



# Magnetic deep eutectic solvents – Fundamentals and applications

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## ABSTRACT

Magnetic deep eutectic solvents (MDES), a relatively new subclass of conventional deep eutectic solvents (DES) containing additional paramagnetic components in their structure. MDES exhibit a strong response toward external magnetic fields, thus they can improve many industrial and analytical applications. In addition, this new group of solvents present unique physicochemical properties that can be easily tuned by selecting the appropriate ingredients for MDES synthesis. Therefore, the reported studies on properties and applications have increased in recent years. This review highlights the structures and mechanism of MDES formation, methods of synthesis, basic physicochemical properties, including melting point/freezing point, decomposition temperature, magnetic susceptibility, dynamic viscosity, density, ionic conductivity surface tension, toxicity, and hydrophobic/hydrophilic character, together with current application in analytical and industrial methods/procedures. Moreover, advantages, limitations, and future perspectives of the application MDES are critically discussed. We hope that this review will inspire many new perspectives and developments in the field of MDES applications.

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## 1. Introduction

Deep eutectic solvents (DES) were discovered in 2003 [1]. Typically, DES are prepared by a simple combination of two chemical compounds from which one acts as hydrogen bond donor (HBD), and the second one as hydrogen bond acceptor (HBA). The formation of specific interactions between HBA and HBD, including

*Abbreviations:* BTPB, butyltriphenylphosphonium bromide; ChCl, Choline chloride; CTAB, Cetyltrimethylammonium bromide; DES, Deep eutectic solvents; DTAB, Dodecyltrimethylammonium bromide; FP, Freezing point; FT-IR, Fourier transform infrared spectroscopy; GC/MS, Gas chromatography–mass spectrometry; GS, 1,3 bis(dodecyldimethylammonio) 2 hydroxypropane dichloride; HBA, Hydrogen bond acceptor; HBD, Hydrogen bond donor; HPLC, High Performance Liquid Chromatography; LPME, Liquid phase microextraction; LOD, Limit of detection; LOQ, Limit of quantification; MC, Magnetic component; MDES, Magnetic deep eutectic solvents; MIP, Molecularly imprinted polymer; MnCl<sub>2</sub>, Manganese (II) chloride; RSD, Relative standard deviation; STAB, Stearyltrimethylammonium bromide; TBAB, Tetrabutylammonium bromide; TBAC, Tetrabutylammonium chloride; TBPB, Tetrabutylphosphonium bromide; THDPB, trihexyltetradecylphosphonium bromide; TOAB, Tetraoctylammonium bromide; TTAB, Tetradecyltrimethylammonium bromide; UALLME-DES, ultrasound-assisted liquid-liquid microextraction based DES.

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hydrogen bonding and electrostatic interactions, leads to a large melting point depression upon the formation of DES. In most cases, pure DES components are solid, while the eutectic mixture is a liquid at room temperature (RT) [2,3].

Magnetic deep eutectic solvents (MDES) are considered a special category of conventional deep eutectic solvents. MDES consists of two or three substances, including HBA, HBD and an additional magnetic component (MC) as metal chloride of i.e. iron (FeCl<sub>3</sub>), manganese (MnCl<sub>2</sub>), gadolinium (GdCl<sub>3</sub>), cobalt (CoCl<sub>2</sub>), nickel (NiCl<sub>2</sub>) [4]. Procedures of MDES synthesis and the assumptions of the mechanisms of interaction between the components are similar to conventional eutectic mixtures. In addition, MDES have similar unique properties as conventional DES. However, MDES also exhibit a strong susceptibility to external magnetic fields [5]. The magnetic properties are particularly advantageous in separation techniques i.e. extraction, microextraction, absorption, and adsorption due to the fact that application of MDES can accelerate, streamline and increase the efficiency of processes, as well as reduce the number of necessary steps [5–9].

Therefore, research on new MDES systems, their properties and potential applications is becoming highly attractive. The growing interest in MDES is illustrated by the graph of the number of published papers during a period of 2010–2022 (Fig. 1). Due to simpler

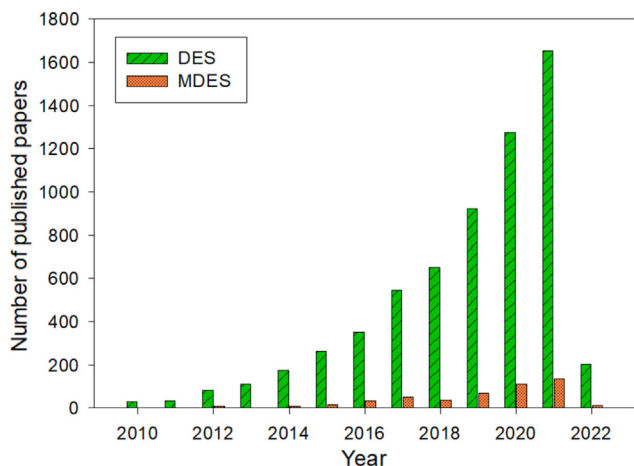


Fig. 1. Number of published papers per year from 2010 to 2022. The graph was build using the Scopus platform, from the topics deep eutectic solvents and magnetic deep eutectic solvents. Access date: 21.01.2022.

and shorter synthesis, the majority of eutectic complexes are still conventional deep eutectic solvents. There is still little information in the literature on the mechanisms of MDES formation, their physicochemical properties and potential applications. To date, only a few MDES combinations have been studied in detail. For the first time in 2017, Khezeli and Daneshfar prepared magnetic complexes consisting of choline chloride:phenol:  $\text{FeCl}_3$  and choline chloride: ethylene glycol:  $\text{FeCl}_3$ , which they called magnetic deep eutectic solvents [10]. The authors studied in detail the physicochemical and structural properties of the new compounds and applied them as new solvents for the extraction of thiophene from fuels in the ultrasound-assisted liquid-liquid microextraction process. However, the first MDES consisting of choline chloride: ethylene glycol:  $\text{MgCl}_2$  and choline chloride:  $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$  were published in 2011 [11,12]. The magnetic properties of the published compounds have not been determined. Only the structural and rheological properties, including viscosity, density, surface tension, and thermal properties of new complexes, were determined. Therefore, the authors included them in the group of conventional ionic liquids.

The present review focuses on the structure, synthesis, physicochemical properties (i.e. melting point/freezing point, decomposition temperature, magnetic susceptibility, dynamic viscosity, density, ionic conductivity surface tension, toxicity, and hydrophobic/hydrophilic character), and current applications of magnetic deep eutectic solvents in analytical as well as industrial methods. In addition, advantages, limitations, and future perspectives of the application MDES are also discussed.

## 2. Structures and preparation of MDES

### 2.1. Structures of magnetic deep eutectic solvents

The structures of the main components commonly used for MDES preparation are shown in Fig. 2. Most MDES consists of quaternary ammonium/phosphonium salts (i.e. Tetraoctylammonium bromide (TOAB), Tetrabutylphosphonium bromide (TPAB), Tetrabutylammonium bromide (TBAB), Tetrabutylammonium chloride (TBAC), Butyltriphenylphosphonium bromide (BTPB), Stearyltrimethylammonium bromide (STAB), Tetrabutylphosphonium bromide (TBPB), Trihexyltetradecylphosphonium bromide (THDPB), Tetracycltrimethylammonium bromide (TTAB), and Choline chloride (ChCl) that act as a hydrogen bond acceptors. They are well known substances commonly used in the synthesis of con-

ventional DES [13–15]. As HBD, carboxylic acids, sugars, phenols, glycols, and amides are commonly used. However, most of these compounds can be used not only as HBA but also as HBD due to the characteristic group i.e. = O, –COOH. As the third component, chloride salts with paramagnetic properties are used. Each one of these components is cheap, readily available, and they are characterized by low toxicity.

During MDES preparation, strong hydrogen bonds and weaker electrostatic interactions between the HBA, HBD, and MC components are formed. This leads to a lower melting point of the new MDES compared to the individual components. There are six basic types of MDES structures that are shown in Fig. 3, which is a modified version of the DES classification [16].

Based on the published works, it can be concluded that in the I and II groups, the MC component is the central point in the MDES structure to which the other components (HBA and HBD) are attached. In 2021 Peng et al., based on density functional theory and Fourier-transform infrared spectroscopy analysis (FTIR), explained the mechanism of lauric acid:decanoic acid: $\text{MnCl}_2$  (1:2:0.5 M ratio) formation. In MDES, Mn atom forms strong coordination bonds (<2.1 Å) with the oxygen atom from –COOH group of two molecules of decanoic acid and lauric acid. In addition, Cl atoms attract to hydrogen atoms from –COOH groups forming strong hydrogen bonds, between acids and MC [17]. In another work, based on the structure of MDES composed of ChCl, phenol, and  $\text{FeCl}_3$  in 1:2:1 M ratio (ChCl:phenol: $\text{FeCl}_3$ ), and ChCl:EG: $\text{FeCl}_3$  (1:4:1) authors suggested that chloride atom from ChCl joins to  $\text{FeCl}_3$  and form  $\text{FeCl}_4^-$  ion. After that, chloride atoms form hydrogen bonding with –OH groups of EG and phenol [10]. The III and IV groups of MDES are simple complexes of two components, which consist of HBA or HBD and a salt with paramagnetic properties. According to the basic classification of DES, these types of MDES can be classified as group  $\text{Cat}^+\text{X}^- + z\text{MCl}_x$  or  $\text{MCl}_x + z\text{RZ}$ , depending on the type of components used to synthesize. The mechanism for the formation of MDES is exactly the same as conventional DES [13,18]. The V and VI groups consist of HBA and hydrated magnetic components, and a mixture of HBA, HBD, and hydrated MC.

### 2.2. Preparation

In most works, the MDESs are prepared in two steps. In the first stage, pure deep eutectic solvents are obtained. This step consists in mixing two substances in appropriate molar ratios. The mixture is then mixed together at an elevated temperature (typically from 40 to 80 °C) until clear liquids are obtained. The resulting DES is then cooled to room temperature, according to standard procedure [1,2,4,17]. In the next step, the obtained DES is mixed with different metal chloride (MC) in appropriate molar ratios, and then a small amount of volatile solvent, i.e. dichloromethane, is added. Everything is mixed for about 24 h. After evaporating under reduced pressure the MDES is obtained [4,17]. A similar procedure can be used for the synthesis of IV type of MDES. The procedure consists in mixing quaternary ammonium salts, MC, and ethanol in appropriate molar ratios, under  $\text{N}_2$  atmosphere, at room temperature for several hours, and then evaporating the solvent, and drying in a vacuum oven at 80 °C [19]. This method consists of several steps, and the entire procedure takes up to several hours. Compared to the preparation of conventional DES, it is much longer and requires more work. In addition, the necessity to use volatile and toxic solvents means that the obtained MDES cannot be classified as green solvents.

In the literature data, there is also a one-step (one-pot) procedure for the preparation of MDES available. In this method, there is no need to use volatile solvents, and the entire procedure is slightly different from the standard procedure for the preparation of conventional DES. The procedure consists in simply mixing the

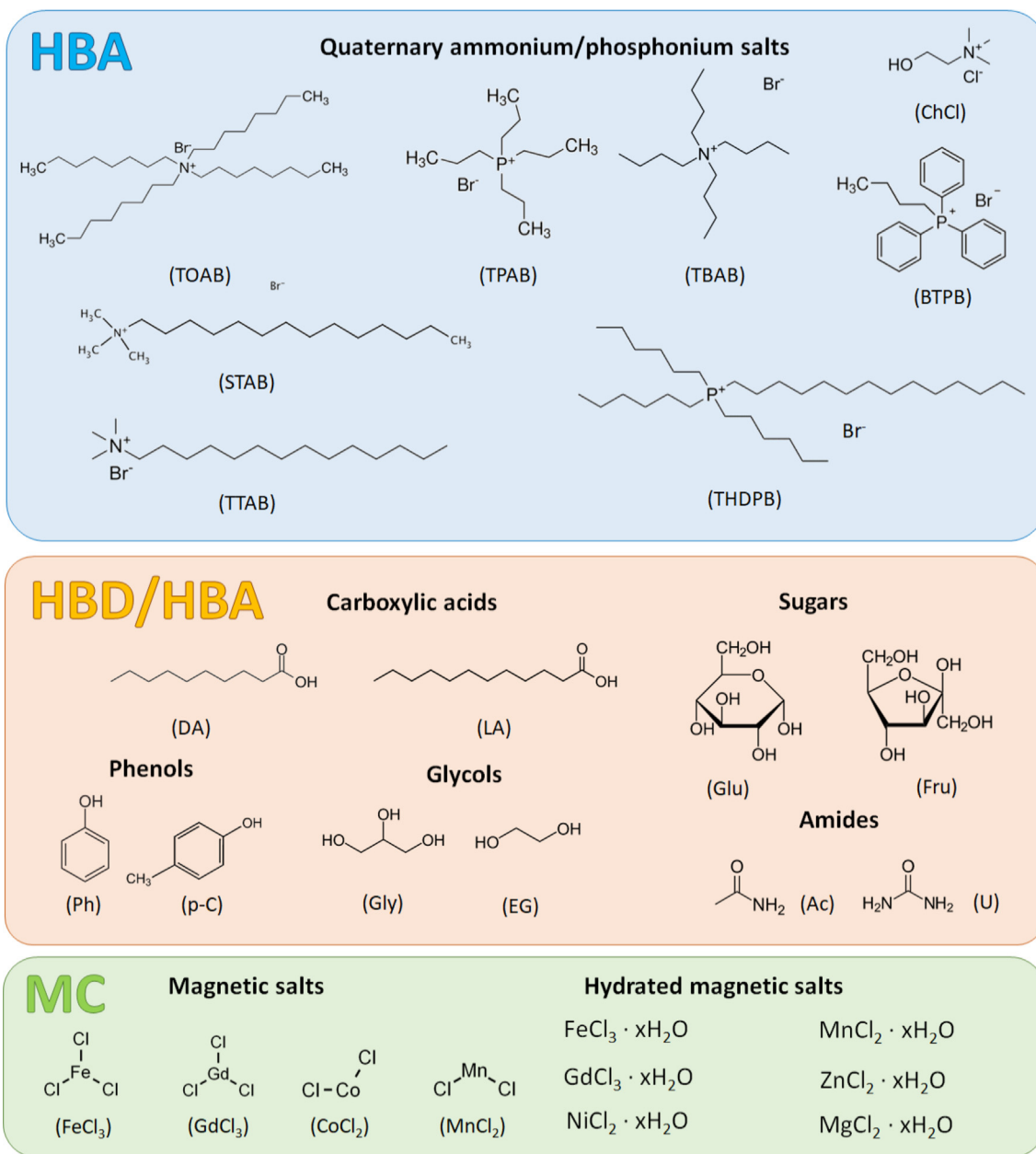


Fig. 2. Typical HBA, HBD, and MC structures in magnetic deep eutectic solvents complexes.

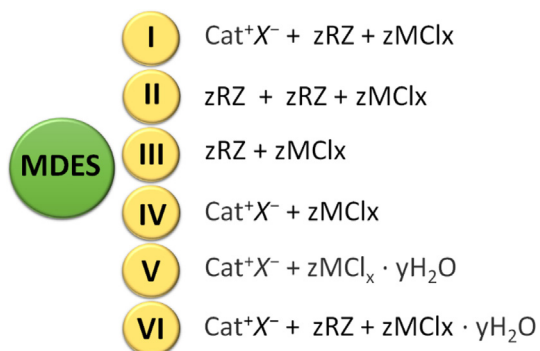


Fig. 3. Modified classification of MDES (where: M - Zn, In, Sn, Al, Fe, Cr, Ni, Cu, Fe, Co; z, y - number of molecules; RZ - compounds with active groups of OH, COOH, CONH<sub>2</sub>).

two or three components HBA, HBD, and MC at a proper molar ratio at a higher temperature (about 80 °C) until the formation of clear and homogeneous liquid [10,20–22]. The great advantage of this method is that there is no need to purify the final product. In addition, the procedure is much less complicated.

Another way to prepare magnetic DES is the simultaneous synthesis and extraction, the so-called “in situ” method. In the first step, the conventional DES are prepared in the appropriate molar ratios according to standard procedure [1,2,4,17]. After that, the obtained DES is introduced into an aqueous sample. The analytes are extracted to pure DES. Then an appropriately weighed portion of iron chloride is added to the solution. After mixture shaking, magnetic DES is formed in the solution [23]. In this approach, the stages of MDES preparation and extraction are significantly reduced, which significantly shortens the entire procedure. However, no structural studies of the obtained MDES have been performed so far. It is still unknown whether hydrogen bonds are

formed solely between the components of MDES, or between water and MDES.

Other methods used in the synthesis of conventional DES include mixing in an extruder [24], freeze-drying method [25], and grinding in a mortar [26]. However, they have not been used for the synthesis of MDES so far.

### 3. Physico-chemical properties

The physico-chemical properties of MDES largely depend on the components used for the synthesis (HBA, HBD, MC) and their stoichiometry. Even a small change in the proportion of components can significantly affect parameters, such as density, viscosity, melting (freezing) point, decomposition point, conductivity, magnetic properties, hydrophobicity, or hydrophilicity. This is an unquestionable advantage of MDES due to the possibility of adjusting parameters depending on further applications. Therefore, practical application of MDES requires knowledge of the basic physicochemical properties. In this section, the main physicochemical features of MDES are discussed and summarized in Table 1.

#### 3.1. Melting point/freezing point

The melting point/freezing point is a key parameter if a new complex has to be classified as a solvent. Among the previously known DES and MDES, many systems have melting points above room temperature. However, only a small group is characterized by a low melting point [2,27–29]. Most of the processes in which MDES can be used are carried out at room temperature. Therefore, only complexes that are liquids at room temperature are considered as useful DES in most analytical and industrial applications, i.e. separation techniques. Only some applications require higher melting points than room temperature to be employed e.g. electrochemical capacitors [30]. According to the definition of DES, it is a mixture of two or more compounds, the melting point of which is much lower than that of the components from which it was obtained. This decrease in melting point comes from a specific interaction, i.e. hydrogen bonds or van der Waals between components. The two-component system can be described by the simple phase diagram (Fig. 4a). However, most MDES consist of three chemical compounds, and the phase diagram is much more complicated and requires a big number measurements (Fig. 4a). Therefore, there are no examples of such a plot relating to MDES in the literature, and only a few studies show phase plots for conventional ternary DES [31,32].

The melting point of two-component MDES highly depends on components used for MDES synthesis. The melting point of MDES composed of quaternary ammonium salts and MC are relatively high and only few complexes have melting point below 25 °C i.e.  $\text{ChCl}:\text{ZnCl}_2$  (2:1),  $\text{TPAB}:\text{FeCl}_3$  (1:1),  $\text{TBPB}:\text{FeCl}_3$  (1:2) which are 23, 15.7, and 15.7 °C, respectively [19]. This is probably due to the fact that pure quaternary ammonium salts are characterized by high MP. In addition the melting point of MDES increases with increasing tetraalkyl ammonium/phosphonium quaternary chain. However, there is no dependency regarding the molar ratio of quaternary ammonium salts to MC concerning the melting point. In some systems, an increase in MC content in the MDES structure increases melting point, and in some systems, a decrease in melting temperature can be observed. Three-component systems are characterized by similar melting points, which are in the range from 11.2 to 13.2 °C. In comparison with conventional DES, melting point of MDES are slightly higher. For example, melting point of  $\text{TOAB}:\text{decanoic acid}$  (1:2) is 8.95 °C [33], while for  $\text{TOAB}:\text{decanoic acid}:\text{MnCl}_2$  (1:2:1) and  $\text{TOAB}:\text{decanoic acid}:\text{CoCl}_2$  (1:2:0.5) are 11.2 and 12.5 °C, respectively [4]. This is probably due to the rela-

tively high melting points of the magnetic components, as well as the weakening of the hydrogen bonds in the DES structure. MDES composed of non-ionic substances such as urea, acetamide, ethylene glycol, 1,6 – hexanediol, in combination with  $\text{ZnCl}_2$  have low melting points in the range from –30 to 9 °C. This is in line with the results for conventional DES [18]. Another solution to achieve low melting points of MDES is to add water. However, there is not enough information on the exact melting points obtained when water is added to the MDES. Moreover, some MDES have a hydrophobic character, therefore the addition of water does not reduce their melting point temperature.

#### 3.2. Decomposition temperature

The decomposition temperature of MDES is an important parameter from the point of view of their use in high-temperature processes. At high temperatures, changes in the structure of MDES, phase changes, breakdown of hydrogen bonding, and electrostatic interaction between HBA, HBD, and MC may occur. Hence, the assessment of the thermal stability of MDES provides information on the temperature at which the solvent can be used without structure changes [34,35].

The decomposition temperature of the three-component MDES is in general higher than that of the conventional DES. For example, DES composed of Tetraoctylammonium bromide (TOAB) and decanoic acid in 1:2 M ratio is characterized by a decomposition temperature of 207.66 °C [33]. Whereas, the decomposition temperatures of  $\text{TOAB}:\text{decanoic acid}:\text{CoCl}_2$  (1:2:0.5) and  $\text{TOAB}:\text{decanoic acid}:\text{MnCl}_2$  (1:2:1) are respectively 440.6 and 390.6 °C [4]. Other ternary systems composed only of non-ionic substances (i.e. lauric acid:decanoic acid: $\text{MnCl}_2$  (1:2:0.5), and lauric acid:decanoic acid: $\text{CoCl}_2$  (1:2:0.8)) also have a high degradation temperature above 380 °C. However, there is no information in the literature about these temperatures for conventional DES. Two component MDES also have higher decomposition temperatures than pure substances used in the synthesis. The decomposition temperatures for  $\text{DTAB}:\text{FeCl}_3$  (1:1),  $\text{TTAB}:\text{FeCl}_3$  (1:1),  $\text{CTAB}:\text{FeCl}_3$  (1:1),  $\text{STAB}:\text{FeCl}_3$  (1:1), acetamide: $\text{MnCl}_2\cdot 4\text{H}_2\text{O}$  (7:1), glycerol: $\text{MnCl}_2\cdot 4\text{H}_2\text{O}$  (3:1), D(+)-glucose:  $\text{MnCl}_2\cdot 4\text{H}_2\text{O}$  (1:1), D(-)-fructose:  $\text{MnCl}_2\cdot 4\text{H}_2\text{O}$  (1:1) are respectively 231, 226, 223, 212, 193, 146, 103, 108 °C. These values are higher than decomposition temperature of separate components used for MDES preparation [19,36]. This means that the new bonds between the components of MDES are strong enough to form stable complexes that can be used in high temperature processes without significant changes in the structures and properties of MDES.

#### 3.3. Density

The density of solvents is one of the fundamental thermophysical properties in order to be employed in separation processes. The density of most conventional deep eutectic solvents is higher than that of water and is between 1.0 g/cm<sup>3</sup> and 1.35 g/cm<sup>3</sup> at 298.15 K [18,37]. MDES density values are also mainly greater than water. For the two-component MDES densities are in the range from 1.195 to 1.63 g/cm<sup>3</sup> [12,19,38–40]. However, for the ternary MDES i.e.  $\text{TOAB}:\text{decanoic acid}:\text{CoCl}_2$  (1:2:0.5),  $\text{TOAB}:\text{decanoic acid}:\text{MnCl}_2$  (1:2:1), lauric acid: decanoic acid: $\text{MnCl}_2$  (1:2:0.5), and lauric acid: decanoic acid: $\text{CoCl}_2$  (1:2:0.8) the densities are close to water density (0.948 – 1.088 g/cm<sup>3</sup>). Two-component MDES composed of BTBAB and various magnetic components are characterized by similar densities [41]. To obtain a good phase separation in extraction processes, the densities of the aqueous and organic phases should be significantly different. Therefore, densities of MDES that are close to that of water is unfavorable for the separation of chemical compounds from aqueous samples. The values of

**Table 1**  
Physicochemical properties of magnetic deep eutectic solvents.

HBA	HBD	Magnetic component (MC)	Molar ratio (HBA:HBD:MC)	Molecular weight, $M_w$ [g/mol]	Magnetic susceptibility [ $\text{emu} \cdot \text{g}^{-1}$ ]	Viscosity at 25 °C mPa·s (cP)	Density at 25 °C ( $\text{g} \cdot \text{cm}^{-3}$ )	Melting point/freezing point [°C]	Decomposition temperature [°C]	Hydrophobicity	Conductivity at 25 °C, $\sigma$ [ $\mu\text{S}/\text{cm}$ ]	Surface tension $\gamma$ ( $\text{mN} \cdot \text{m}^{-1}$ )	Ref.
TOAB	decanoic acid	MnCl <sub>2</sub>	1:2:1	1017.2	$3.85 \cdot 10^{-5}$	$2.864 \times 10^5$	0.9478	11.2	390.6	Yes	N/D	N/D	[4]
TOAB	decanoic acid	CoCl <sub>2</sub>	1:2:0.5	956.2	$1.31 \cdot 10^{-5}$	$2.915 \times 10^4$	0.9689	12.5	440.6	Yes	N/D	N/D	[4]
ChCl	phenol	FeCl <sub>3</sub>	1:2:1	490.0	$0.546 \cdot 10^{-6}$	N/D	N/D	N/D	N/D	No	N/D	N/D	[10]
ChCl	p-cresol	FeCl <sub>3</sub>	1:3:1	593.9	$0.165 \cdot 10^{-6}$	N/D	N/D	N/D	N/D	Yes	N/D	N/D	[20]
ChCl	ethylene glycol	FeCl <sub>3</sub>	1:4:1	524.2	$5.14 \cdot 10^{-6}$	N/D	N/D	N/D	N/D	No	N/D	N/D	[10]
Lauric	acid	decanoic acid	MnCl <sub>2</sub>	1:2:0.5	607.7	$2.65 \cdot 10^{-5}$	437.01	1.0853	12.5	388.5	Yes	N/D	N/D
[17] Lauric	acid	decanoic acid	CoCl <sub>2</sub>	1:2:0.8	648.7	$2.14 \cdot 10^{-5}$	1759.7	1.0876	13.2	498.9	Yes	N/D	N/D
[17] ChCl	glycerol	MgCl <sub>2</sub>	1:2:0.04	330.3	N/D	175 <sup>e)</sup>	1.11	< RT	N/D	No	2090 <sup>e)</sup>	N/D	[45]
ChCl	urea	MgCl <sub>2</sub>	1:2:0.04	266.2	N/D	245 <sup>e)</sup>	1.102	< RT	N/D	No	2900 <sup>e)</sup>	N/D	[45]
ChCl	ethylene glycol	MgCl <sub>2</sub>	1:2:0.04	270.2	N/D	60 <sup>e)</sup>	1.131	< RT	N/D	No	5000 <sup>e)</sup>	N/D	[45]
ChCl	ethylene glycol	MgCl <sub>2</sub>	1:2:0.2	296.2	N/D	60 <sup>d)</sup>	N/D	< RT	120	No	9100 <sup>d)</sup>	59 <sup>d)</sup>	[11]
ChCl	ethylene glycol	MgCl <sub>2</sub>	1:2:0.3	312.4	N/D	70 <sup>d)</sup>	N/D	< RT	120	No	8300 <sup>d)</sup>	62 <sup>d)</sup>	[11]
ChCl	ethylene glycol	MgCl <sub>2</sub>	1:2:0.4	328.6	N/D	80 <sup>d)</sup>	N/D	< RT	120	No	7100 <sup>d)</sup>	65 <sup>d)</sup>	[11]
ChCl	ethylene glycol	MgCl <sub>2</sub>	1:2:0.5	344.9	N/D	110 <sup>d)</sup>	N/D	< RT	120	No	6400 <sup>d)</sup>	67 <sup>d)</sup>	[11]
ChCl	ethylene glycol	NiCl <sub>2</sub> ·6H <sub>2</sub> O	1:2:1	501.4	N/D	96.78 <sup>c)</sup>	N/D	< RT	N/D	No	N/D	N/D	[46]
ChCl	ethylene glycol	NiCl <sub>2</sub> ·9H <sub>2</sub> O	1:2:1	555.4	N/D	48.05 <sup>c)</sup>	N/D	< RT	N/D	No	N/D	N/D	[46]
ChCl	ethylene glycol	NiCl <sub>2</sub> ·12H <sub>2</sub> O	1:2:1	609.4	N/D	7.15 <sup>c)</sup>	N/D	< RT	N/D	No	N/D	N/D	[46]
ChCl	ethylene glycol	NiCl <sub>2</sub> ·15H <sub>2</sub> O	1:2:1	663.4	N/D	4.05 <sup>c)</sup>	N/D	< RT	N/D	No	N/D	N/D	[46]
ChCl	ethylene glycol	NiCl <sub>2</sub> ·18H <sub>2</sub> O	1:2:1	717.4	N/D	2 <sup>c)</sup>	N/D	< RT	N/D	No	N/D	N/D	[46]
ChCl	urea	NiCl <sub>2</sub> ·6H <sub>2</sub> O	1:2:0.1	283.5	N/D	970	1.23	< RT	215	No	31	N/D	[38]
ChCl	urea	NiCl <sub>2</sub> ·6H <sub>2</sub> O	1:2:0.2	307.3	N/D	1200	1.27	< RT	215	No	120	N/D	[38]
ChCl	urea	NiCl <sub>2</sub> ·6H <sub>2</sub> O	1:2:0.3	331.0	N/D	1150	1.29	< RT	215	No	130	N/D	[38]
ChCl	urea	NiCl <sub>2</sub> ·6H <sub>2</sub> O	1:2:0.4	354.8	N/D	1450	1.32	< RT	215	No	133	N/D	[38]
DTAB	-	FeCl <sub>3</sub>	1:0:1	470.5	$4.65 \cdot 10^{-5}$	N/D	1.27	32	231	No	14000 <sup>g)</sup>	23 <sup>g)</sup>	[19]
TTAB	-	FeCl <sub>3</sub>	1:0:1	498.6	$3.84 \cdot 10^{-5}$	N/D	1.23	50	226	No	3000 <sup>g)</sup>	28.98 <sup>g)</sup>	[19]
CTAB	-	FeCl <sub>3</sub>	1:0:1	526.7	$3.59 \cdot 10^{-5}$	N/D	1.19	62	223	No	2600 <sup>g)</sup>	26 <sup>g)</sup>	[19]
STAB	-	FeCl <sub>3</sub>	1:0:1	474.8	$3.24 \cdot 10^{-5}$	N/D	1.15	72	212	No	350 <sup>g)</sup>	30.55 <sup>g)</sup>	[19]
TPAB	-	FeCl <sub>3</sub>	2:0:1	694.7	N/D	1750	1.195	15.7	N/D	No	100	N/D	[22]
TPAB	-	FeCl <sub>3</sub>	1.5:0:1	671.2	N/D	6500 <sup>d)</sup>	1.23	38.1	N/D	No	220	N/D	[22]
ChCl	-	ZnCl <sub>2</sub>	1:0:1	275.9	N/D	N/D	N/D	65	320	No	N/D	N/D	[85]
ChCl	-	ZnCl <sub>2</sub>	2:0:1	415.5	N/D	$2.81 \cdot 10^5$	N/D	23	322.8	No	N/D	N/D	[85]
ChCl	-	ZnCl <sub>2</sub>	3:0:1	555.1	N/D	N/D	N/D	45	328.9	No	N/D	N/D	[85]
TBPB	-	FeCl <sub>3</sub>	1:0:2	663.8	N/D	1900	1.23	15.7	N/D	N/D	100 <sup>c)</sup>	N/D	[22]
TBPB	-	FeCl <sub>3</sub>	1:0:1.5	582.7	N/D	6500 <sup>d)</sup>	1.2	38.1	N/D	N/D	210 <sup>c)</sup>	N/D	[22]
BTPB	-	FeCl <sub>3</sub>	1:0:1	501.5	N/D	N/D	N/D	57.01	N/D	N/D	N/D	N/D	[86]

(continued on next page)

Table 1 (continued)

HBA	HBD	Magnetic component (MC)	Molar ratio (HBA:HBD:MC)	Molecular weight, $M_W$ [g/mol]	Magnetic susceptibility [ $\text{emu} \cdot \text{g}^{-1}$ ]	Viscosity at 25 °C mPa·s (cP)	Density at 25 °C ( $\text{g} \cdot \text{cm}^{-3}$ )	Melting point/freezing point [°C]	Decomposition temperature [°C]	Hydrophobicity	Conductivity at 25 °C, $\sigma$ [ $\mu\text{S}/\text{cm}$ ]	Surface tension $\gamma$ ( $\text{mN} \cdot \text{m}^{-1}$ )	Ref.
BTPB	-	FeCl <sub>3</sub>	1.5:0:1	671.2	N/D	N/D	N/D	52.5	N/D	N/D	N/D	N/D	[86]
BTBAB	-	AlCl <sub>3</sub>	1:0:2	623.1	N/D	12.8	1.0007	< RT	129.4	N/D	16	N/D	[41]
BTBAB	-	CuCl <sub>2</sub>	1:0:2	625.3	N/D	13.8	1.0039	< RT	240.3	N/D	11	N/D	[41]
BTBAB	-	FeCl <sub>3</sub>	1:0:2	680.8	N/D	14.8	1.0001	< RT	310.6	N/D	22	N/D	[41]
BTBAB	-	SnCl <sub>4</sub>	1:0:2	806.6	N/D	14.6	1.0043	< RT	147.5	N/D	12	N/D	[41]
BTBAB	-	ZnCl <sub>2</sub>	1:0:2	629.0	N/D	13.5	1.0014	< RT	116.2	N/D	9.5	N/D	[41]
ChCl	-	MnCl <sub>2</sub> ·6H <sub>2</sub> O	1:0:1	373.5	N/D	48 <sup>f)</sup>	1.34	16.15	N/D	No	31 <sup>f)</sup>	N/D	[12]
ChCl	-	MnCl <sub>2</sub> ·6H <sub>2</sub> O	1:0:1.5	490.4	N/D	63 <sup>f)</sup>	1.348	18.35	N/D	No	36 <sup>f)</sup>	N/D	[12]
ChCl	-	MnCl <sub>2</sub> ·6H <sub>2</sub> O	1:0:2	607.3	N/D	71 <sup>f)</sup>	1.36	44.02	N/D	No	39 <sup>f)</sup>	N/D	[12]
ChCl	-	MnCl <sub>2</sub> ·6H <sub>2</sub> O	1:0:2.5	724.2	N/D	102 <sup>f)</sup>	1.372	84.15	N/D	No	250 <sup>f)</sup>	N/D	[12]
ChCl	-	CrCl <sub>3</sub> ·6H <sub>2</sub> O	1:0:2	672.3	N/D	2346	N/D	4	N/D	No	370	N/D	[87]
ChCl	-	CoCl <sub>3</sub> ·6H <sub>2</sub> O	1:0:2	408.0	N/D	392	N/D	16	N/D	No	1700	N/D	[43]
ChCl	-	CrCl <sub>3</sub> ·6H <sub>2</sub> O	2.5:0:1	615.4	N/D	N/D	1.334	< RT	N/D	No	N/D	78.0	[79]
ChCl	-	CrCl <sub>3</sub> ·9H <sub>2</sub> O	2.5:0:1	669.4	N/D	881.8	1.301	< RT	N/D	No	N/D	71.9	[39]
ChCl	-	CrCl <sub>3</sub> ·12H <sub>2</sub> O	2.5:0:1	723.4	N/D	209.9	1.287	< RT	N/D	No	N/D	69.5	[39]
ChCl	-	CrCl <sub>3</sub> ·15H <sub>2</sub> O	2.5:0:1	777.4	N/D	169.8	1.275	< RT	N/D	No	N/D	66.5	[39]
ChCl	-	CrCl <sub>3</sub> ·18H <sub>2</sub> O	2.5:0:1	831.4	N/D	57.9	1.242	< RT	N/D	No	N/D	63.8	[39]
ChCl	-	CrCl <sub>3</sub> ·6H <sub>2</sub> O	2:0:0.5	545.6	N/D	N/D	1.589	< RT	N/D	No	N/D	83.13	[40]
ChCl	-	CrCl <sub>3</sub> ·9H <sub>2</sub> O	2:0:1	669.4	N/D	223.34	1.522	< RT	N/D	No	N/D	72.84	[40]
ChCl	-	CrCl <sub>3</sub> ·12H <sub>2</sub> O	2:0:1	653.6	N/D	83.34	1.401	< RT	N/D	No	N/D	69.21	[40]
ChCl	-	CrCl <sub>3</sub> ·15H <sub>2</sub> O	2:0:1	707.6	N/D	32.10	1.363	< RT	N/D	No	N/D	66.30	[40]
ChCl	-	CrCl <sub>3</sub> ·18H <sub>2</sub> O	2:0:1	761.6	N/D	21.98	1.316	< RT	N/D	No	N/D	50.31	[40]
GS	-	FeCl <sub>3</sub> ·6H <sub>2</sub> O	1:0:2	879.6	10.66·10 <sup>-6</sup>	N/D	N/D	65	N/D	N/D	N/D	37.58	[83]
-	acetamide	MnCl <sub>2</sub> ·4H <sub>2</sub> O	0:7:1	611.3	N/D	112.8 <sup>a)</sup>	N/D	< RT	193	No	127.23 <sup>b)</sup>	N/D	[53]
-	glycerol	MnCl <sub>2</sub> ·4H <sub>2</sub> O	0:3:1	474.1	N/D	1221.25 <sup>a)</sup>	N/D	< RT	146	No	30.67 <sup>b)</sup>	N/D	[53]
-	glucose	MnCl <sub>2</sub> ·4H <sub>2</sub> O	0:1:1	378.0	N/D	434.3 <sup>a)</sup>	N/D	< RT	103	No	98.9 <sup>b)</sup>	N/D	[53]
-	fructose	MnCl <sub>2</sub> ·4H <sub>2</sub> O	0:1:1	378.0	N/D	570.4 <sup>b)</sup>	N/D	< RT	108	No	77.03 <sup>b)</sup>	N/D	[53]
-	fructose	MnCl <sub>2</sub> ·4H <sub>2</sub> O	0:1:1	378.0	N/D	6689.25 <sup>b)</sup>	N/D	< RT	103	No	6.82 <sup>b)</sup>	N/D	[53]

N/D – no data available;  $M_W$  - Molecular weight [g/mol] which has been determined using the following equation:  $M_W = x_{\text{HBA}} \cdot M_{\text{HBA}} + x_{\text{HBD}} \cdot M_{\text{HBD}} + x_{\text{MC}} \cdot M_{\text{MC}}$ , where:  $x_{\text{HBA}}$  - the number of HBA moles in the MDES structure [-];  $x_{\text{HBD}}$  - the number of HBD moles in the MDES structure [-];  $x_{\text{MC}}$  - the number of MC moles in the MDES structure [-];  $M_{\text{HBA}}$  - molar mass of HBA [g/mol];  $M_{\text{HBD}}$  - molar mass of HBD [g/mol];  $M_{\text{MC}}$  - molar mass of MC [g/mol]; <sup>a)</sup> Measurements at 21 °C; <sup>b)</sup> Measurements at 29 °C; <sup>c)</sup> Measurements at 30 °C; <sup>d)</sup> Measurements at 40 °C; <sup>e)</sup> Measurements at 65 °C; <sup>f)</sup> Measurements at 70 °C; <sup>g)</sup> 30 mM solution of MDES in water;

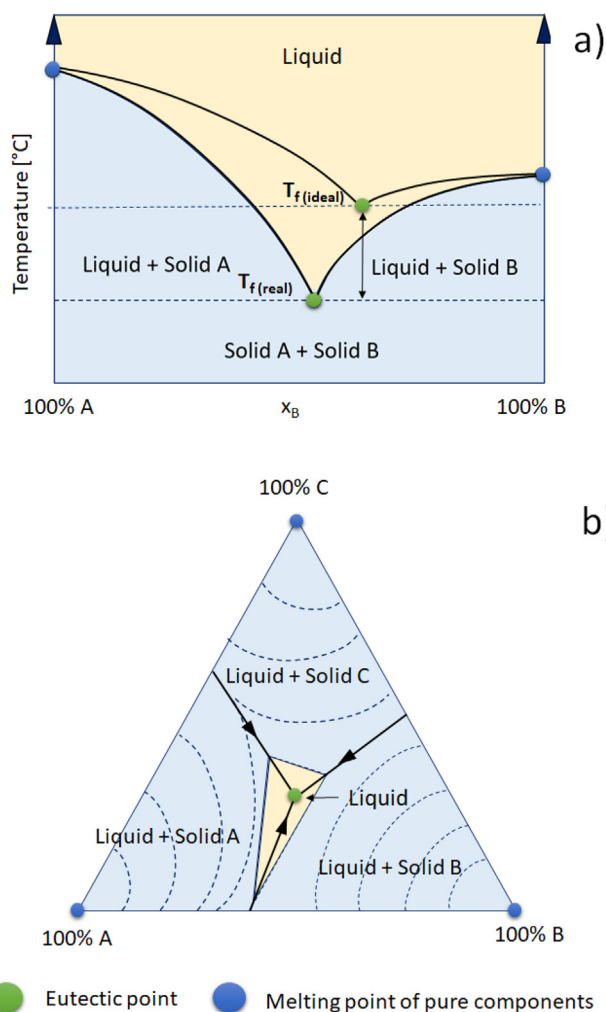


Fig. 4. a) Binary and b) ternary phase diagram for eutectic mixtures.

density depend on the components used for MDES synthesis and their molar ratio. It can be observed the component that has the greatest impact on the density of MDES is HBA (or HBD in two-component MDES), because it causes the formation of the so-called “gaps” in MDES structures which contribute to the increase in DES density. The magnetic component influences the density changes to a much lesser extent due to the simpler structure [41]. Theoretically, the use of hydrated MC should significantly reduce the density. However, a relatively small addition of water only slightly reduces this parameter. Probably much more water should be used to significantly affect the solvent density [39,40]. In separation techniques, i.e. extraction, the addition of water can increase the difference between the densities of the phases, ensuring easier and faster separation. However, such modification is limited to hydrophilic MDES. The temperature also has a significant influence on the MDES density values. The decrease in temperature of MDES affects a decrease in the kinetic energy of the molecules, which causes a density increase. This is due to the fact that at low temperatures the decrease in the movement of the MDES molecules and a consequent decrease in the molar volume of the eutectic complexes can be observed [42,43]. However, many industrial processes require temperatures close to room temperature. It is related to the economics of the processes. Moreover, in extraction processes, a change in the temperature of the solvent also changes the temperature of the second phase, i.e. it does not improve the phase separation.

### 3.4. Viscosity

Viscosity is a crucial parameter in many applications of MDES. The low viscosity of MDES makes solvents easy to handle and decreases energy costs. However, conventional DES and MDES are characterized by high viscosity (greater than 100 cP) [1,2,18]. The exact viscosity of the eutectic liquids depends mainly on the nature of components used in their preparation (i.e. HBA, HBD, MC), molar ratios, as well as the strength and type of interactions between the components. The viscosity of MDES in most cases is higher than that of conventional deep eutectic solvents. Viscosity of ternary MDES i.e. TOAB: decanoic acid:CoCl<sub>2</sub> (1:2:0.5) and TOAB: decanoic acid:MnCl<sub>2</sub> (1:2:1) are respectively 286400 and 29150 cP at room temperature [4]. While the viscosity of TOAB: decanoic acid (1:2) is 472.6 cP, which is 61 and 605 times lower than the MDES, respectively [33].

The high viscosity of MDES is caused, among others, by: (1) Presence of very strong hydrogen bonds between HBA and HBD which cause lower mobility of free species within the eutectic molecule; (2) Large ion sizes in HBA structure and small empty volumes. It is a so-called steric effect which can be quantified by the hole theory [44]; (3) The occurrence of relatively strong electrostatic and van der Waals interactions between HBA, HBD and MC; (4) The length of the alkyl chain of HBA or HBD. The longer the chain, the higher the MDES viscosity; (5) High content of the magnetic substance in the structure of DES, leads to the enhancement of the van der Waals interactions between MC and HBA and HBD molecules. In addition, an increase in the content of MC in the MDES structure may lead to the formation of the so-called bridges connecting MC to other groups of molecules. As the MC content increases, the number of bridges increases and forms a network between the different active groups of MDES, and consequently contributes to an increase in viscosity [45]; (6) The addition of water to eutectic structures with anhydrous magnetic salts usually leads to a decrease in dynamic viscosity. It is noticeable in MDES structures i.e. ChCl:ethylene glycol:NiCl<sub>2</sub>·xH<sub>2</sub>O (1:2:1), ChCl:CrCl<sub>3</sub>·xH<sub>2</sub>O (2.5:1), and ChCl:CrCl<sub>3</sub>·xH<sub>2</sub>O (2:1) where x increase from 6 to 18. For those MDES viscosity decrease from 96.8 to 2.0 cP at 30 °C, from 881.8 to 57.9 (at 30 °C), and from 223.3 to 22 cP (at 25 °C), respectively [39,40,46]. The decrease in viscosity can be explained by the lower viscosity of water in comparison to DES. In addition, the viscosity of MDES diminishes greatly with increasing temperatures, which can be described by Arrhenius or Vogel-Fulcher-Tammann model. This is due to the fact that an increase in temperature cause an increase in the average speed of the selected MDES components in the liquid phase, which decreases the intermolecular forces. This can reduce the fluid resistance to flow and change the viscosity [47].

### 3.5. Magnetic properties

The greatest difference between conventional DES and MDES is the paramagnetic properties of the solvents, under the application of an external magnetic. This property is particularly important in extraction, microextraction, manipulation within microfluidic devices, and magnet-based sensor processes [6]. High magnetic moments of MDES accelerate and simplify the after mentioned processes, as there is no need for a tedious centrifugation step. Moreover, MDES can be isolated easily from the sample solution through the use of a magnetic field [20]. It should be mentioned that MDES does not retain any magnetization properties without an externally applied magnetic field, because thermal motion causes the spins to become randomly oriented without it, as measured by a superconducting quantum interference device magnetometer [47]. The paramagnetic properties are influenced by the selection of the appropriate MC component, as well as its molar

ratio in the MDES structure. The higher the degree of magnetization of pure MC salts, the better magnetic properties of MDES can be expected. The dependence of popular magnetic components can be observed according to decreasing magnetic susceptibility  $GdCl_3 > FeCl_3 > MnCl_2 > CoCl_2 > CrCl_3 > NiCl_2 > MgCl_2 > ZnCl_2$ . Theoretically to obtain the best MDES properties,  $GdCl_3$  should be used as the main component in MDES structure. However, to date, no MDES have been prepared with a melting point below RT. Among MDES, the most popular components of MC are  $FeCl_3$  and  $MnCl_2$  due to their high availability, low price, low melting point compared to other paramagnetic salts, as well as relatively good magnetic susceptibility. However, so far only a few MDES have been tested for paramagnetic properties. The magnetic susceptibility of MDES are  $3.81 \cdot 10^{-5}$ ,  $2.65 \cdot 10^{-5}$ ,  $2.14 \cdot 10^{-5}$ ,  $1.31 \cdot 10^{-5}$ ,  $0.0546 \cdot 10^{-5}$ ,  $0.0514 \cdot 10^{-5}$ , and  $0.0165 \cdot 10^{-5} \text{ emu} \cdot \text{goe}^{-1}$  for TOAB: decanoic acid:  $MnCl_2$  (1:2:1), lauric acid: decanoic acid:  $MnCl_2$  (1:2:0.5), lauric acid: decanoic acid:  $CoCl_2$  (1:2:0.8), TOAB: decanoic acid:  $CoCl_2$  (1:2:0.5), ChCl: phenol:  $FeCl_3$  (1:2:1), ChCl: ethylene glycol:  $FeCl_3$  (1:4:1), and ChCl: p-cresol:  $FeCl_3$  (1:3:1), respectively [4,17,20]. On the basis of the obtained results, it can be observed that MDES with  $MnCl_2$  are characterized by the highest magnetic susceptibility. Slightly lower values can be observed for MDES consisting of  $CoCl_2$ . In addition, it can be observed that the higher the MC content and the higher the magnetic moment of MC, the better the paramagnetic parameters of MDES are. However, due to insufficient available data, it is difficult to determine the effect of the remaining components of MDES on increasing or decreasing magnetic susceptibility.

### 3.6. Hydrophobicity / hydrophilicity

According to the definition, hydrophobic substances do not have an affinity to water, and tend to repel or not absorb it. Solvents which are able to absorb more than 0.2 wt% of water are considered hydrophilic substances [11]. Most of the MDES are hydrophilic due to the strong hygroscopic nature of magnetic component. Due to the necessity to obtain paramagnetic properties, the MC content in the MDES structure must be high and, thus it is very difficult to obtain MDES that are hydrophobic in nature. Nevertheless, hydrophobicity is a key parameter that allows, among others, extraction of substances from water samples. In the literature there are only a few examples of such substances, including TOAB: decanoic acid:  $MnCl_2$  (1:2:1), TOAB: decanoic acid:  $CoCl_2$  (1:2:0.5) [4], Lauric acid: decanoic acid:  $MnCl_2$  (1:2:0.5), and Lauric acid: decanoic acid,  $CoCl_2$  (1:2:0.8) [17], and ChCl: p-cresol:  $FeCl_3$  (1:3:1) [20]. In one of the published studies, the hydrophobic character of MDES was proved by a simple test that measures the water content of the MDES before and after mixing with water. The concentration of water in MDES before tests was  $1.205 \cdot 10^4$  ppm and  $0.913 \cdot 10^4$  ppm for TOAB: decanoic acid:  $MnCl_2$  (1:2:1), TOAB: decanoic acid:  $CoCl_2$  (1:2:0.5), respectively. After water addition, the concentration of water in MDES increased slightly to  $2.097 \cdot 10^4$  and  $1.914 \cdot 10^4$  ppm, respectively [4]. For the remaining MDES, i.e. lauric acid: decanoic acid:  $MnCl_2$  (1:2:0.5), and lauric acid: decanoic acid:  $CoCl_2$  (1:2:0.8), and ChCl: p-cresol:  $FeCl_3$  (1:3:1) only visual tests were performed to confirm their hydrophobicity. Nevertheless, the results indicate that the use of highly hydrophobic HBA and HBD is necessary to obtain a hydrophobic MDES.

### 3.7. Ionic conductivity

Ionic conductivity is a very important parameter in many electrochemical applications [48]. This parameter strongly depends on the mobility of the ions, which is associated with dynamic viscosity and the number of charge carriers [49]. Theoretically, ion association can cause a reduction in ionic conductivity due to the decrease

of the number of available diffusible ions. Therefore, MDES with few ion-ion interactions and delocalized charges should show high conductivities. In addition, the ionic conductivity of MDES with quaternary ammonium and phosphonium salts decrease as the alkyl chain length increases [49–51]. This is due to the fact that longer alkyl chains cause higher hydrophobicity of MDES [19]. On the basis of the data compiled in Table 1, it can be concluded that the conductivity is influenced by both, the type of HBD and the type of MC and their molar ratios in MDES structures. However, it is closely related to the MDES dynamic viscosity. It can be noted that the ionic conductivity decreases with the increase of viscosity, due to the fact that high viscosity prevents the movement of ions. The ionic conductivity of three components MDES composed of choline chloride,  $MgCl_2$ , and different HBD is in the range from 2090 to 9100  $\mu\text{S}/\text{cm}$ , which is comparable with conventional DES [1,11,45,52]. The ionic conductivity of quaternary ammonium salts and  $FeCl_3$  in various molar ratios, as well as MDES, contain hydrated magnetic component are lower (6.82 – 220  $\mu\text{S}/\text{cm}$ ) and they are comparable to aqueous systems [22,38,53]. In addition, high temperatures can reduce the viscosity and increase the ionic conductivity of MDES, which is in line with the standard behavior of liquids [54].

### 3.8. Surface tension

Surface tension is the parameter that measures cohesive forces and the intensity of interactions between components in the mixture at the surface. According to the definition, the surface tension is the energy required to increase the unit area of a new surface or as the force to close unit length in the surface of a liquid. This parameter is of great importance in separation processes i.e. distillation, absorption, extraction, and microextraction [55–57]. However, only few papers provide MDES surface tension data. Based on the previous studies on ionic liquids and conventional DES it can be concluded that many factors can influence the surface tension of MDES i.e. temperature, type of HBA, HBD, MC, and their amounts in the DES structures [55–57]. The surface tension of conventional DES and ionic liquids are typically in the range from 40 to 65  $\text{mN} \cdot \text{m}^{-1}$  at 25 °C [55,58]. On the other hand, the values of MDES are within this range of 23 – 83.1  $\text{mN} \cdot \text{m}^{-1}$ , which shows a much wider range of surface tension of individual MDES, which depends on the type of substances used for their synthesis [11,39,40]. The lowest surface tension values are observed for DTAB:  $FeCl_3$  (1:1), TTAB:  $FeCl_3$  (1:1), CTAB:  $FeCl_3$  (1:1), and STAB:  $FeCl_3$  (1:1), which are 23, 29, 26, and 31  $\text{mN} \cdot \text{m}^{-1}$ , respectively [19]. The low surface tension of MDES is probably caused by long alkyl chains in the ammonium quaternary salts in MDES structures, which decreased charge density, thus decreasing the importance of electrostatic interactions between MDES components. The surface tension of MDES decrease with an increase in temperature, which shows the typical behavior of liquids [59].

### 3.9. Critical evaluation of MDES properties

Compared to conventional organic solvents and DES, MDES have several advantages and limitations. The greatest advantage of MDES is their paramagnetic property, which is very useful in the case of separation processes as extraction or microextraction. This allows easier phase separation through a magnetic field without a tedious centrifugation step. However, the paramagnetic property of MDES is relatively low. Therefore, it is necessary to use strong neodymium magnets, rather than the popular, cheap ferrite magnets. Very often even the use of strong magnets may not be enough to separate the phases. To obtain enough paramagnetic properties, the content of the magnetic component in the MDES structure must be high. The increase in MC content signifi-



cantly affects other physicochemical parameters compared to conventional DES. The first property that determines the further usefulness of MDES is their melting/freezing point. Based on a literature review, there are a very limited number of MDES that are liquids at room temperature. This is a major drawback of MDES due to the fact that many processes, both analytical and industrial, require the application of solvents that are liquid at 20 °C. The drop in the melting/freezing point of MDES compared to pure substances is slight. Therefore, according to the previous work, it can be assumed that we are rather dealing with simple eutectic mixtures than deep eutectic solvents [60]. This is likely due to the formation of weaker electrostatic interactions between MDES components rather than strong hydrogen bonds. Consequently, this may cause MDES structures to break down in contact with primary solvent i.e., water in the extraction process, which will form competing stronger H-bonds with the individual components. This significantly limits the usefulness of MDES. However, the mechanisms of MDES formation are still poorly understood. Therefore, more detailed studies should be conducted to confirm these assumptions.

The relatively high MC content in the MDES structures can reduce solvent hydrophobicity. This is due to the hydrophilic nature of common MCs. The solubility of FeCl<sub>3</sub>, GdCl<sub>3</sub>, CoCl<sub>2</sub> and MnCl<sub>2</sub> in water varies from 436 to 946.5 g/L. Therefore, it is difficult to obtain MDES that are stable in aqueous solutions and do not tend to dissolve in water. This affects the problems of the selection of appropriate solvent for the extraction of substances from aqueous samples. The presence of a magnetic component in MDES structures also affects other basic rheological properties, including density and dynamic viscosity. Both of them can accelerate and simplify the extraction processes. To obtain a good phase separation in extraction processes, the densities of the primary solvent and MDES should be significantly different. However, so far known hydrophobic MDES have a similar density to water, which significantly limits their usefulness in extraction processes. Hydrophilic MDESs show a much greater diversity in density values, which can be tuned by selecting the appropriate HBA, HBD, and MC depending on the type of sample matrix.

The dynamic viscosity of MDES is higher compared to conventional organic solvents. In most applications, such a high viscosity

will negatively affect the mass transfer processes. Nevertheless, there are several studies in which it has been proved that higher viscosity has a positive effect on phase separation in the extraction process [61]. Moreover, when using MDES as impregnating substances, one should aim for the highest possible viscosity to permanently deposit the MDES on the surface of the adsorbent [62,63]. Therefore, the choice of MDES should be dictated by the end-use.

From an economical point of view, the thermal decomposition temperature of MDES is an important parameter due to the fact that in many processes, solvents are regenerated at high temperatures. Whereas, regeneration is carried out to remove impurities from solvents and reuse them. Therefore, the decomposition temperature should be as high as possible to avoid weakening or decaying the interactions between HBA, HBD, and MC, which can lead to changes in physicochemical properties. Fortunately, the published data show that MDESs are characterized by higher thermal decomposition temperatures than conventional organic solvents and DES, which potentially increases the range of the MDES application. In addition, MDES are characterized by a wide range of surface tension, which can also increase the scope of application.

There are some serious limitations of MDES compared to conventional DES. Despite the similar procedures for the preparation of eutectic mixtures, the synthesis of DES is much simpler and shorter than that of MDES. In order to obtain DES, it is usually sufficient to mix the ingredients for a few minutes at an elevated temperature (about 80–90 °C). In contrast, to obtain MDES, the mixing process must be much longer and may take up to several hours.

From the point of view of green chemistry and green engineering, it is important to use only non-toxic and biodegradable solvents. However, no toxicity and biodegradability studies have yet been established with MDES. When considering the application of MDES as solvents in industrial processes, they should also be non-corrosive. However, it can be assumed that MDES will be characterized by its ability to corrode most of the metals due to the high content of highly corrosive MC in MDES the structures [64–66]. Nevertheless, more research needs to be done to prove these assumptions.

All these advantages and disadvantages of MDES in comparison to conventional DES, are presented in Fig. 5.

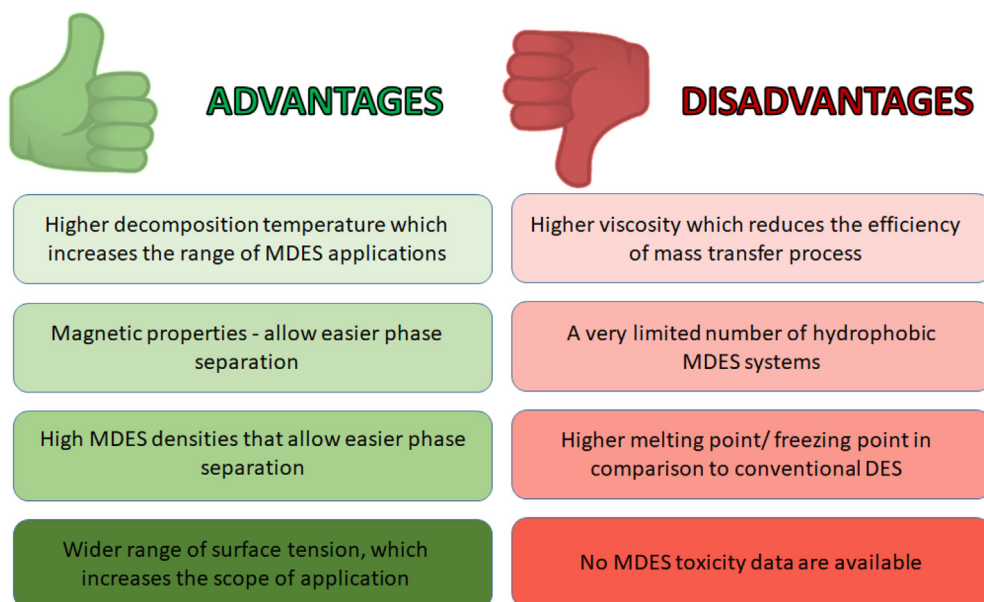


Fig. 5. Comparison of the pros and cons of MDES to conventional DES.

## 4. MDES applications

An overview of all MDES presented so far in the literature is shown in Table 2. As can be seen, by choosing proper components, it will be possible to apply MDES for many uses in laboratory research as well as potentially as sustainable solvents in industry. All the applications are further discussed in the below sections. Presented applications are categorized in two sections, as a media for analytical microextraction, and as solvents in the synthesis of catalysts.

### 4.1. Extraction processes

Ferrofluids based on MDES are uniform solid–liquid composite material containing magnetic nanoparticles suspended in a (hydrophobic) DES. During extraction, they are stable in solution and mostly their densities are lower than water. After extraction, the extracting ferrofluid can be easily separated from the aqueous solution by an external magnet. The first application of ferrofluid in liquid phase microextraction (LPME) was reported in 2010 by Lee group [67]. They used a ferrofluid which was composed of silica-coated magnetic particles and 1-octanol as the extractant solvent for the extraction of sixteen polycyclic aromatic hydrocarbons as model compounds from river water. However, using DESs as emerging green solvents for this purpose is new. The first report in this area was probably a work by Khezli and Daneshfar which was published in 2017 [10]. The authors described the importance on using magnetic DESs as: “In our previous reported method, ultrasound-assisted liquid–liquid microextraction based DES (UALLME-DES) was used to extract of three phenolic acids. Although UALLME-DES has excellent extraction efficiency, the separation of dispersed microdroplets of DESs created by the ultrasonication of sample solution was difficult and needs centrifuge instrument. Therefore, in this study, to overcome the shortcoming of UALLME-DES method, two novel hydrophilic MDESs were prepared”. This sentence clearly shows the main advantage of microextraction by using magnetic DESs in comparison to DESs. They prepared two MDES as ChCl:phenol:FeCl<sub>4</sub> and ChCl: ethylene glycol:FeCl<sub>4</sub>. After full characterization, MDES were applied in UALLME of thiophene in *n*-heptane as a model analyte. Initial results indicated that ChCl:phenol:FeCl<sub>4</sub> has higher extraction efficiency than ChCl: ethylene glycol:FeCl<sub>4</sub>. MDES was obtained simply by mixing the ChCl with EG and anhydrous FeCl<sub>3</sub> at a molar ratio of ChCl:ethylene glycol:FeCl<sub>3</sub> of 1:4:1 at 80 °C until a homogeneous clear liquid was formed. For performing microextraction, 1.5 mL of *n*-heptane containing thiophene and 20 µL of MDES were put in a vial placed inside an ultrasound water bath for 5 min. After that, the fine dispersed droplets of MDES were collected by putting a magnetic rod ( $B = 0.66$  T) in the sample solution until *n*-heptane phase was cleared. Finally, ~1 µL of *n*-heptane phase was injected into the GC for analysis. Another advantage of using MDESs in comparison to magnetic ionic liquids is “MDES can be prepared more cheaply (from common reagents) and easily (by simple complexation of the salt with the hydrogen bond donor). Moreover, the synthesis of magnetic ionic liquids is a time-consuming process but MDES can be successfully prepared with high purity in a short time”, as the authors of the article explain.

One year later, hydrophobic deep eutectic solvents were prepared and combined with magnetic clay to form a ferrofluid and used for direct microextraction of 11 explosive residues including 2-nitrotoluene, 3-nitrotoluene, 1,2-dinitrobenzene, 1,3,5-trinitrobenzene, 2,6-dinitrotoluene, cyclotetramethylene tetranitramine, cyclotrimethylenetrinitramine, hexanitrohexaazaisowurtzitane, tetryl, and pentaerythritol tetranitrate, and 2,4-dinitrotoluene in soil and water samples

[68]. To synthesize hydrophobic DESs, decanoic, caprylic, oleic, lauric, valeric, propionic, lactic, butyric, acrylic, acetic, stearic, palmitic, glutamic, succinic, tartaric, malonic, or oxalic acid were mixed with DL-menthol as HBA in different molar ratios before addition of 50 mg of magnetic montmorillonite clay/Fe<sub>3</sub>O<sub>4</sub> nanocomposite (nanoclay) to 1 mL of them. It was found that the obtained ferrofluid ponded a stable and uniform solid–liquid composition. To perform extraction, 50 µL of this ferrofluid was placed in a 15 mL vial containing 10 mL sample and stirred firmly for 30 min and after extraction, the micro-drop was removed with a rod magnet and dissolved in 500 µL of acetonitrile and sonicated for 4 min to desorb explosives. Finally, 50 µL of the resulting solution were injected into a HPLC. Limits of detection values were in the range of 0.22–0.91 µg/L, the enrichment factors varied between 23 and 93 and the relative standard deviations and recoveries were < 10 % and between 88 and 104 %, respectively. This research indicates the potential use of hydrophobic magnetic ferrofluid as a green solvent for enhancing the extraction of emerging materials from water and soil samples.

For the first time, Liu et al [69] used a DES as function monomers in molecular imprinted technology. MDES was prepared and adopted as functional monomer in a molecularly imprinted polymer (MIP) for the selective recognition and separation of Bovine hemoglobin. The obtained MIPMDES could separate proteins rapidly by an external magnetic field. They used it to separate template protein from the mixture of proteins and real samples. Additionally, compared to other magnetic MIPs, such as dopamine and acrylamide, the MIPMDES presented an enhanced adsorption capacity and imprinting factor to proteins. Meanwhile, the synthesis of DES function monomer was simple. Adsorption capacity of magnetic MIPMDES was found to be 169.32 mg g<sup>-1</sup>, which was almost four times higher than that of magnetic non-imprinted polymer, prepared in the same way as MIPMDESs. Isotherms were in accordance with Langmuir model. After three adsorption/elution cycles, the adsorption capacity was only about 7.93 % less.

In a paper published in 2020, Xia and colleagues reported the application of a combined MIPMDES composed of a ternary DES to selectively extract baicalein from the *Scutellaria baicalensis* Georgi [70]. The ternary DES was prepared with ChCl, oxalic acid and 1,2-propanediol, and Fe<sub>3</sub>O<sub>4</sub> particles were selected as the magnetic cores for preparation of MIPMDES. The system was characterized through morphology, core–shell structure, particle size, chemical bonds, weight ratio of modified layer, magnetic property and specific surface area. Moreover, binding experiments and selectivity test of MIPMDES were discussed. After extraction, quantitation of the analyte was performed by HPLC. Extraction was performed simply in batch mode, i.e. 20 mg of MIPMDES was added to 1.5 mL extract solution sample and the mixture shaken at 120 rpm for 60 min at 35 °C in a vibrator. MIPMDES was collected by a magnet. This adsorbent could be used for at least six extraction cycles, but its adsorption capacity was decreased slightly after that. The method was a linear range of 0.500–179 µg mL<sup>-1</sup>, LOD of 0.0387 µg mL<sup>-1</sup>, LOQ of 0.129 µg mL<sup>-1</sup>; with an intra-day RSD 1.43 % and Inter-day RSD 1.61 %. A high selectivity toward baicalein extractants permitted enriching it efficiently from real samples, being followed the pseudo-second-order model for adsorption kinetics of this compound.

MIPMDES was also used to separate transferrin from human serum [71]. For its preparation, 30 mg of previously prepared Fe<sub>3</sub>O<sub>4</sub> were sonicated in 10 mL phosphate buffer (20 mM, pH = 5.0). Then, 1 mg of transferrin, 11 mg of N,N-methylenebisacrylamide and 50 µL of ChCl and acrylic acid (molar ratio of 1:2) DES were added to the mixture and shake for 1 h to proceed pre-polymerization. Tetramethylethylenediamine (20 % aqueous solution, 70 µL) were added to the system to initiate the polymerization. The system was polymerized in dark for 24 h at

**Table 2**  
Applications of MDES-based microextraction techniques.

Analyte/sample	Microextraction method	DES components	Magnetic part	Ref
<b>Drugs</b>				
Thiophene in <i>n</i> -heptane	Ultrasound-assisted liquid-liquid microextraction	Choline chloride/phenol and choline chloride/ethylene glycol	FeCl <sub>4</sub>	[10]
Mefenamic acid in human urine	Vortex assisted liquid microextraction	Acetic acid with DL-Menthol	Oleic acid coated Fe <sub>3</sub> O <sub>4</sub> nanoparticles	[76]
Meloxicam in human blood plasma and urine	Ferrofluid was quickly injected into the sample solution using a glass syringe	Choline chloride and ethylene glycol	Silica-coated Fe <sub>3</sub> O <sub>4</sub> nanoparticles	[78]
Warfarin in plasma and urine samples	Ferrofluid was quickly injected into the sample solution using a syringe	Tetramethylammonium chloride and thymol	Magnetic-activated charcoal	[80]
Doxycycline in urine, blood plasma and milk	Synthesized ferrofluid was used in a vortex-assisted dispersive liquid-liquid microextraction	Octanoic acid and DL-menthol	Fe <sub>3</sub> O <sub>4</sub> magnetic nanoparticles	[81]
<b>Herbicides and pesticides</b>				
16 pesticides in sea, river, spring, agricultural, and underground water	Polymeric hydrogel	Acrylic acid-menthol	Fe <sub>3</sub> O <sub>4</sub> in the structure of DES	[72]
Triazine herbicides in rice and maize	Vortex assisted dispersive liquid-liquid extraction	Tetrabutylammonium chloride/ethylene glycol	FeCl <sub>4</sub> in the structure of DES	[23]
<b>Protein and DNA</b>				
Bovine hemoglobin in calf blood	MDES was used as molecularly imprinted polymer for batch extraction	Choline chloride and methacrylic acid (molar ratio 1:2)	Fe <sub>3</sub> O <sub>4</sub> in the structure of DES	[69]
Plasmid DNA from a bacterial cell lysate	Liquid-liquid microextraction	Decanoic acid and tetraoctylammonium bromide mixed by different metal chlorides	FeCl <sub>3</sub> , MnCl <sub>2</sub> , CoCl <sub>2</sub> and GdCl <sub>3</sub> metal chlorides	[4]
Plasmid DNA from a bacterial cell lysate	Vortex assisted liquid microextraction	Decanoic acid and lauric acid mixed by different metal chlorides	FeCl <sub>3</sub> , MnCl <sub>2</sub> , CoCl <sub>2</sub> and GdCl <sub>3</sub> metal chlorides	[17]
Transferrin in human serum	Ultrasound-assisted dispersive solid liquid microextraction	Choline chloride and acrylic acid	Fe <sub>3</sub> O <sub>4</sub>	[71]
<b>Explosives</b>				
11 explosive residues in soil and water	Liquid-liquid microextraction in a vial	A long list of fatty acids in combination with DL-menthol	Magnetic montmorillonite clay/Fe <sub>3</sub> O <sub>4</sub> nanocomposite	[68]
<b>Polycyclic aromatic hydrocarbons</b>				
16 polycyclic aromatic hydrocarbons in saliva and urine samples	Air-assisted liquid-liquid microextraction	Choline chloride and stearic acid	toner powder was used as magnetic particles and was acted as DE support in the preparation of ferrofluid	[67]
16 polycyclic aromatic hydrocarbons in grilled meats	Ultrasonic assisted liquid microextraction	Menthol and decanoic acid	Fe <sub>3</sub> O <sub>4</sub> nanoparticles coated with tetraethoxy silane	[74]
31 polycyclic aromatic hydrocarbons in grilled meats	Magnetic dispersive micro solid phase extraction-dispersive liquid-liquid microextraction	Choline chloride and decanoic acid	Fe nanoparticles	[75]
<b>Foodstuff</b>				
Morin in apple and grape juices, extract of onion and green tea infusion	Ultrasonic assisted micro-solid phase extraction	Tetramethylammonium chloride/ethylene glycol	SiO <sub>2</sub> @Fe <sub>3</sub> O <sub>4</sub> nanoparticles	[79]
Naringenin, gallic acid and hesperetin in orange, red grape and sour cherry juices	Ultrasonic assisted micro-solid phase extraction	Choline chloride-Ethylene glycol, tetramethylammonium chloride-ethylene glycol, and tetraethylammonium chloride-ethylene glycol	Fe <sub>3</sub> O <sub>4</sub> with adipic acid	[80]
Hexanal and heptanal in edible oils	Ultrasonic assisted liquid-liquid microextraction	Choline chloride/ <i>para</i> -cresol	FeCl <sub>4</sub>	[20]
Chiral mefenitruconazole in cereal	Dispersive liquid-liquid microextraction	Octyltrimethylammonium bromide, cobalt chloride, acetic acid	CoCl <sub>2</sub>	[82]
<b>Cation</b>				
Cobalt in tap water, bottled, mineral water, seawater, and river water	Ultrasonic assisted dispersive liquid phase microextraction	Menthol/decanoic acid	Fe <sub>3</sub> O <sub>4</sub> modified with sodium dodecyl benzene sulfonate	[77]
<b>Plants extracts</b>				
Baicalein from <i>Scutellaria baicalensis</i> Georgi	Batch extraction with solid MIP-MDES	Choline chloride, oxalic acid and 1,2-propanediol	Fe <sub>3</sub> O <sub>4</sub> nanoparticles	[70]
<b>Catalyst production</b>				
Industrial use of MDE in production of a catalyst	This catalyst was used for high yielding benzoin condensation and the efficient synthesis of pyrrole derivatives. It could be reused at least 4 times	Magnetic gemini-surfactant-based deep eutectic from a synthetic gemini-surfactant and FeCl <sub>3</sub> ·6H <sub>2</sub> O	gemini-surfactant 1,3 bis (dodecyltrimethylammonio) 2 hydroxypropane dichloride	[83]
Industrial use of MDE in production of a catalyst	This catalyst was used for the synthesis of substituted tetrahydropyrazolopyridines and pyrroles under very mild conditions	1:4 mol ratio of CoCl <sub>2</sub> :choline chloride	CoCl <sub>4</sub> <sup>2-</sup>	[84]

25 °C. Finally, the prepared MIP-MDES eluted by 2 % sodium dodecyl sulphate and 2 % acetic acid for removing template molecules. In this synthesis, DES acted as the functional monomer and *N,N*-methylenebisacrylamide as the crosslinker in the polymerization, Tetramethylethylenediamine as the initiator, and acrylic acid functionalized Fe<sub>3</sub>O<sub>4</sub> as a donor of magnetic properties and the material matrix. For separation and detection of transferrin, 4 mg of MIP-MDES were ultrasonically dispersed in 1 mL of the protein solution, shaking for 1 h. After adsorption, a magnet was used to separate MIP-MDES from the solution and the supernatant was measured by Coomassie blue-ultraviolet detection method. Then, sodium dodecyl sulphate-polyacrylamide gel electrophoresis was used to further verify the selective adsorption and the competitive adsorption experiment. Prepared MIP-MDES could be reused for at least 6 times. This adsorbent showed a fast adsorption for transferrin due to the existing electrostatic adsorption and low template molecule usage.

A MIP-MDES polymeric hydrogel was prepared through a thermal frontal polymerization in 4 min, using acrylic acid-menthol DES (as a functional monomer), ammonium persulfate (as initiator), and acrylic acid-Fe<sub>3</sub>O<sub>4</sub> nanoparticles as cross-linker [72]. The hydrogel was utilized as a sorbent in magnetic solid-phase microextraction of 16 pesticides coupled with GC- $\mu$ ECD for their determination. The LODs were in the range of 0.002–0.120  $\mu\text{g L}^{-1}$ , and the linear range was between 0.003 and 20  $\mu\text{g L}^{-1}$ . RSDs were in the ranges of 0.8–6.8 % and enrichment factors were from 152 to 550.

A new ferrofluid prepared from toner powder and DES was used in air-assisted liquid-liquid microextraction procedure for extraction of sixteen polycyclic aromatic hydrocarbons (i.e., anthracene, acenaphthene, benzo[*a*]anthracene, acenaphthylene, benzo[*b*]fluoranthene, benzo[*ghi*]perylene, fluorene, benzo[*k*]fluoranthene, indeno[1,2,3-*cd*]pyrene, chrysene, benzo[*a*]pyrene, fluoranthene, naphthalene, dibenzo[*a,h*]anthracene, phenanthrene, and pyrene) from urine and saliva samples of tobacco smokers by Jouyban, et al [73]. In this work, a hydrophobic DES was prepared by mixing ChCl and stearic acid under mild conditions and used as a support solvent in the preparation of ferrofluid from toner powder. Then, a few microliters of the prepared ferrofluid was mixed with the sample by performing aspirating/dispersing cycles. To collect the ferrofluid, a magnet was placed at the outside of the tube and the solution was discarded. The analytes in the collected phase were back-extracted into *n*-heptane and determined by GC/MS. LOD in the range of 18–63 ng/L in saliva and urine samples. Extraction recoveries and enrichment factors ranged from 61 to 84 % and 305 to 420, respectively. Aliquat 336 was used as the surfactant to prevent particles from agglomeration.

In another paper [74], Jouyban, et al. reported the use of a ferrofluid prepared from Fe<sub>3</sub>O<sub>4</sub> nanoparticles coated with Tetraethoxy silane mixed with menthol and decanoic acid DES. By using ultrasound assisted liquid microextraction, they could preconcentrate the same 16 polycyclic aromatic hydrocarbons using this ferrofluid. Analytes were back extracted to *n*-hexane before GC/MS analysis.

Polycyclic aromatic hydrocarbons were also determined in five mascara samples using deep eutectic solvent-coated magnetic nanoparticles for magnetic dispersive micro solid phase extraction-dispersive liquid-liquid microextraction of them [75]. Deep eutectic solvent coated magnetic nanoparticles were synthesized sonochemically and fully characterized. For the preparation of the sorbent, 5 mL of ChCl:decanoic acid DES was mixed with 1.0 mL dimethylformamide and Fe(CO)<sub>5</sub> was added and sonicated at 60 °C for 3 h at a power of 100 w. Color change of solution from bright-orange to black was considered as the end of the reaction. The obtained nanoparticles were magnetically separated and used for the extraction. Microextraction was a multi-step procedure as follows. First, analytes were extracted from mascara into an aqueous solution composed of methanol and deionized water (30:70, v: v), then the sorbent was added into the solution and the mixture was vortexed. After that, the sorbent was separated from the aqueous solution and the analytes were desorbed by methanol with the aid of vortexing. The entire elution solvent was collected and mixed with CCl<sub>4</sub> and dispersed into NaCl solution. Their method was validated and LOD and LOQ within the ranges of 0.33–0.57 and 1.1–1.9 ng g<sup>-1</sup>, respectively; with RSD values  $\leq$  8.6 %. Adsorbent could be used for 3 times with an extraction recovery between 80 and 95 %. Enrichment factors were not reported.

In a key paper [4], Ding's group discussed synthesis of four hydrophobic magnetic deep eutectic solvents and their application in DNA separation. Four hydrophobic DES based on HBD decanoic acid and HBA tetraoctylammonium bromide were prepared and mixed with different metal chlorides (FeCl<sub>3</sub>, MnCl<sub>2</sub>, CoCl<sub>2</sub> and GdCl<sub>3</sub>), to prepare hydrophobic MDES for the extraction of DNA from a bacterial cell lysate. These MDES compared to traditional DES, can be easily separated and collected through application of an external magnetic field, allowing fast extraction process without tedious and time-consuming centrifugation steps. They also showed the possibility of synthesizing hydrophobic MDES with adjustable physical and chemical properties. By changing the molar ratio and cation of mixed metal chloride, hydrophobic MDESs with certain magnetism could be obtained. The hydrophobicity of DES allows separation and purification of samples in aqueous environment (see Fig. 6). The developed hydrophobic MDES-based extraction procedure performed rapid and highly efficient extraction of nucleic acid from a matrix containing metal ions or

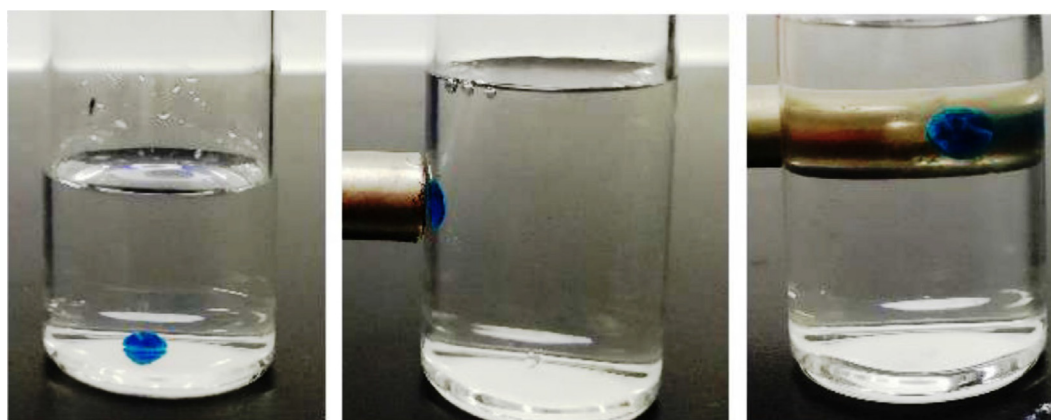


Fig. 6. After performing extraction, hydrophobic MDES can be quickly collected by an external magnet (from ref [4], with permission).

proteins. It could also extract plasmid DNA from bacterial cell lysate to obtain a high-quality template for polymerase chain reaction. Only 25.0  $\mu\text{L}$  of hydrophobic MDES were used to extract different DNA from a 1.0 mL solution. The instrument used for this purpose was a simple spectrophotometer which has its own merits of simplicity and cheapness.

The same group at the same year [17] reported a very similar work for the extraction of DNA from bacterial cell lysate again by using hydrophobic MDES. They prepared a series of four low-viscosity hydrophobic MDES by mixing decanoic acid and lauric acid with metal ion chloride which was used in their previous work. Synthesis was simulated by density functional theory calculation. Prepared hydrophobic MDESs again were used for the extraction of DNA. Interaction and corresponding binding sites between hydrophobic MDESs and DNA were investigated by FT-IR and density functional theory calculation. Interactions between DNA and the hydrophobic MDES are shown in Fig. 7. This time, a vortex extraction method was applied for selective extraction of DNA. This technique could extract the analyte from a complicated matrix in only 5 s. For a 1.0 mL sample solution volume, containing 1000.0 nM DNA; by using 20.0  $\mu\text{L}$  volume of hydrophobic MDES, extraction efficiency better than 77 % was achieved.

In another report of using hydrophobic MDES as ferrofluid for LPME,  $\text{Fe}_3\text{O}_4$  nanoparticles combined with hydrophobic DES was prepared and coupled with vortex-assisted LPME, to preconcentrate and determine mefenamic acid in urine samples, following HPLC [76]. The effect of parameters affecting microextraction, as pH, ferrofluid volume, ionic strength of the sample solution and vortex time were optimized using response surface methodology

based on central composite design. Hydrophobic DES was prepared by mixing acetic acid with DL-menthol (1:1 M ratio) by sonication together with 50 mg of oleic acid-coated  $\text{Fe}_3\text{O}_4$  nanoparticles, as magnetic nanoparticles, in 1 mL volume of DES was dispersed. For preparation of oleic acid-coated  $\text{Fe}_3\text{O}_4$  nanoparticles, after treating  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$  and  $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$  in ammonium hydroxide solution,  $\text{Fe}_3\text{O}_4$  magnetic nanoparticles were coated with oleic acid by mixing 0.5 g of  $\text{Fe}_3\text{O}_4$  nanoparticles with 10 % v/v of the acid, followed by the formation of the viscous solution via vigorous stirring at 150 rpm for 2 h. Under the optimum extraction conditions, the LOD and LOQ were 1.35  $\text{ng mL}^{-1}$  and 4.57  $\text{ng mL}^{-1}$ , respectively, with linearity in the range of 5–900  $\text{ng mL}^{-1}$  and RSD% better than 4.2 %. The extraction efficiencies of mefenamic acid in urine samples were between 80.25 % and 97.44 % with an RSD < 4.60 %.

In another application of using ferrofluids for microextraction, a hydrophobic MDES-ferrofluid method was prepared by Ghasemi, et al [77] and employed for dispersive LPME of cobalt from tap water, bottled, mineral water, seawater, and river water samples. After fully optimization of the extraction method, and by using a flame atomic absorption spectrometer for quantitative analysis, the limit of detection and enrichment factor were 0.7 and 50 mg/L, respectively. The relative standard deviation was 2.6 %. Ferrofluid was prepared from  $\text{Fe}_3\text{O}_4$  modified with sodium dodecyl benzene sulfonate and menthol/decanoic acid hydrophobic DES. The obtained ferrofluid showed lower density than water and high hydrophobicity and stability during the extraction. For synthesis of hydrophobic ferrofluid, co-precipitation were prepared by  $\text{Fe}_3\text{O}_4$  nanoparticle following reaction of  $\text{FeCl}_3$  and  $\text{FeCl}_2$  in ammonia solution. Then, 0.5 g of 1.0 % solution of sodium dodecyl benzene

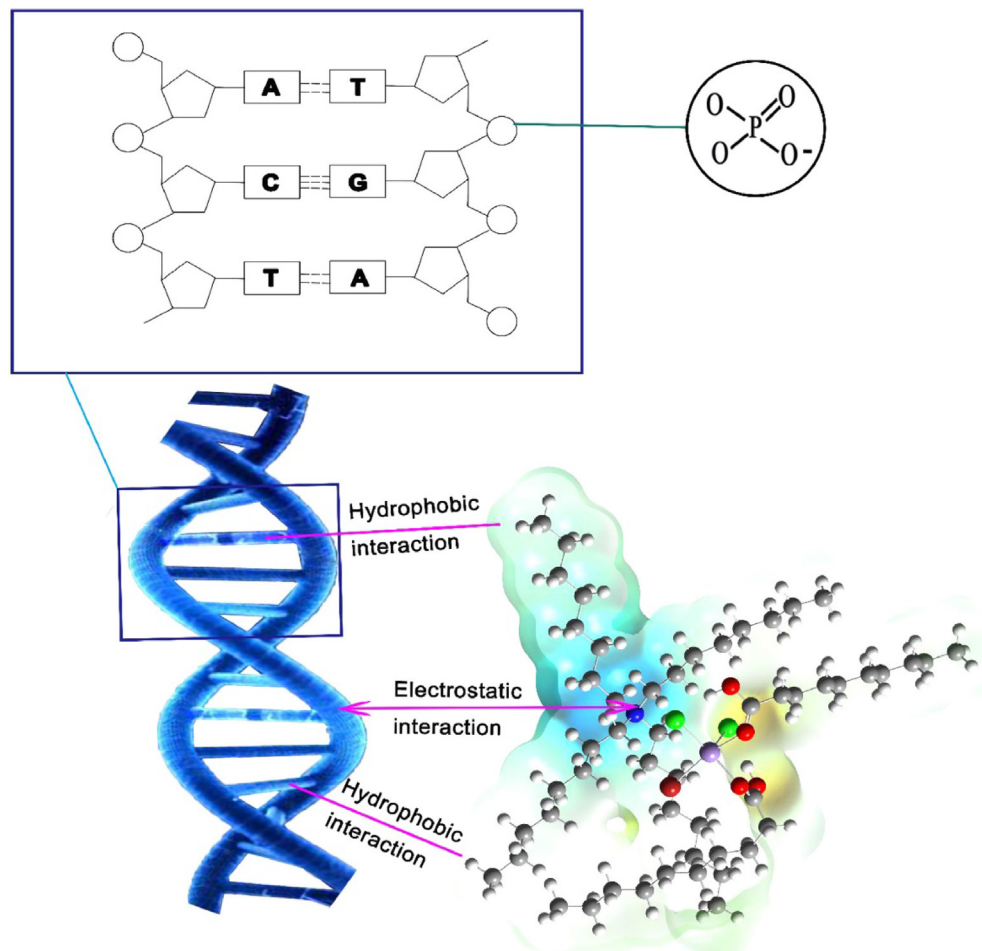


Fig. 7. Interactions between DNA and the hydrophobic MDES (from ref [4], with permission).

sulfonate was added to a beaker containing 3.0 g of  $\text{Fe}_3\text{O}_4$  nanoparticles, followed by 15-min sonication. The magnetic solid was collected using a magnetic bar and dispersed in hydrophobic DES carrier and treated by ultrasonication. Hydrophobic DES was prepared as 1:1 ratio of menthol:decanoic acid.

Although DES based ferrofluid showed good performance in the field of microextraction, its performance was limited by its poor dispersion stability. In 2021, Piao et al. proposed an in-situ formed MDES combined with the LPME method, which had both the magnetic characteristics of the ferrofluid and the good dispersion of the extraction medium [23]. This new type of magnetic DES showed a high affinity and could greatly simplify the extraction process through magnetic separation technology. Five triazine herbicides, desmetryn, secbumeton, terbumeton, terbuthylazine and prometryn were determined in rice and maize after their dispersive liquid-liquid extraction using a TBAB:ethylene glycol:  $\text{FeCl}_4$  MDES before HPLC analysis. DES were prepared by mixing ethylene glycol and tetrabutylammonium chloride at four different molar ratio (1:1, 2:1, 3:1 and 4:1) and heated for 30 min at 80 °C. 250  $\mu\text{L}$  of this DES (molar ratio of ethylene glycol to tetrabutylammonium chloride 2:1) were added to 4 mL *n*-hexane extract of the sample solution and vortexed. After adsorption, 40 mg of iron chloride were added in order to in-situ formation of MDES, following by addition of 90 mg of carbonyl iron powder to enhance the magnetic properties. Finally, by using an external magnet, phase separation was performed. Parameters affecting extraction were fully studied and optimized and under optimal conditions, calibration curves for the target triazine herbicides were obtained in the ranges of 5–1000  $\text{ng g}^{-1}$ , with correlation coefficients greater than 0.991. The limits of detection and quantification were in the range of 1.49–3.10  $\text{ng g}^{-1}$  and 4.96–10.34  $\text{ng g}^{-1}$ , respectively. The precision of intra-day and inter-day were under 6.2 % and 9.6 %, respectively, and the precision between laboratories were lower than 7.5 %. The accuracy of the method varied from 84.9 to 117.5 %.

The same methodology was used by Rastbood, et al. in 2020 [78] for drug meloxicam which was determined in human blood plasma and urine samples by HPLC analysis with a ferrofluid magnetic dispersive micro-solid phase extraction method based on a DES as a carrier. Extracting ferrofluid was prepared by mixing silica-coated magnetic nanoparticles with ethylene glycol/ $\text{ChCl}$  DES as carrier. To prepare this extracting ferrofluid,  $\text{Fe}_3\text{O}_4$  magnetic nanoparticles were prepared with a procedure similar to that used in ref [76]. Functionalized silica magnetic nanoparticles were prepared and mixed with a DES which was prepared by mixing  $\text{ChCl}$  as the HBA and ethylene glycol as the HBD at different molar ratios. The mixture was placed in a water bath at 80 °C for 10 min. During this step, the chlorine atom of  $\text{ChCl}$  formed a hydrogen bond with the hydrogen atom of ethylene glycol. Thus, the DES was gradually formed in the entire solution. To perform MDES micro-solid phase extraction, 2 mg of the  $\text{SiO}_2@ \text{Fe}_3\text{O}_4$  nanoparticles were dispersed in 250 mL of DES ( $\text{ChCl}$ :ethylene glycol) followed by sonication until a uniform ferrofluid was achieved. Then, the ferrofluid was quickly injected into 10 mL of the sample solution using a glass syringe to form a dark suspension. After the adsorption process, the adsorbent was separated from the solution using a magnet and target analyte eluted with ethanol, from that, 20  $\mu\text{L}$  of was injected into a HPLC. 250-fold excess of sodium, potassium, and calcium and 1000-fold excess of urea, thiourea, glucose, and sucrose had no significant effect on the extraction of mefenamic determination thus evidencing the selectivity. Analytical features of the method were as: linear ranges of 10–500  $\mu\text{g/L}$  with extraction recoveries above 89.2 %, limit of detections was < 3.0  $\mu\text{g/L}$ , 44.6 folds enrichment factors and RSDs lower than 6.2 %.

Magnetic dispersive micro-solid-phase extraction based on MDES applied for the extraction of morin in apple and grape juices,

diluted and acidic extract of dried onion and green tea infusion samples [79], warfarin in biological samples [80] and phenolic compounds in fruit juice [80]. While the carrier used in the extracting ferrofluid were different, the same protocol of preparation of the MDES was followed in all cases.

It was reported HPLC determination of oxycycline in urine, blood plasma and milk by a ferrofluid prepared by adding  $\text{Fe}_3\text{O}_4$  magnetic nanoparticles to a hydrophobic DES prepared by mixing octanoic acid and DL-menthol at 1:1 M ratio [81].

For detection of drugs by HPLC in biological fluids, magnetic nanoparticles (mainly  $\text{Fe}_3\text{O}_4$ ) were treated with different DESs that featured various polarities and used for liquid phase microextraction in different modes. Extraction and separation can be performed rapidly without need of centrifugation. However, no information is provided if during the desorption step of analytes, MDES are also washed out and enter into the chromatographic columns.

Ultrasonic assisted microextraction is the method of choice when it comes to the extraction of different analytes with MDES from foodstuff. Enrichment factors up to 50 with extraction time of <3 min achieved by using these methods.

$\text{ChCl}$ :*p*-cresol: $\text{FeCl}_3$  MDES was employed for ultrasound assisted liquid-liquid microextraction of hexanal and heptanal from edible oil samples followed by gas chromatography [20]. The analytical protocol was as follows: 1.5 mL of oil sample diluted with *n*-hexane for reduction of its viscosity were mixed with 40  $\mu\text{L}$  of MDES by sonication. After extraction, MDES droplets were collected by placing a magnetic rod ( $B = 0.66 \text{ T}$ ). Analytes were back extracted to cyclohexane:ethyl acetate; 1:1 v/v and 1  $\mu\text{L}$  of the back-extraction solvent was injected into the GC-FID system for analysis.

In a very recently published paper [82], for the first time, a ternary MDES was used as the extraction solvent for enantioselective determination of chiral mefentrifluconazole fungicide in cereal samples. In this report, Jia and colleagues applied a dispersive liquid-liquid microextraction method in order to selectively extract mefentrifluconazole before its determination by HPLC. The ternary MDES [octyltrimethylammonium bromide][cobalt chloride][acetic acid] was synthesized at a molar ratio of 1: 0.06: 5 as the extractant. In fact, acetic acid was functioned as the dispersant to promote the in situ dispersion of binary MDES of octyltrimethylammonium bromide and cobalt chloride. One important feature of this method is its fastness. The dispersion and separation procedures were completed only in 30 s, because MDES is generated in situ inside the sample solution. Characteristics of the analytical properties of this method evinced that the linearity of the analyte was within the range of 0.01–2  $\mu\text{g g}^{-1}$  with  $R^2$  values greater than 0.999. The LOD and LOQ of mefentrifluconazole enantiomers were 0.003  $\mu\text{g g}^{-1}$  and 0.01  $\mu\text{g g}^{-1}$ . The RSDs were 1.5–1.8 % for intra-day analysis and 2.9–3.1 % for inter-day analysis. Extraction recovery values obtained for S-mefentrifluconazole and R-mefentrifluconazole were 82.9–95.0 %. no information provided regarding the possibility of reusability of the method or the extraction enrichment factor.

Table 2 summarizes the main aspects of the articles published on analytical microextraction application of MDESs. As can be seen, there are unique advantages for microextraction using MDESs, such as replacing the centrifugation step with a magnet for separation, simple synthetic processes of MDES and lower price of them. Moreover, components used for preparation of MDESs mainly consist of environmentally friendly materials, in most of the cases, choline chloride. However, in many instances, still there is a need for shaking, vortexing, microwaving, and ultrasonication for extraction which prolongs the pretreatment time and is inconvenient. Moreover, reusability of the extractant is generally limited to 3 times. Low recovery is another drawback of using

MDESs as microextraction media. Almost all of the methods reported recoveries lower than 95 %, even as low as 61 %. Still with this low recovery, excellent enrichment factors, up to 550 folds were achieved.

#### 4.2. Catalyst preparation

Tamaddon and Tadayonfar [83] prepared and characterized a magnetic gemini-surfactant-based deep eutectic from a synthetic gemini-surfactant and  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$  as HBA and HBD components. They replaced a magnetically-separable surfactant prepared by incorporation of the magnetic complex anion of  $[\text{FeCl}_4]^-$  in surfactant-based DES to be used in benzoin condensation and multi-component synthesis of pyrrole derivatives. In their protocol, water was added at the end of the reaction and the magnetic aqueous solution of DES was isolated by an external magnet, and the precipitated catalyst was filtered and washed with water. They prepared this catalyst to address reusability issues and recovery drawbacks of acid catalysts in aqueous media. Efficacy could be improved by hosting of surface-active gemini-surfactants in the structure of the catalyst instead of simple surfactants due to their lower critical micelle concentration, higher polarity, and their self-assembly. The cost of production of the catalyst was also lower and recovery of this viscose liquefy catalyst is simply by using an external magnet. The catalyst could be reused without loss of its activity even after four consequent cycles. In another report [84], Tamaddon and Khorram used magnetic-responsive deep eutectic catalyst based on  $\text{Co}^{2+}/\text{ChCl}$  for the synthesis of tetrahydropyrazolopyridines and pyrroles in water. They examined the components at different mole ratios in the solid-liquid equilibrated mixtures of  $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$  and  $\text{ChCl}$  followed by vacuum evaporation. Among these complexes, the bluish complex  $2\text{ChCl} \cdot 2\text{Ch}^+ \cdot \text{CoCl}_4^{2-}$  ( $\text{Co}_4\text{ChDES}$ ), given at 1:4 mol ratio of  $\text{CoCl}_2:\text{ChCl}$  showed a very deep decrease in melting point and paramagnetic properties. After full characterization, they found that the structure of this MDES is so that the anionic complex  $\text{CoCl}_4^{2-}$  provides magnetically recovering of  $\text{Co}_4\text{ChDES}$  in cooperation with the four choline groups, which are HBA and HBD components of this MDES. A vibrating sample magnetometry curve showed that the prepared MDES

had paramagnetic properties with a magnetic saturation of 224  $\text{memu/g}$ . This prepared MDES represented high catalytic performance in the water-based multi-component reactions for the synthesis of substituted tetrahydropyrazolopyridines and pyrroles under mild conditions. The authors showed that besides high efficiency, simple recovery, and reusability of this catalyst, it is also non-corrosive. This value is higher than gemini surfactant cobalt complex they reported previously [21]. Due to the blue color of MDES and high magnetic saturation, the authors claimed that there is a tetrahedral magnetic anionic complex  $\text{CoCl}_4^{2-}$  in the structure of DES formed at  $\text{CoCl}_2 \cdot 4\text{ChCl}$  and hence proposed the structure indicated in Fig. 8 for their prepared MDES.

The reported studies clearly show that DES can be used as an appropriate media to improve catalyst reactions and that the incorporation of metal chloride to DES structure offers a possibility for the recovery of catalysts after their use in a cheap and fast way.

#### 5. Conclusion and outlook

In recent years, the number of papers and studies on “green” solvents, i.e. deep eutectic solvents, has increased significantly. Nevertheless, there are still a very limited number of DES with magnetic properties. Magnetic susceptibility is a very useful property in many laboratory and industrial application in order to improve extraction, microextraction, or catalyst use due to the fact that allows easier phase separation through a magnetic field without a tedious centrifugation step. Therefore, an increase in research into new MDES combinations can be expected in a near future. Since MDES are still not commercially available, and information about the physicochemical properties of the already known MDES complexes is very limited, a lot of effort still needs to be done to gain a better insight into the MDES structures and their impact on properties. There is a lack of detailed information on polarity, surface tension, conductivity, thermal stability, magnetic susceptibility, viscosity, and density of MDES, as well as the influence of temperature or water addition on these parameters. So, the knowledge about these parameters is necessary to favor their subsequent applications. Based on the physicochemical parameters of MDES examined so far, we can assume that they may in the future replace many of the currently used toxic organic solvents. However, in order to consider MDES as a “green” alternative to conventional solvents, it is essential to perform MDES toxicity, biotoxicity, and volatility studies, which clearly evidence these aspects.

Current applications of MDES presented in the literature are limited to processes such as microextraction, extraction, or catalysts synthesis. However, taking into account the use of other magnetic solvents, such as magnetic ionic liquids, we can expect a significant increase of applications in the future, including in the polymer industry for the production of nanostructures and reduced dimensionality materials, or in the electronic industry as new electrochromic materials for the manufacturing of different electronic devices (information displays, anti-glare rearview of automobiles, and smart windows), as well as increasing the range of applications of MDES in separation processes. In this aspect, the future is open and research in this field must advance both, fundamental characterization and their application.

#### CRediT authorship contribution statement

**Patrycja Makoś-Chełstowska:** Conceptualization, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Massoud Kaykhaii:** Writing – original draft, Writing – review & editing. **Justyna Plotka-Wasyłka:** Writing – review & editing. **Miguel de la Guardia:** Writing – review & editing.

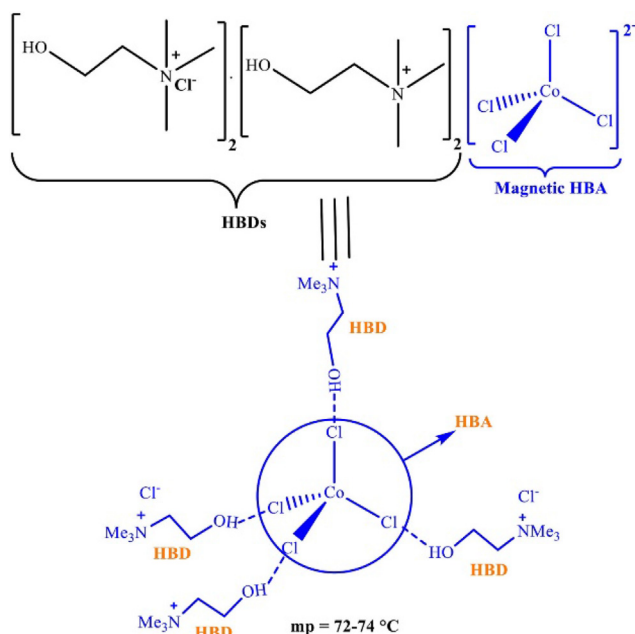


Fig. 8. The proposed formula for  $\text{CoCl}_4^{2-} \cdot 2\text{Ch}^+ \cdot 2\text{ChCl}$  (from ref [71], with permission).

## Data availability

No data was used for the research described in the article.

## Declaration of Competing Interest

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

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