural deep eutectic solvents
Tm	Melting temperature