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# Assessment and design of greener deep eutectic solvents – a multicriteria decision analysis

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#### 8 ABSTRACT

Deep eutectic solvents (DES) are often considered as green solvents because of their 9 properties, such as negligible vapor pressure, biodegradability, low toxicity or natural origin 10 of their components. Due to the fact that DES are cheaper than ionic liquids, they have gained 11 many applications in a short period of time. However, claims about their greenness 12 sometimes seem to be exaggerated. Especially, bearing in mind lots of data gaps for DES 13 14 properties as well as their individual components. To clarify the situation on their greenness status, a comprehensive assessment of commonly used hydrogen bond acceptors and donors 15 separately and as DES is performed. The application of multicriteria decision analysis 16 (TOPSIS ranking) with combination of biological effect modeling for DES to rank these 17 alternatives according to greenness criteria is proposed. Also traditional organic solvents and 18 19 ionic liquids as greenness reference points for better understanding are introduced. The ranking results show that many DES, which are synthetized by mixing sugars alcohols, 20 21 alcohols, sugars and amides are promising environmentally friendly solvents, more than some imidazolium-based ionic liquids. Mixtures including components with metal ions and organic 22 acids are less green. 23

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25 Keywords: green chemistry; deep eutectic solvents; MCDA; TOPSIS; green solvent

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# 27 **1. Introduction**

Green chemistry refers to "design of chemical products and processes to reduce or eliminate 28 the use and generation of hazardous substances" [1,2]. According to one of 12 principles of 29 green chemistry, the use of harmful solvents should be avoided, replaced by more 30 environmentally benign ones or their amount should be reduced [<sup>3</sup>]. The best replacement for 31 32 conventional organic solvents is simply water, however usually more nonpolar solvents are 33 required. Then, supercritical fluids, carbonates, bio-based solvents (from biomass or food waste), ionic liquids (ILs) or deep eutectic solvents (DES) are readily used. The last two 34 35 groups of compounds have fairly similar physicochemical properties but ILs are more expensive [<sup>4</sup>] and harder to be obtained. Therefore, there is a noticeable growth of interest in 36 DES, which are mixtures of two or more compounds with particular molar ratio - hydrogen 37 bond acceptor (HBA) and hydrogen bond donor (HBD). In contrary to traditional organic 38 solvents belonging to volatile organic compounds (VOCs), DES are rather nonvolatile, non-39 flammable due to the low vapour pressure [<sup>5</sup>]. Moreover, in comparison to ILs (as solvents of 40 similar characteristic), apart from their low cost, they possess other advantages such as 41 simpler synthesis and natural origin (mainly in case of natural deep eutectic solvent -42 NADES). 43

DES show excellent applicability in many areas, for instance separation processes, biodiesel production [6], electrochemistry [7], absorption and solubility of carbon dioxide [8], medical and pharmaceutics usage [9], chemical synthesis [10], activation of enzymes and biocatalysis [11]. However, despite the wide range of applications, the claims about their low harmfulness, non-toxicity or high biodegradability are not unequivocal. Several studies proved that not all
DES are highly biodegradable or nontoxic and lack of data may be serious problem while
environmental evaluations [12, 13, 14]. Estimation of DES greenness should be performed in
more comprehensive way.

The tools that are helpful in assessments according to many factors simultaneously are multicriteria decision analysis algorithms (MCDA). Among many The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) gained much interest due to its simplicity. MCDA methods have been already successfully applied in greenness assessments of solvents [15,16], derivatization agents [17], nanoparticles [18,19] and ionic liquids [20].

To authors best knowledge, it is the first study that considers variety of criteria (not only toxicity) to rank HBA and HBD as DES components and DES in respect to their environmental benigness. The results of this study may be useful for researchers and practitioners at the first stage of DES selection, especially for separation processes. The presented tools allow to assess how individual compounds, as well as their molar ratios can affect the greenness of DES.

## 2. Materials and Methods

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#### 2.1.Data collection

Our study includes binary and ternary DES, which have been found in numerous scientific papers. An extensive search has been conducted particularly targeted library databases: ACS, Elsevier, Springerlink, RSC and Wiley – till first 150 hits, when available by the keywords "DES", "Deep eutectic solvents", "Green deep eutectic solvents" or "Environmentally friendly deep eutectic solvents".

The dataset has been divided into HBAs and HBDs, as well as DES mixtures. In first case, for
each of HBA and HBD properties referring to environmental and safety issues as hazardous

and precautionary statements, signal wording, flash point, hazardous decomposition products, 72 73 vapor pressure, toxicity towards Daphnia magna, algae, fish and rodents, octanol-water partition coefficient, biodegradability and pH have been collected. Whereas, for each of 74 binary and ternary DES mixtures parameters such as melting point, density, viscosity, 75 conductivity, surface tension, pH, refractive index, Kamlet-Taft parameters, spectroscopic 76 polarity index as  $E_T^N$ , toxicity towards Vibrio fischeri, Escherichia coli, fish and cell line of 77 CCO fish and MCF-7 or HeLa human tumor, phytotoxicity towards wheat seeds - Triticum 78 aestivum, biodegradability and solubility of gases as carbon dioxide, sulphur dioxide, 79 ammonia has been gathered according to corresponding articles. All information are presented 80 81 in Supplementary Information 2. Due to many gaps in dataset some of initially collected data was not included in the assessments. The criteria that have been taken for TOPSIS rankings 82 are summarized in Table 1. 83

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**Table 1.** Criteria for HBDs and HBAs TOPSIS rankings.

Criterion	Remarks	Source
H-stat	Descriptions are transferred into numerical values	MSDS
P-stat	Descriptions are transferred into numerical values	MSDS
Signal wording	Descriptions are transferred into numerical values	MSDS
Flash point	The temperature in which compound flashes	MSDS, papers
Hazardous decomposition products	Descriptions are transferred into numerical values	MSDS
Vapour pressure	In 25 °C	MSDS, papers, databases
Toxicity Daphnia magna	48 h test data was preferable; if not available 24 h test data was taken	Papers
Toxicity algae	72 h test data was preferable; if not available 96 h test data was taken	Papers
Toxicity fish	96 h test data was preferable; if not available 48 h data was taken	Papers
Toxicity rodents via ingestion	Rat was the preferable organism, if data was not available data for mouse was taken	Papers
logKow	Logarithm of partitioning coefficient between octanol and water	Papers, MSDS, databases
Biodegradability	28 day test	Papers, MSDS,

		ualabases
pН	-	MSDS, papers
Solubility in water	In 25 °C	MSDS

databasas

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For the specific references to paper, please see descriptions in Supplementary Information 85 The majority of properties are taken from scientific papers, describing chemical 86 characteristics of DES. Then information are supported by the chemical on-line databases 87 such as ECHA, PubChem, Chemspider. Moreover, data for analysis in this work is provided 88 by the Material Safety Data Sheets (MSDS) supplied by different companies, mainly Sigma-89 Aldrich, Merck, Thermo Fisher Scientific, Santa Cruz Biotechnology Inc., Iolitec. Especially 90 91 information and parameters as: alternative names, CAS number, molecular formula, molecular weight, signal wording, special hazards arising from the substance or 92 mixture/hazardous decomposition products. 93

The properties of DES are not fully available, so in case of lack of data, parameters have been completed by predicted or estimated values (calculated in QSAR, EPISuite, etc.) or missing points are substituted with the values of the chemically similar compounds / group of compounds as proposed by Adler et al. [21] as summarized in **Tables S1, S5 and S7-S16**. Additionally, wherever several datapoints are available (for instance toxicity values for different fish / algae / rodent spices), always the most unbeneficial one is selected, according to precautionary principle.

101 Traditional organic solvents and ionic liquids are included in the dataset as reference points, 102 for better understanding of a green nature of HBAs and HBDs being the DES components 103 (the same properties as for the HBAs and HBDs are collected). Some of data require 104 transformations from descriptions to numerical values, what is presented in **Tables S2-S6**.

### 2.2.TOPSIS algorithm

106 TOPSIS is algorithm developed by Hwang and Yoon [22], it is based on finding an 107 alternative characterised by the shortest distance from the positive ideal solution and

simultaneously the furthest distance from the negative ideal solution. This mathematical 108 model allows for combination of different (often contradictory) criteria into a single score 109 leading to creation of ranking of available alternatives. The ranking is defined by the values of 110 similarity to ideal solution, for each alternative, ranged between 0 and 1. The value 0 is 111 112 assigned to completely non-ideal alternative (the worst values for all criteria), while the value 1 for an ideal solution (the best values for all criteria). Only basic information about TOPSIS 113 algorithm are described above. Its mathematical algorithm is presented in Section 2 of 114 Supplementary Information 1. More details may be found in the articles, including its 115 fundamentals [23, 24]. The calculations involving TOPSIS are performed in Excel program 116 117 (Microsoft 2016). TOPSIS was selected over other MCDA tools as it is fully applicable for 118 many alternatives assessment, its outcome is easily interpretable and its algorithm is relatively 119 simple.

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## 2.3.TOPSIS algorithm for DES components – HBA and HBD

121 Evaluation of HBAs and HBDs is carried out for each group separately. The number of alternatives is 95 for HBA, 181 for HBD, 16 and 14 for organic solvents and 7 for ILs. The 122 difference in the amount of commercially used organic solvents is due to fact that n-butanol 123 124 and phenol are also a DES component in case of HBDs assessment. The selection of ionic liquids is dictated by the data availability. Nevertheless, attempts are made to include salts 125 126 with different cations and anions. Moreover, substances like 1-butyl-3-methylimidazolium chloride ([C<sub>4</sub>C<sub>1</sub>im][Cl]) and tetrabutylphosphonium bromide ([P<sub>4444</sub>][Br]) may be classified as 127 a ILs as well as a HBD. 128

2.4.TOPSIS algorithm for DES

Environmental assessment of DES including binary and ternary mixtures are based on resultsobtained with TOPSIS analysis for HBAs and HBDs and calculations of common effects. Due

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to fact, that DES are composed of HBA and one (for binary mixtures) or two HBDs (for
ternary mixtures), the evaluation includes common responses, calculated with toxicological
model, according to the equation:

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$$E(C_{mix}) = 1 - \prod_{i=1}^{n} (1 - E(C_i))$$
 (1)

where E(Cmix) is combined effect at the mixture concentration (Cmix), and E(Ci) is the 136 similarity to ideal solution (calculated for HBA and HBD with TOPSIS) of individual mixture 137 138 component (i) applied at the concentration (Ci) [25]. Bearing in mind, fact that DES mixtures may have different ratios of HBA and HBD, this information is introduced by fractions, 139 e.g. for HBA:HBD mixtures with ratios of 1:1 and 1:3, the fractions are equal <sup>1</sup>/<sub>2</sub> and <sup>1</sup>/<sub>2</sub> as well 140 as 1/4 and 3/4, respectively. Selected 35 binary and 2 ternary mixtures, considered by the 141 authors of respective publications as green solvents are evaluated. All these DES are listed in 142 143 Table S18. together with an information about areas of application and justification why authors consider them green. Ionic liquids and traditional organic solvents are also included as 144 145 reference points. To obtain an adequate level of comparability with DES mixtures, combined 146 value of addition effect for each solvent is calculated by multiplication values of similarity to ideal solution of HBA and HBD for particular solvent according to equation 1 (solvent is 147 treated as mix of two individuals). 148

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# 2.5. Weights and confidence rankings

The advantage of MCDA tools is possibility of assigning weights to criteria to give them relative importance in accordance to the purpose of the analysis. To provide a comprehensive ranking thirteen criteria with different importance are simultaneously considered in the assessment. Toxicity towards *Daphnia magna*, fish, algae and rats via ingestion are assessed to have higher influence on the greenness character of DES components (0.14), while biodegradability has weight value of 0.1. Information about hazard and precautionary statements, vapor pressure are found to be less important with weight value equal 0.06. Then lower weights are considered for hazardous decomposition products (0.02), signal word (0.02), flash point (0.04), pH (0.04) and logKow (0.04). The toxicity criteria are assigned with the highest weights as they refer more to the greenness assessment than other criteria. Hazards and precautionary statements, signal wordings, decomposition products, flash point, pH and logKow are given low weights as they are characterized by lower variability and the criteria translated from descriptions can be treated as semi-quantitative information.

## 163 **2.6.** Sensitivity Analysis

The sensitivity analysis is performed to investigate how changes in input values and/or weights influence the final ranking results. It is also applied to consider measurement errors of input variables. The input values are changed randomly for +10% or -10% and next analysis is performed to see if differences in ranking are significant.

# 168 **3. Results and discussion**

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# 3.1.Results of TOPSIS ranking of HBA

The results of TOPSIS analysis for HBAs with proposed criteria and assigned weight values
are presented in **Table 2**. Traditional organic solvents and ionic liquids are highlighted light
blue and light green, respectively.

It is found that the best alternative is triethylene glycol (0.5883), which is nontoxic to all evaluated organisms. Moreover, it does not undergo bioaccumulation due to low value of log  $K_{OW}$  and it is easily biodegradable. This DES component is also described by small number of hazard and precautionary statements and in case of its decomposition there is no risk of arising hazardous products. Then for next 5 compounds the values of similarities to ideal solutions decrease from 0.18 to ~0.14. These compounds are mainly amino acids (betaine hydrochloride, betaine, histidine) and traditional organic solvents such as methanol and heptane. The high position of amino acids in the ranking is due to low toxicities towards at least two of organisms, high flash points, small values of log K<sub>OW</sub> and ease of biodegradation. These two organic solvents are highly ranked because of low toxicity towards rats via ingestion and good biodegradability. Moreover, methanol is characterized by low value of logK<sub>OW</sub> and is rather non-toxic towards other analyzed organisms.

The ranking scores for latter compounds are gradually decreasing from 0.0962 for serine to 185 186 0.0244 for glycerol. These compounds are monosaccharides, such as mannose, D-glucose and D-fructose, which are characterized by small number of hazardous statements and low value 187 of K<sub>OW</sub>, as well as by the high values of flash point and low toxicity towards majority of test 188 organisms. Moreover, mannose is favorable due to high biodegradability. Within this part of 189 ranking ethyl acetate is localized, because of low toxicities towards the most of evaluated 190 organisms and low risk of bioaccumulation. All ionic liquids included are located in the 191 192 second half of this ranking. For these salts the common features are low biodegradability and considerable toxicities towards all organisms, as well as high number of decomposition 193 194 products and. Also HBA that are organometallic compounds are located in the second part of 195 the ranking. For the last ranks the scores change to <0.007 for ammonium and phosphonium salts, dodecanoic acid and solvents, like chlorobenzene, tetrahydrofuran and diethyl ether. 196 197 They are ranked low because of high toxicity in all included tests, in case of organic solvents also high volatility. 198

**Table 2.** Results of TOPSIS analysis for HBA and comparison with traditional organic solvents and ionic liquids combined with sensitivity analysis for changes in range of  $\pm 10\%$ 

No.	Substance name (HBA/organic solvent/IL)	CAS number	Similarity to ideal solution	Ranking difference for ±10% changes
1	triethylene glycol	112-27-6	0.5880	0
2	betaine hydrochloride	590-46-5	0.1812	3
3	betaine	107-43-7	0.1734	1

4	heptane	142-82-5	0.1644	2
5	histidine	71-00-1	0.1485	-3
6	methanol	67-56-1	0.1459	-3
7	serine	56-45-1	0.0962	0
8	mannose	3458-28-4	0.0900	1
9	L-proline	147-85-3; 609-36-9	0.0597	-1
10	citric acid	77-92-9	0.0542	0
11	potassium carbonate	584-08-7	0.0532	0
12	D-glucose	50-99-7	0.0383	0
13	D-fructose	57-48-7	0.0381	0
14	acetamide	60-35-5	0.0317	3
15	ethylene glycol	107-21-1	0.0293	-1
16	ethyl acetate	141-78-6	0.0280	0
17	glycerol	56-81-5	0.0244	-2
18	hexane	110-54-3	0.0209	0
19	uea	57-13-6	0.0183	0
20	calcium chloride hexahydrate	7774-34-7	0.0129	3
21	alanine	302-72-7	0.0124	3
22	sodium glutamate	6106-04-3	0.0123	-2
23	cyclohexane	110-82-7	0.0117	-2
24	toluene	108-88-3	0.0115	1
25	L-carnitine	541-15-1	0.0115	-3
26	polyethylene glycol	25322-68-3	0.0111	1
27	monoethanolamine hydrochloride	2002-24-6	0.0109	23
28	acetic acid	64-19-7	0.0108	-2
29	ethylammonium chloride	557-66-4	0.0107	-1
30	glycine	56-40-6	0.0106	0
31	lithium perchlorate	7791-03-9	0.0104	1
32	β-alanine	107-95-9	0.0103	-1
33	triethanolamine hydrochloride	637-39-8	0.0103	4
34	malonic acid	141-82-2	0.0102	-1
35	ethylammonium bromide	593-55-5	0.0100	-1
36	magnesium chloride hexahydrate	7791-18-6	0.0100	2
37	dimethylurea	598-94-7	0.0100	4
38	chloroethyltrimethylammonium chloride	999-81-5	0.0100	1
39	1-ethyl-3-methylimidazolium	65039-03-4	0.0098	-3
40	L-menthol	2216-51-5	0.0097	0
41	anisole	100-66-3	0.0096	12
42	lithium nitrate	7790-69-4	0.0096	7
43	dimethylammonium chloride	506-59-2	0.0095	31
44	tetraethylammonium chloride	56-34-8	0.0094	73
45	tetramethylammonium chloride	75-57-0	0.0094	15
46	cyclohexanone	108-94-1	0.0094	16
47	DL-menthol	89-78-1; 1490-04-6	0.0093	-5
48	malic acid or DL-malic acid	617-48-1	0.0093	-5
49	1,2-decanediol	1119-86-4	0.0093	-3
50	tert-butanol	75-65-0	0.0092	-2
51	diethylamine hydrochloride	660-68-4	0.0092	-4

52	caprolactam	105-60-2	0.0092	4
53	n-butanol	71-36-3	0.0091	-9
54	lithium chloride	7447-41-8	0.0091	1
55	zinc nitrate hexahydrate	10196-18-6	0.0091	2
56	furoic acid	88-14-2	0.0091	3
57	lithium hexafluorophosphate	21324-40-3	0.0091	-12
58	1-butyl-3-methylimidazolium bromide	85100-77-2	0.0089	30
59	1-butyl-3-methylimidazolium nitrate	179075-88-8	0.0089	-5
60	choline iodide	2260-50-6	0.0089	-2
61	1-tetradecanol	112-72-1	0.0088	7
62	choline chloride	67-48-1	0.0088	1
63	1-ethyl-3-methylimidazolium chloride	65039-09-0	0.0088	-2
64	tetrapropylammonium bromide	1941-30-6	0.0088	2
65	methyltriphenylphosphonium bromide	1779-49-3	0.0088	-1
66	potassium thiocyanate	333-20-0	0.0088	1
67	1-butyl-3-methylimidazolium	174501-64-5	0.0088	-16
68	lactic acid	70 33 /	0.0087	2
60	quanidina	112 00 8	0.0087	2 14
09 70	juandine	113-00-0	0.0087	14
70	initiazoie	200-32-4	0.0086	1
/1	N benzyl 2 bydroxy N N	10023-77-1	0.0080	-19
72	dimethylethanaminium chloride	7221-40-1	0.0086	-7
73	1-butyl-3-methylimidazolium	174899-66-2	0.0085	-4
74	acetylcholine chloride	60-31-1	0.0085	5
74	guanidine bydrochloride	50 01 1	0.0085	12
76	tetraethylammonium bromide	71_91_0	0.0085	12 34
70	1 butyl 3 methylimidazolium chlorida	70017 00 1	0.0085	34
78	zirconyl chloride octabydrate	13520.02.8	0.0085	39 0
70	decanoic acid	334 48 5	0.0085	5
80	manganese(II) chloride tetrahydrate	13//6_3/_9	0.0083	_8
81	hutyltriphenylphosphonium bromide	1779_51_7	0.0084	-0
82	A-methyl-imidazole	872_36_6	0.0084	1
83	vulenes	1330-20-7	0.0084	-4
84	chromium(III) chloride hevahydrate	10060-12-5	0.0084	-10
85	1_ethyl_3_methylimidazolium acetate	1/331/-17-/	0.0084	-8
86	thymol	89-83-8	0.0083	-0
87	triethylmethylammonium chloride	56375_79_2	0.0083	-10
88	benzyltriethylammonium chloride	56-37-1	0.0083	-13
89	benzyltrimethylammonium chloride	56-93-9	0.0082	-13
90	lidocaine	137-58-6	0.0082	_1
91	atropine	51-55-8	0.0081	-1
92	tetrahentylammonium chloride	10247-90-2	0.0081	-0
92	nyrazole	288_13_1	0.0000	
93 Q/	tetraoctylammonium bromide	14866-33-7	0.0000	-2
94 05	tin(II) chloride	7772_00_8	0.0079	-2 _0
95 96	guanidine thiocyanate	503_8/ N	0.0079	-9 /
07	tetrabutylphosphonium bromida	3115 69 2	0.0079	4
21	icu aoury ipnospholinum bronnuc	5115-00-2	0.0078	-5

98	tetrabutylammonium bromide	1643-19-2	0.0078	-3
99	ethyltriphenylphosphonium iodide	4736-60-1	0.0078	-2
100	iron(III) chloride	7705-08-0	0.0078	3
101	1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide	174899-83-3	0.0077	12
102	zinc bromide	7699-45-8	0.0077	0
103	aluminum trichloride	7446-70-0	0.0077	-7
104	tetrabutylphosphonium chloride	2304-30-5	0.0076	3
105	1-butyl-3-methylimidazolium tetrafluoroborate	174501-65-6	0.0076	-7
106	phenol	108-95-2	0.0076	-7
107	1-napthol	90-15-3	0.0076	-6
108	tetrahexylammonium bromide	4328-13-6	0.0075	-3
109	lithium bis[(trifluoromethyl)sulfonyl]imide	90076-65-6	0.0074	-5
110	benzyltributylammonium chloride	23616-79-7	0.0074	-1
111	tetrabutylammonium chloride	1112-67-0	0.0073	-5
112	zinc chloride	7646-85-7	0.0073	-4
113	chlorobenzene	108-90-7	0.0072	-1
114	benzyltriphenylphosphonium chloride	1100-88-5	0.0068	1
115	methyltrioctylammonium chloride	5137-55-3	0.0068	-1
116	dodecanoic acid	143-07-7	0.0063	2
117	tetrahydrofuran	109-99-9	0.0038	-82
118	diethyl ether	60-29-7	0.0014	-89

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# 3.2. Results of TOPSIS ranking of HBD

The results of TOPSIS analysis for HBD including proposed criteria and assessed weight values are presented in **Table 3.** ILs and organic solvents, which are also highlighted with light green and light blue, respectively.

The first rank is mannitol (0.5743), which is characterized by very low toxicities towards all evaluated organisms. Moreover, this sugar is not bioaccumulative and does not decompose to form harmful products and is described only by very few hazard and precautionary statements and no signal wording. The second, the third and the fourth ranks are disaccharides: isomaltose (0.4024), maltose (0.4009), D-sucrose (0.3675) which are non-toxic to *Daphnia magna* and rodents via ingestion, highly biodegradable. Furthermore, they are characterized by high flash point, low value of logK<sub>OW</sub>. After few alternatives with clearly higher values of similarities to ideal solution, there are betaine, m-aminobenzoic acid, serine, L-proline, citric acid and stearic acid with score values 0.11-0.23. These amino acids and are favorable due to low toxicity towards at least two of tested organisms, higher flash point, small value of logKow and average to high percentage of biodegradation. Organic acids also appear in this range and the reason for their high positions is high biodegradability and each of compound has low and average toxicity towards tested organisms.

220 Then, straight-chain alcohols (1,2-propanediol, 1,4-butanediol), sugar alcohols (glycerol, sorbitol), sugars (D-fructose, D-glucose) and their derivatives (glucosamine) are placed in the 221 222 ranking. They are characterized by high to average toxicity endpoints at least for two organisms, low values of logKow and acceptable to high biodegradability level for almost all 223 sugar-like HBDs. Between these compounds there are also traditional organic solvents as 224 ethyl acetate, hexane or acetic acid, which are rather green solvents. Gradually, aminoacids 225 226 appear, which begin the dominance of compounds containing an amino group as amino acids (e.g. alanine), amines (e.g. triethanolamine) and amides (e.g. urea). The majority of these 227 228 chemicals have small values of logK<sub>ow</sub>, average level of toxicity, pH value close to neutral 229 and are biodegradable. In the next part of the ranking organic acids occur (nicotinic, myristic, L-tartaric, succinic, itaconic), which are characterized by certain greenness issues, related to 230 231 pH value, toxicity and hazards or precautionary statements.

In lower part ranking ionic liquids are located, indicating that they cause more problems than the most of HDB. Imidazolium salts owe their low position due to unfavourable toxicity endpoints, as well as great numbers of hazard and precautionary statements together with hazardous decomposition products. The ranking is closed with diethyl ether that is nonbiodegradable and toxic to algae, flammable and very volatile. The majority of inorganic salts with metal cations as magnesium chloride hexahydrate, chromium(III) chloride hexahydrate, 238 iron(III) chloride, zinc bromide, zinc chloride, zinc chloride hydrate, cobalt(II) chloride

239 hexahydrate are localized in latter parts of HBD ranking.

Table 3. Results of TOPSIS analysis for HBD and comparison with traditional organic solvents and ionic liquids combined with sensitivity analysis for changes in range of  $\pm 10\%$ . Comparison of different toxicity evaluation – marked by colors: green, yellow, red (more details in *Discussion – Comparison of obtained results* section)

No.	Substance name (HBD/organic solvent/IL)	CAS number	Similarity to ideal solution	Ranking difference for ±10% changes
1	mannitol	69-65-8	0.5743	0
2	isomaltose	499-40-1	0.4024	1
3	maltose	6363-53-7	0.4009	-1
4	D-sucrose	57-50-1	0.3675	0
5	betaine	107-43-7	0.2353	2
6	m-aminobenzoic acid	99-05-8	0.2208	-1
7	heptane	142-82-5	0.1979	-1
8	serine	56-45-1	0.1455	1
9	L-proline	147-85-3; 609-36-9	0.1293	-1
10	citric acid	77-92-9	0.1230	0
11	stearic acid	57-11-4	0.1120	0
12	methanol	67-56-1	0.0463	1
13	xylose	58-86-6	0.0447	1
14	methionine	63-68-3	0.0332	-2
15	tricarballylic acid	99-14-9	0.0297	0
16	ethyl acetate	141-78-6	0.0290	1
17	aconitic acid	499-12-7	0.0282	2
18	lanthanum(III) chloride hexahydrate	17272-45-6	0.0251	-2
19	D-glucose	50-99-7	0.0249	-1
20	D-fructose	57-48-7	0.0246	2
21	glucosamine	3416-24-8	0.0242	-1
22	meso-erythritol	149-32-6	0.0230	-1
23	1,2-propanediol	57-55-6	0.0221	0
24	D-sorbitol	50-70-4	0.0214	1
25	α-cyclodextrin	10016-20-3	0.0206	-1
26	cis-9-octadecenoic acid	112-80-1	0.0205	2
27	L-sorbose	87-79-6	0.0203	2
28	1,2-butanediol	26171-83-5	0.0196	-1
29	pentaerythritol	115-77-5	0.0195	-3
30	alanine	302-72-7	0.0189	0
31	hexane	110-54-3	0.0189	1
32	diethylene glycol	111-46-6	0.0182	3
33	raffinose	512-69-6	0.0179	0
34	phytic acid	83-86-3	0.0178	0
35	adonitol	488-81-3	0.0176	5
36	toluene	108-88-3	0.0174	1

37	mannose	3458-28-4	0.0173	1
38	calcium chloride hexahydrate	7774-34-7	0.0172	7
39	urea	57-13-6	0.0172	9
40	polyethylene glycol	25322-68-3	0.0170	1
41	D-trehalose	99-20-7	0.0168	2
42	cyclohexane	110-82-7	0.0167	-3
43	acetamide	60-35-5	0.0166	1
44	ethylene glycol	107-21-1	0.0165	-8
45	acetic acid	64-19-7	0.0163	-14
46	D-isosorbide	652-67-5	0.0162	0
47	triethanolamine	102-71-6	0.0161	6
48	DL-glutamic acid	617-65-2	0.0161	-1
49	glycerol	56-81-5	0.0159	0
50	β-alanine	107-95-9	0.0159	10
51	1,4-butanediol	110-63-4	0.0158	0
52	D-galactose	59-23-4	0.0157	0
53	nicotinic acid	59-67-6	0.0156	3
54	arginine	74-79-3	0.0155	-4
55	zinc nitrate hexahydrate	10196-18-6	0.0155	11
56	threonine	72-19-5	0.0155	2
57	1,3-propanediol	504-63-2	0.0155	-3
58	magnesium chloride hexahydrate	7791-18-6	0.0154	4
59	myristic acid	544-63-8	0.0154	2
60	1,6-hexanediol	629-11-8	0.0154	9
61	formamide	75-12-7	0.0154	14
62	DL-aspartic acid	617-45-8	0.0154	15
63	L-tartaric acid	87-69-4	0.0153	11
64	N-methylacetamide	79-16-3	0.0153	-7
65	succinic acid	110-15-6	0.0153	-23
66	malonic acid	141-82-2	0.0152	2
67	itaconic acid	97-65-4	0.0152	4
68	triethylene glycol	112-27-6	0.0152	8
69	L-diethyl tartrate	87-91-2	0.0152	17
70	1,3-dimethylurea	96-31-1	0.0152	10
71	p-hydroxybenzaldehyde	123-08-0	0.0151	-1
72	aluminum trichloride	7446-70-0	0.0151	-9
73	N-methyldiethanolamine	105-59-9	0.0151	0
74	A-L-rhamnose	3615-41-6; 116908-	0.0151	7
		82-8	0.0170	
75	vanillin	121-33-5	0.0150	-11
76	malic acid or DL-malic acid	617-48-1	0.0150	3-
77	suberic acid	505-48-6	0.0150	5
78	1,5-pentanediol	111-29-5	0.0150	-11
79	glutaric acid	110-94-1	0.0150	-1
80	gallic acid	149-91-7	0.0149	-25
81	p-ethylphenol	123-07-9	0.0149	-16
82	adipic acid	124-04-9	0.0149	-23
83	anisole	100-66-3	0.0148	-11

85         propionamide         79-05-0         0.0148         7           86         methylurea         598-50-5         0.0148         -3           87         1-butyl-3-methylimidazolium nitrate         179075-88-8         0.0147         16           88         o-chlorobenzoic acid         118-91-2         0.0147         6           90         3-amino-1-propanol         156-87-6         0.0147         15           91         caffici acid         331-39-5         0.0146         6           92         p-chlorobenzoic acid         74-11-3         0.0146         11           93         coumarin         91-64-6         0.0145         .7           94         pyrtvic acid         127-17-3         0.0146         11           95         ammonium thiocyanate         1762-95-4         0.0145         .7           96         tetramethylammonium chloride         75.57-0         0.0144         13           97         DL-lactic acid         90-64-2; 611-72-3         0.0144         13           98         1-butyl-3-methylimidazolium bromide         85100-77-2         0.0143         .2           910         hottylichesukydrate         10060-12-5         0.0143         .2	84	phenylacetic acid	103-82-2	0.0148	1
86         methylurea         598-50-5         0.0148         -3           87         1-bury1-3-methylimidazolium nitrate         179075-88-8         0.0147         15           88         o-chlorobenzoic acid         118-91-2         0.0147         15           90         3-amino-1-propanol         156-87-6         0.0147         15           91         caffeic acid         331-39-5         0.0146         61           92         p-chlorobenzoic acid         74-11-3         0.0146         61           93         coumarin         91-64-6         0.0145         71           94         pyruvic acid         127-17-3         0.0145         73           95         ammonium thiocyanate         1762-95-4         0.0145         71           96         tetramethylammonium chloride         75-57-0         0.0144         13           99         1-bury1-3-methylimidazolium bromide         85100-77-2         0.0144         15           100         chromium(III) chloride hexahydrate         100060-12-5         0.0143         -2           104         p-toleensulfonic acid         104-45-4         0.0143         3           104         guaiacol         90-05-1         0.0143	85	propionamide	79-05-0	0.0148	7
87       1-butyl-3-methylimidazolium nitrate       179075-88-8       0.0147       15         88       o-chlorobenzoic acid       118-91-2       0.0147       6         89       glycolic acid       79-14-1       0.0147       65         90       3-amino-1-propanol       156-87-6       0.0147       15         91       caffeic acid       331-39-5       0.0146       61         92       p-chlorobenzoic acid       74-11-3       0.0146       11         93       coumarin       91-64-6       0.0145       33         91       coumarin       191-64-6       0.0145       37         97       DL-lactic acid       50-21-5       0.0145       17         98       DL-mandelic acid       90-64-2; 611-72-3       0.0144       13         99       1-butyl-3-methylimidazolium bromide       85100-77-2       0.0143       -12         101       chromium(II) chloride hexahydrate       10060-12-5       0.0143       -22         101       p-toluenesulfonic acid       104-15-4       0.0143       -3         102       allylurea       557-11-9       0.0143       -12         102       allylurea       557-11-9       0.0143       -12 <td>86</td> <td>methylurea</td> <td>598-50-5</td> <td>0.0148</td> <td>-3</td>	86	methylurea	598-50-5	0.0148	-3
88         o-chlorobenzoic acid         118-91-2         0.0147         6           89         glycofic acid         79-14-1         0.0147         15           90         3-amino-1-propanol         156-87-6         0.0146         6           92         p-chlorobenzoic acid         74-11-3         0.0146         -1           93         coumarin         91-64-6         0.0146         11           94         prytvic acid         127-17-3         0.0146         11           95         ammonium thiocyanate         1762-95-4         0.0145         .7           96         DL-mardelic acid         90-64-2: 611-72-3         0.0144         13           99         1-butyl-3-methylimidazolium bromide         85100-77-2         0.0144         15           101         chromium(III) chloride hexahydrate         10060-12-5         0.0143         .4           101         chromium(III) chloride hexahydrate         10060-12-5         0.0143         .4           102         allylurea         557-11-9         0.0143         .4           104         guaiacol         90-05-1         0.0143         .4           105         succinonitrile         110-61-2         0.0143         .4	87	1-butyl-3-methylimidazolium nitrate	179075-88-8	0.0147	15
89glycolic acid $79-14-1$ $0.0147$ $-5$ 903-amino-1-propanol156-87-6 $0.0147$ 1591caffeic acid331-39-5 $0.0146$ $-1$ 92p-chlorobenzoic acid $74+11-3$ $0.0146$ $-1$ 93coumarin $91-64-6$ $0.0145$ $-7$ 94pyruvic acid $127-17-3$ $0.0145$ $-7$ 95armonium thiocyanate $1762-95-4$ $0.0145$ $-7$ 96tetramethylanmonium chloride $75-57-0$ $0.0145$ $-7$ 97DL-lactic acid $90-64-21-5$ $0.0144$ $13$ 99I-butyl-3-methylimidazolium $90-64-21-5$ $0.0144$ $91$ 91butyl-3-methylimidazolium $174501-64-5$ $0.0144$ $15$ 101chromium(III) chloride hexahydrate $10060-12-5$ $0.0143$ $-12$ 102allylurea $557-11-9$ $0.0143$ $-12$ 103guaiacol $90-05-1$ $0.0143$ $-14$ 104guaiacol $90-05-1$ $0.0143$ $-14$ 105succinonitrile $110-61-2$ $0.0143$ $-14$ 106p-coumaric acid $79-33-4$ $0.0143$ $-12$ 107lactic acid $79-33-4$ $0.0143$ $-6$ 108berxamide $55-21-0$ $0.0143$ $-6$ 109furcic acid $88-14-2$ $0.0143$ $-6$ 101oxalic acid $122-76-2$ $0.0142$ $-14$ 113pentaethylenchexamine $4067-16-7$	88	o-chlorobenzoic acid	118-91-2	0.0147	6
903-amino-1-propanol156-87-60.01471591caffeic acid331-39-50.0146692p-chlorobenzoic acid74-11-30.01461193coumarin91-64-60.01461194pyruvic acid127-17-30.01461195ammonium thiocyanate1762-95-40.01457396tetramethylammonium chloride75-57-00.01451397DL-lactic acid90-64-2; 611-72-30.014413991-butyl-3-methylimidazolium bromide85100-77-20.014491100hexafluorophosphate174501-64-50.0143-12101chromium(III) chloride hexahydrate10060-12-50.0143-2102allylurea557-11-90.0143-2103p-toluenesulfonic acid104-15-40.01433104guaiacol90-05-10.0143-14105succinonitrile110-61-20.0143-14106p-coumaric acid7440-08-00.0143-12107lactic acid79-33-40.0143-6108succinonitrile110-61-20.0143-6109counstric acid735-80-80.0143-18110furcic acid235-80-80.0143-18111m-chlorobenzoic acid535-80-80.0142-14115cinamic acid123-76-20.0142-18115cinamic acid101-21-13-	89	glycolic acid	79-14-1	0.0147	-5
91caffeic acid $331-39-5$ $0.0146$ 692p-chlorobenzoic acid $74+11-3$ $0.0146$ $-1$ 93coumarin $91-64-6$ $0.0146$ $11$ 94pryuvic acid $127-17-3$ $0.0146$ $11$ 95ammonium thiocyanate $1762-95-4$ $0.0145$ $3$ 97DL-lactic acid $90-64-2; 611-72-3$ $0.0144$ $13$ 991-butyl-3-methylimidazolium bromide $85100-77-2$ $0.0144$ $91$ 100hexafluorophosphate $174501-64-5$ $0.0143$ $-12$ 101chromium(III) chloride hexahydrate $10060-12-5$ $0.0143$ $-2$ 97p-toluenesulfonic acid $104+15-4$ $0.0143$ $-2$ 98p-toluenesulfonic acid $10060-12-5$ $0.0143$ $-2$ 991-butyl-3-methylimidazolium bexafluorophosphate $0006-12-5$ $0.0143$ $-12$ 101chromium(III) chloride hexahydrate $10060-12-5$ $0.0143$ $-2$ 90p-toluenesulfonic acid $104+15-4$ $0.0143$ $-3$ 104guaiacol $90-05-1$ $0.0143$ $-2$ 105succinonitrile $110-61-2$ $0.0143$ $-2$ 106p-coumaric acid $7400-08-0$ $0.0143$ $-6$ 107lactic acid $79-33-4$ $0.0143$ $-6$ 108benzamide $555-21-0$ $0.0143$ $-6$ 109furcic acid $88-14-2$ $0.0143$ $-18$ 111m-chlorobenzoic acid $99-96-7$	90	3-amino-1-propanol	156-87-6	0.0147	15
92p-chlorobenzoic acid74-11-30.0146-193coumarin91-64-60.01461194pyruvic acid127-17-30.0146195ammonium thiocyanate1762-95-40.0145397DL-lactic acid50-21-50.01451798DL-actic acid90-64-2; 611-72-30.014419911-buty1-3-methylimidazolium bromide85100-77-20.014419911-buty1-3-methylimidazolium174501-64-50.014312101chromium(III) chloride hexahydrate10060-12-50.0143-2102allylurea557-11-90.0143-2103p-toluenesulfonic acid104-15-40.01433104guaiacol90-05-10.0143-2105succionitrile110-61-20.0143-4106p-coumaric acid7400-08-00.0143-12107lactic acid79-33-40.0143-6108benzamide552-1-00.0143-14109furoic acid88-14-20.0143-18110n-chlorobenzoic acid535-80-80.0143-18112DL-menthol89-78-1; 1490-04-60.0142-14118trans-cinnamic acid10125-13-00.0141-11119decan-1-ol1123-0-10.0140-2108caj146-62-70.0142-5116copper(II) chloride dihydrate10125-13-0 </td <td>91</td> <td>caffeic acid</td> <td>331-39-5</td> <td>0.0146</td> <td>6</td>	91	caffeic acid	331-39-5	0.0146	6
93coumarin91-64-60.01461194pyruvic acid127-17-30.0146195ammonium thiocyanate1762-95-40.0145396tetramethylammonium chloride75-57-00.0145397DL-lactic acid90-64-2; 611-72-30.014413991-butyl-3-methylimidazolium bromide85100-77-20.0144131001-butyl-3-methylimidazolium174501-64-50.0143-12101chromium(III) chloride hexahydrate10060-12-50.0143-12102allylurea557-11-90.0143-12103uenesulfonic acid104-15-40.01433104guaiacol90-05-10.0143-14105succinonitrile110-61-20.01434106p-coumaric acid7400-08-00.0143-14107lactic acid7400-08-00.01434108benzamide55-21-00.0143-6109oxalic acid144-62-70.0143-6111m-chlorobenzoic acid89-78-1; 1490-04-60.0142-14113pentaethylenehexamine4067-16-70.0142-18111levulinic acid621-82-90.0141-13111bertaethylenehexamine4067-16-70.0141-11114cand dihydrate10125-13-00.0141-11115cinamic acid140-10-30.0141-11116couper(II	92	p-chlorobenzoic acid	74-11-3	0.0146	-1
94pyruvic acid $127-17-3$ $0.0146$ 195ammonium thiocyanate $1762-95-4$ $0.0145$ $-7$ 96tetramethylammonium chloride $75-57-0$ $0.0145$ $3$ 70DL-lactic acid $90-64-2; 611-72-3$ $0.0144$ $13$ 97DL-mandelic acid $90-64-2; 611-72-3$ $0.0144$ $91$ 1001-butyl-3-methylimidazolium bromide $85100-77-2$ $0.0144$ $91$ 101chromium(III) chloride hexahydrate $10060-12-5$ $0.0143$ $-12$ 102allylurca $557-11-9$ $0.0143$ $-2$ 104guaiacol $90-05-1$ $0.0143$ $-14$ 105succinonitrile $110-61-2$ $0.0143$ $41$ 106p-cournaric acid $7400-08-0$ $0.0143$ $12$ 107lactic acid $79-33-4$ $0.0143$ $46$ 108benzamide $55-21-0$ $0.0143$ $46$ 109furoic acid $88-14-2$ $0.0143$ $-66$ 110oxalic acid $123-76-2$ $0.0142$ $-14$ 12DL-methol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 13nentathylenehexamine $4067-16-7$ $0.0143$ $-14$ 14tocia acid $621-82-9$ $0.0142$ $-18$ 118trans-cinnamic acid $123-76-2$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120<	93	coumarin	91-64-6	0.0146	11
95ammonium thiocyanate $1762-95.4$ $0.0145$ $.7$ 96tetramethylammonium chloride $75-57.0$ $0.0145$ $3$ 97DL-lactic acid $50-21-5$ $0.0144$ $13$ 991-butyl-3-methylimidazolium bromide $85100-77.2$ $0.0144$ $9$ 100h-butyl-3-methylimidazolium $174501-64-5$ $0.0144$ $9$ 101chromium(III) chloride hexahydrate $10060-12-5$ $0.0143$ $-12$ 102allylurea $557-11-9$ $0.0143$ $-2$ 103p-tolucnesulfonic acid $104+15.4$ $0.0143$ $-3$ 104guaiacol $90-05-1$ $0.0143$ $-14$ 105succinonitrile $110-61-2$ $0.0143$ $-14$ 106p-coumaric acid $7400-08-0$ $0.0143$ $-6$ 107lactic acid $79-33-4$ $0.0143$ $-6$ 108benzamide $55-21-0$ $0.0143$ $-6$ 109coumaric acid $535-80-8$ $0.0143$ $-18$ 110chrobrobenzoic acid $535-80-8$ $0.0143$ $-18$ 111pentaethylenehexamine $4067-16-7$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0141$ $-13$ 114levulinic acid $123-76-2$ $0.0142$ $-18$ 115cinnamic acid $612-82-9$ $0.0142$ $-18$ 115cinnamic acid $99-96-7$ $0.0141$ $-13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$	94	pyruvic acid	127-17-3	0.0146	1
96tetramethylammonium chloride $75-57-0$ $0.0145$ $3$ 97DL-lactic acid $50-21-5$ $0.0145$ $17$ 98DL-madelic acid $90-64-2; 611-72-3$ $0.0144$ $13$ 991-butyl-3-methylimidazolium $85100-77-2$ $0.0144$ $9$ 1001-butyl-3-methylimidazolium $174501-64-5$ $0.0143$ $-12$ 101chromium(III) chloride hexahydrate $10060-12-5$ $0.0143$ $-12$ 102allylurea $557-11-9$ $0.0143$ $-3$ 104guaiacol $90-05-1$ $0.0143$ $-14$ 105succinonitrile $110-61-2$ $0.0143$ $4$ 106p-coumaric acid $7400-08-0$ $0.0143$ $12$ 107lactic acid $79-33-4$ $0.0143$ $-6$ 108benzamide $55-21-0$ $0.0143$ $-6$ 109guroic acid $88-14-2$ $0.0143$ $-6$ 101cacid $144-62-7$ $0.0143$ $-6$ 102oxalic acid $123-76-2$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0141$ $-18$ 114levulinic acid $621-82-9$ $0.0142$ $-18$ 115cinnamic acid $613-56-6$ $0.0140$ $-7$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $-7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $-2$ 124capro	95	ammonium thiocyanate	1762-95-4	0.0145	-7
97         DL-lactic acid         50-21-5         0.0145         17           98         DL-mandelic acid         90-64-2; 611-72-3         0.0144         13           99         1-butyl-3-methylimidazolium bromide hexafluorophosphate         85100-77-2         0.0144         9           100         hexafluorophosphate         174501-64-5         0.0143         -12           101         chromium(III) chloride hexahydrate         10060-12-5         0.0143         -2           014         guaiacol         90-05-1         0.0143         -2           014         guaiacol         90-05-1         0.0143         -14           105         succinonitrile         110-61-2         0.0143         -12           107         lactic acid         79-33-4         0.0143         -6           109         furoic acid         88-14-2         0.0143         -6           109         furoic acid         535-80-8         0.0143         -6           101         oxalic acid         123-76-2         0.0142         -14           113         pentaethylenehxamine         4067-16-7         0.0141         -13           114         levulnic acid         123-76-2         0.0142         -18	96	tetramethylammonium chloride	75-57-0	0.0145	3
98         DL-mandelic acid         90-64-2; 611-72-3         0.0144         13           99         1-butyl-3-methylimidazolium bromide hexafluorophosphate         85100-77-2         0.0144         9           100         heromium(III) chloride hexahydrate         10060-12-5         0.0143         -12           102         allylurea         557-11-9         0.0143         -2           103         p-toluenesulfonic acid         104-15-4         0.0143         3           104         guaiacol         90-05-1         0.0143         -14           105         succinonitrile         110-61-2         0.0143         12           106         p-coumaric acid         7400-08-0         0.0143         12           107         lactic acid         79-33-4         0.0143         12           108         benzamide         55-21-0         0.0143         -6           109         furoic acid         144-62-7         0.0143         -6           101         benzamide         535-80-8         0.0142         -14           110         pentachylenehexamine         4067-16-7         0.0142         -18           111         m-chlorobenzoic acid         621-82-9         0.0141         61 <td>97</td> <td>DL-lactic acid</td> <td>50-21-5</td> <td>0.0145</td> <td>17</td>	97	DL-lactic acid	50-21-5	0.0145	17
991-butyl-3-methylimidazolium bromide hexafluorophosphate85100-77-20.014491001-butyl-3-methylimidazolium hexafluorophosphate174501-64-50.014315101chromium(III) chloride hexahydrate10060-12-50.0143-203p-toluenesulfonic acid104-15-40.01433104guaiacol90-05-10.0143-14105succinonitrile110-61-20.0143-4106p-coumaric acid7400-08-00.0143-6107lactic acid79-33-40.0143-6108benzamide55-21-00.0143-6109furoic acid88-14-20.0143-6101oxalic acid144-62-70.0143-23111m-chlorobenzoic acid535-80-80.0143-18112DL-menthol89-78-1; 1490-04-60.0142-13113hevulinic acid123-76-20.0141-6114levulinic acid621-82-90.0141-6115cinnamic acid621-82-90.0141-6117p-hydroxybenzoic acid99-96-70.0141-11118trans-cinnamic acid140-10-30.0141-11119decan-1-ol112-30-10.0140-2120oxalic acid dihydrate6153-56-60.0139-21212,2,2-trifluoroacetamide354-38-10.0139-2122triazole288-88-00.013913<	98	DL-mandelic acid	90-64-2; 611-72-3	0.0144	13
1001-buryl-3-methylimidazolium hexafluorophosphate174501-64-5 $0.0144$ 15101chromium(III) chloride hexahydrate10060-12-5 $0.0143$ -12102allylurea557-11-9 $0.0143$ 3104guaiacol90-05-1 $0.0143$ -14105succinonitrile110-61-2 $0.0143$ 4106p-coumaric acid7400-08-0 $0.0143$ 12107lactic acid79-33-4 $0.0143$ -6108benzamide55-21-0 $0.0143$ -6109furoic acid88-14-2 $0.0143$ -6110oxalic acid144-62-7 $0.0143$ -23111m-chlorobenzoic acid535-80-8 $0.0143$ -18112DL-menthol89-78-1; 1490-04-6 $0.0142$ -14113pentaethylenehexamine4067-16-7 $0.0142$ -18114levulinic acid123-76-2 $0.0141$ -6115cinamic acid621-82-9 $0.0142$ -18116copper(II) chloride dihydrate10125-13-0 $0.0141$ -11119decan-1-ol112-30-1 $0.0140$ -2120oxalic acid dihydrate6153-56-6 $0.0140$ 71212,2,2-trifluoroacetamide354-38-1 $0.0139$ -2122triazole288-88-0 $0.0139$ 6131-bexadecanol36653-82-4 $0.0139$ 39124caprolactam105-60-2 $0.0138$ -11 <td>99</td> <td>1-butyl-3-methylimidazolium bromide</td> <td>85100-77-2</td> <td>0.0144</td> <td>9</td>	99	1-butyl-3-methylimidazolium bromide	85100-77-2	0.0144	9
101chromium(III) chloride hexahydrate10060-12-50.0143-12102allylurea $557-11-9$ 0.01433104guaiacol90-05-10.01433104guaiacol90-05-10.01434105succinonitrile110-61-20.01434106p-coumaric acid7400-08-00.014312107lactic acid79-33-40.0143-6108benzamide55-21-00.01434109furoic acid88-14-20.0143-6110oxalic acid144-62-70.0143-23111m-chlorobenzoic acid535-80-80.0143-18112DL-menthol89-78-1; 1490-04-60.0142-14113pentaethylenehexamine4067-16-70.0142-14118tevalinic acid621-82-90.0142-5116copper(II) chloride dihydrate10125-13-00.0141-6117p-hydroxybenzoic acid99-96-70.0141-13118trans-cinnamic acid140-10-30.0141-11119decan-1-ol112-30-10.0140-2120oxalic acid dihydrate6153-56-60.0139-61212,2,2-trifluoroacetamide35653-82-40.013961231-hexadecanol36653-82-40.0139-6124caprolactam105-60-20.013922125butanoic acid107-92-60.0139	100	1-butyl-3-methylimidazolium hexafluorophosphate	174501-64-5	0.0144	15
102allylurea $557-11-9$ $0.0143$ $-2$ 103p-toluenesulfonic acid $104-15-4$ $0.0143$ $3$ 104guaiacol $90-05-1$ $0.0143$ $-14$ 105succinonitrile $110-61-2$ $0.0143$ $4$ 106p-coumaric acid $7400-08-0$ $0.0143$ $12$ 107lactic acid $79-33-4$ $0.0143$ $-6$ 108benzamide $55-21-0$ $0.0143$ $4$ 109furoic acid $88-14-2$ $0.0143$ $-6$ 110oxalic acid $144-62-7$ $0.0143$ $-23$ 111m-chlorobenzoic acid $535-80-8$ $0.0143$ $-18$ 112DL-menthol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0142$ $-13$ 114levulinic acid $123-76-2$ $0.0142$ $-5$ 115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $7$ 121 $2,2,2-trifluoroacetamide$ $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $39$ 125butanoic acid $107-92-6$ $0.0139$ $32$ 125butanoic acid $107-92$	101	chromium(III) chloride hexahydrate	10060-12-5	0.0143	-12
103p-toluenesulfonic acid $104-15-4$ $0.0143$ $3$ 104guaiacol $90-05-1$ $0.0143$ $-14$ 105succinonitrile $110-61-2$ $0.0143$ $4$ 106 $p$ -coumaric acid $7400-08-0$ $0.0143$ $12$ 107lactic acid $79-33-4$ $0.0143$ $-6$ 108benzamide $55-21-0$ $0.0143$ $4$ 109furoic acid $88-14-2$ $0.0143$ $-6$ 110oxalic acid $144-62-7$ $0.0143$ $-23$ 111m-chlorobenzoic acid $535-80-8$ $0.0143$ $-18$ 112DL-menthol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0142$ $-13$ 114levulinic acid $123-76-2$ $0.0142$ $-18$ 115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $7$ 120oxalic acid dihydrate $653-56-6$ $0.0140$ $7$ 121 $2,2,2-trifluoroacetamide$ $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0139$ $39$ 126dodecyl alcohol $112-53-8$ $0.0139$ $-2$ 127aminomethylpropanol	102	allylurea	557-11-9	0.0143	-2
104guaiacol $90-05-1$ $0.0143$ $-14$ 105succinonitrile $110-61-2$ $0.0143$ $4$ 106p-coumaric acid $7400-08-0$ $0.0143$ $12$ 107lactic acid $79-33-4$ $0.0143$ $-6$ 108benzamide $55-21-0$ $0.0143$ $4$ 109furoic acid $88-14-2$ $0.0143$ $-6$ 110oxalic acid $144-62-7$ $0.0143$ $-23$ 111m-chlorobenzoic acid $535-80-8$ $0.0143$ $-18$ 112DL-menthol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0142$ $-13$ 114levulinic acid $123-76-2$ $0.0142$ $-58$ 115cinnamic acid $621-82-9$ $0.0141$ $-13$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-6$ 123 $1$ -hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0138$ $-11$ 128octanol $111-42-2$ $0.0138$ $-8$ 129diethylene triamine $111-40-0$	103	p-toluenesulfonic acid	104-15-4	0.0143	3
105succinonitrile $110-61-2$ $0.0143$ $4$ 106p-coumaric acid $7400-08-0$ $0.0143$ $12$ 107lactic acid $79-33-4$ $0.0143$ $-6$ 108benzamide $55-21-0$ $0.0143$ $4$ 109furoic acid $88-14-2$ $0.0143$ $-6$ 110oxalic acid $144-62-7$ $0.0143$ $-23$ 111m-chlorobenzoic acid $535-80-8$ $0.0143$ $-18$ 112DL-menthol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0142$ $-18$ 114levulinic acid $123-76-2$ $0.0142$ $-51$ 115cinnamic acid $621-82-9$ $0.0142$ $-51$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-6$ 123 $1$ -hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0139$ $22$ 126dodecyl alcohol $112-53-8$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-42-2$ $0.0138$ $-8$ 130diethylene triamine	104	guaiacol	90-05-1	0.0143	-14
106p-coumaric acid7400-08-0 $0.0143$ 12107lactic acid79-33-4 $0.0143$ -6108benzamide55-21-0 $0.0143$ 4109furoic acid88-14-2 $0.0143$ -6110oxalic acid144-62-7 $0.0143$ -23111m-chlorobenzoic acid535-80-8 $0.0143$ -18112DL-menthol89-78-1; 1490-04-6 $0.0142$ -14113pentaethylenehexamine4067-16-7 $0.0142$ -13114levulinic acid123-76-2 $0.0142$ -18115cinnamic acid621-82-9 $0.0142$ -5116copper(II) chloride dihydrate10125-13-0 $0.0141$ 6117p-hydroxybenzoic acid99-96-7 $0.0141$ 13118trans-cinnamic acid140-10-3 $0.0141$ -11119decan-1-ol112-30-1 $0.0140$ -2120oxalic acid dihydrate6153-56-6 $0.0140$ 71212,2,2-trifluoroacetamide354-38-1 $0.0139$ 61231-hexadecanol36653-82-4 $0.0139$ 13124caprolactam105-60-2 $0.0139$ 39125butanoic acid107-92-6 $0.0139$ 39126dodecyl alcohol112-53-8 $0.0139$ -2127aminomethylpropanol124-68-5 $0.0138$ -11128octanol111-87-5 $0.0138$ -15129diethylene tr	105	succinonitrile	110-61-2	0.0143	4
107lactic acid $79-33-4$ $0.0143$ $-6$ 108benzamide $55-21-0$ $0.0143$ $4$ 109furoic acid $88-14-2$ $0.0143$ $-6$ 110oxalic acid $144-62-7$ $0.0143$ $-23$ 111m-chlorobenzoic acid $535-80-8$ $0.0143$ $-18$ 112DL-menthol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0142$ $-13$ 114levulinic acid $123-76-2$ $0.0142$ $-18$ 115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $-3$ 124caprolactam $105-60-2$ $0.0139$ $39$ 125butanoic acid $107-92-6$ $0.0139$ $-2$ 125butanoic acid $112-53-8$ $0.0139$ $-2$ 126dodecyl alcohol $112-63-5$ $0.0138$ $-11$ 128octanol $111-42-2$ $0.0138$ $-15$ 129diethylene triamine $1$	106	p-coumaric acid	7400-08-0	0.0143	12
108benzamide $55-21-0$ $0.0143$ $4$ 109furoic acid $88-14-2$ $0.0143$ $-6$ 110oxalic acid $144-62-7$ $0.0143$ $-23$ 111m-chlorobenzoic acid $535-80-8$ $0.0143$ $-18$ 112DL-menthol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0142$ $-13$ 114levulinic acid $123-76-2$ $0.0142$ $-18$ 115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $-2$ 1231-hexadecanol $36653-82-4$ $0.0139$ $33$ 124caprolactam $105-60-2$ $0.0139$ $39$ 125butanoic acid $107-92-6$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-40-0$ $0.0138$ $12$	107	lactic acid	79-33-4	0.0143	-6
109furoic acid $88-14-2$ $0.0143$ $-6$ 100oxalic acid $144-62-7$ $0.0143$ $-23$ 111m-chlorobenzoic acid $535-80-8$ $0.0143$ $-18$ 112DL-menthol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0142$ $-13$ 114levulinic acid $123-76-2$ $0.0142$ $-18$ 115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $6$ 1231-hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-40-0$ $0.0138$ $12$	108	benzamide	55-21-0	0.0143	4
10oxalic acid $144-62-7$ $0.0143$ $-23$ 111m-chlorobenzoic acid $535-80-8$ $0.0143$ $-18$ 112DL-menthol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0142$ $-18$ 114levulinic acid $123-76-2$ $0.0142$ $-18$ 115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $39$ 125butanoic acid $107-92-6$ $0.0139$ $39$ 126dodecyl alcohol $112-53-8$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-40-0$ $0.0138$ $12$	109	furoic acid	88-14-2	0.0143	-6
111m-chlorobenzoic acid $535-80-8$ $0.0143$ $-18$ 112DL-menthol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0142$ $13$ 114levulinic acid $123-76-2$ $0.0142$ $-18$ 115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $6$ 1231-hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0139$ $39$ 126dodecyl alcohol $112-53-8$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-40-0$ $0.0138$ $12$	110	oxalic acid	144-62-7	0.0143	-23
112DL-menthol $89-78-1; 1490-04-6$ $0.0142$ $-14$ 113pentaethylenehexamine $4067-16-7$ $0.0142$ $13$ 114levulinic acid $123-76-2$ $0.0142$ $-18$ 115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $6$ 1231-hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0139$ $22$ 125butanoic acid $112-53-8$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-40-0$ $0.0138$ $12$	111	m-chlorobenzoic acid	535-80-8	0.0143	-18
113pentaethylenehexamine $4067-16-7$ $0.0142$ $13$ 114levulinic acid $123-76-2$ $0.0142$ $-18$ 115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $6$ 123 $1$ -hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $39$ 125butanoic acid $107-92-6$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-42-2$ $0.0138$ $-8$ 130diethylene triamine $111-40-0$ $0.0138$ $12$	112	DL-menthol	89-78-1; 1490-04-6	0.0142	-14
114levulinic acid $123-76-2$ $0.0142$ $-18$ 115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $6$ 1231-hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $39$ 125butanoic acid $107-92-6$ $0.0139$ $39$ 126dodecyl alcohol $112-53-8$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-40-0$ $0.0138$ $12$	113	pentaethylenehexamine	4067-16-7	0.0142	13
115cinnamic acid $621-82-9$ $0.0142$ $-5$ 116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $6$ 1231-hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0139$ $39$ 126dodecyl alcohol $112-53-8$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-42-2$ $0.0138$ $-8$ 130diethylene triamine $111-40-0$ $0.0138$ $12$	114	levulinic acid	123-76-2	0.0142	-18
116copper(II) chloride dihydrate $10125-13-0$ $0.0141$ $6$ 117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $6$ 1231-hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0139$ $39$ 126dodecyl alcohol $112-53-8$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-40-0$ $0.0138$ $12$	115	cinnamic acid	621-82-9	0.0142	-5
117p-hydroxybenzoic acid $99-96-7$ $0.0141$ $13$ 118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $6$ 1231-hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0139$ $39$ 126dodecyl alcohol $112-53-8$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-42-2$ $0.0138$ $-8$ 130diethylene triamine $111-40-0$ $0.0138$ $12$	116	copper(II) chloride dihydrate	10125-13-0	0.0141	6
118trans-cinnamic acid $140-10-3$ $0.0141$ $-11$ 119decan-1-ol $112-30-1$ $0.0140$ $-2$ 120oxalic acid dihydrate $6153-56-6$ $0.0140$ $7$ 121 $2,2,2$ -trifluoroacetamide $354-38-1$ $0.0139$ $-2$ 122triazole $288-88-0$ $0.0139$ $6$ 1231-hexadecanol $36653-82-4$ $0.0139$ $13$ 124caprolactam $105-60-2$ $0.0139$ $22$ 125butanoic acid $107-92-6$ $0.0139$ $39$ 126dodecyl alcohol $112-53-8$ $0.0139$ $-2$ 127aminomethylpropanol $124-68-5$ $0.0138$ $-11$ 128octanol $111-87-5$ $0.0138$ $-15$ 129diethanolamine $111-40-0$ $0.0138$ $12$	117	p-hydroxybenzoic acid	99-96-7	0.0141	13
119decan-1-ol112-30-10.0140-2120oxalic acid dihydrate6153-56-60.014071212,2,2-trifluoroacetamide354-38-10.0139-2122triazole288-88-00.013961231-hexadecanol36653-82-40.013913124caprolactam105-60-20.013922125butanoic acid107-92-60.013939126dodecyl alcohol112-53-80.0139-2127aminomethylpropanol124-68-50.0138-11128octanol111-87-50.0138-15129diethanolamine111-42-20.0138-8130diethylene triamine111-40-00.013812	118	trans-cinnamic acid	140-10-3	0.0141	-11
120oxalic acid dihydrate6153-56-60.014071212,2,2-trifluoroacetamide354-38-10.0139-2122triazole288-88-00.013961231-hexadecanol36653-82-40.013913124caprolactam105-60-20.013922125butanoic acid107-92-60.013939126dodecyl alcohol112-53-80.0139-2127aminomethylpropanol124-68-50.0138-11128octanol111-87-50.0138-15129diethanolamine111-42-20.0138-8130diethylene triamine111-40-00.013812	119	decan-1-ol	112-30-1	0.0140	-2
1212,2,2-trifluoroacetamide354-38-10.0139-2122triazole288-88-00.013961231-hexadecanol36653-82-40.013913124caprolactam105-60-20.013922125butanoic acid107-92-60.013939126dodecyl alcohol112-53-80.0139-2127aminomethylpropanol124-68-50.0138-11128octanol111-87-50.0138-15129diethanolamine111-42-20.0138-8130diethylene triamine111-40-00.013812	120	oxalic acid dihydrate	6153-56-6	0.0140	7
122triazole288-88-00.013961231-hexadecanol36653-82-40.013913124caprolactam105-60-20.013922125butanoic acid107-92-60.013939126dodecyl alcohol112-53-80.0139-2127aminomethylpropanol124-68-50.0138-11128octanol111-87-50.0138-15129diethanolamine111-42-20.0138-8130diethylene triamine111-40-00.013812	121	2,2,2-trifluoroacetamide	354-38-1	0.0139	-2
1231-hexadecanol36653-82-40.013913124caprolactam105-60-20.013922125butanoic acid107-92-60.013939126dodecyl alcohol112-53-80.0139-2127aminomethylpropanol124-68-50.0138-11128octanol111-87-50.0138-15129diethanolamine111-42-20.0138-8130diethylene triamine111-40-00.013812	122	triazole	288-88-0	0.0139	6
124caprolactam105-60-20.013922125butanoic acid107-92-60.013939126dodecyl alcohol112-53-80.0139-2127aminomethylpropanol124-68-50.0138-11128octanol111-87-50.0138-15129diethanolamine111-42-20.0138-8130diethylene triamine111-40-00.013812	123	1-hexadecanol	36653-82-4	0.0139	13
125butanoic acid107-92-60.013939126dodecyl alcohol112-53-80.0139-2127aminomethylpropanol124-68-50.0138-11128octanol111-87-50.0138-15129diethanolamine111-42-20.0138-8130diethylene triamine111-40-00.013812	124	caprolactam	105-60-2	0.0139	22
126dodecyl alcohol112-53-80.0139-2127aminomethylpropanol124-68-50.0138-11128octanol111-87-50.0138-15129diethanolamine111-42-20.0138-8130diethylene triamine111-40-00.013812	125	butanoic acid	107-92-6	0.0139	39
127aminomethylpropanol124-68-50.0138-11128octanol111-87-50.0138-15129diethanolamine111-42-20.0138-8130diethylene triamine111-40-00.013812	126	dodecyl alcohol	112-53-8	0.0139	-2
128 octanol111-87-50.0138-15129 diethanolamine111-42-20.0138-8130 diethylene triamine111-40-00.013812	127	aminomethylpropanol	124-68-5	0.0138	-11
129diethanolamine111-42-20.0138-8130diethylene triamine111-40-00.013812	128	octanol	111-87-5	0.0138	-15
130 diethylene triamine 111-40-0 0.0138 12	129	diethanolamine	111-42-2	0.0138	-8
, ····································	130	diethylene triamine	111-40-0	0.0138	12

131	cyclohexanone	108-94-1	0.0138	1
132	1-tetradecanol	112-72-1	0.0138	1
133	sulfolane	126-33-0	0.0137	2
134	1-butyl-3-methylimidazolium chloride	79917-90-1	0.0137	5
135	chloroethyltrimethylammonium chloride	999-81-5	0.0137	-15
136	potassium thiocyanate	333-20-0	0.0137	-2
137	1-butyl-3-methylimidazolium trifluoromethanesulfonate	174899-66-2	0.0137	-12
138	α-tocopherol	59-02-9	0.0136	3
139	butyltriphenylphosphonium bromide	1779-51-7	0.0136	9
140	phenylpropanoic acid	501-52-0	0.0136	0
141	ethanolamine	141-43-5	0.0135	-18
142	decanoic acid	334-48-5	0.0135	-11
143	propionic acid	79-09-4	0.0135	1
144	ibuprofen	15687-27-1	0.0135	-7
145	hexanoic acid	142-62-1	0.0134	-2
146	1-ethyl-3-methylimidazolium acetate	143314-17-4	0.0134	17
147	imidazole	288-32-4	0.0134	2
148	m-cresol	108-39-4	0.0133	2
149	hexan-1-ol	111-27-3	0.0133	5
150	lidocaine	137-58-6	0.0133	-21
151	cyclohexanol	108-93-0	0.0133	0
152	p-cresol	106-44-5	0.0133	7
153	tin(II) chloride	7772-99-8	0.0132	-6
154	resorcinol	108-46-3	0.0132	-2
155	10-undecanoic acid	112-38-9	0.0132	0
156	bis(trifluoromethylsulfonyl)imide	82113-65-3	0.0132	-11
157	acetic acid	64-19-7	0.0132	-4
158	iron(III) chloride	7705-08-0	0.0132	-1
159	xylenes	1330-20-7	0.0131	-21
160	octanoic acid	124-07-2	0.0131	-4
161	ethambutol	74-55-5	0.0131	0
162	atropine	51-55-8	0.0130	12
163	benzyltriethylammonium chloride	56-37-1	0.0130	-3
164	tert-butanol	75-65-0	0.0130	-2
165	1-butanol	71-36-3	0.0130	-7
166	furfuryl alcohol	98-00-0	0.0129	3
167	zinc bromide	7699-45-8	0.0129	0
168	valeric acid	109-52-4	0.0129	12
169	salicylic acid	69-72-7	0.0129	4
170	chloroacetic acid	79-11-8	0.0129	-4
171	tetrabutylphosphonium bromide	3115-68-2	0.0129	6
170	1-butyl-3-methylimidazolium	174900 92 2	0.0129	7
172	bis(trifluoromethylsulfonyl)imide	1/4899-83-3	0.0128	- /
173	1-butyl-3-methylimidazolium	174501-65-6	0.0128	8
151	tetrafluoroborate		0.0120	0
174	thiourea	62-56-6	0.0128	-3
175	benzoic acid	65-85-0	0.0127	0
176	thymol	89-83-8	0.0127	0

177	DL-camphor	21368-68-3	0.0127	-5
178	o-cresol	95-48-7	0.0126	-8
179	trifluoromethanesulfonic acid	1493-13-6	0.0125	3
180	p-chlorophenol	106-48-9	0.0125	-1
181	trichloroacetic acid	76-03-9	0.0125	-3
182	zinc chloride	7646-85-7	0.0124	7
183	phenol	108-95-2	0.0123	3
184	acrylic acid	79-10-7	0.0123	7
185	2,3-xylenol	526-75-0	0.0122	-1
186	tetramethyl urea	632-22-4	0.0121	-3
187	2,6-dimethylphenol	576-26-1	0.0120	-2
188	cobalt(II) chloride hexahydrate	7791-13-1	0.0120	5
189	diazabicyclo[5.4.0]undec-7-ene	6674-22-2	0.0120	3
190	zinc chloride hydrate	29604-34-0	0.0120	-3
191	1-propanol	71-23-8	0.0119	3
192	tetraethylenepentamine	112-57-2	0.0118	-2
193	chlorobenzene	108-90-7	0.0116	-5
194	ethylenediamine	100-36-7	0.0115	-26
195	DL-borneol	507-70-0	0.0111	0
196	perfluorodecanoic acid	335-76-2	0.0102	0
197	dodecanoic acid	143-07-7	0.0096	1
198	formic acid	64-18-6	0.0085	-1
199	2,2,2-trifluoroethanol	75-89-8	0.0065	0
200	tetrahydrofuran	109-99-9	0.0046	0
201	hexafluoroisopropanol	920-66-1	0.0026	0
202	diethyl ether	60-29-7	0.0018	0

# **3.3.Results of TOPSIS ranking of DES**

The results of DES mixtures evaluation including proposed criteria and modeling of their combined greenness, calculated with equation 1, are presented in **Table 4**. ILs and organic solvents are included in the analysis and they are marked light green and light blue, respectively.

The best alternative among selected set is citric acid:D-sucrose (1:3), followed by the citric acid:D-maltose (4:1) and glycerol:L-proline:D-sucrose (9:4:1). On the other hand, last three DES are represented by the iron(III) chloride hexahydrate:ethylene glycol (2:1), choline chloride:zinc chloride (1:1.2) and tetrabutylammonium bromide:formic acid (1:1). In general, places in the ranking for DES mixtures are similar to those obtained for separate analyses of HBA and HBD. For instance, citric acid as HBA and D-maltose as HBD have high positions,

256	their mixture is also in the top. Tetrabutylammonium bromide and formic acid take lower
257	positions in the rankings of HBA and HBD, then their mixture is also unsatisfactorily ranked.
258	In case of DES with choline chloride as a HBA (choline chloride:1,2-propanediol, choline
259	chloride:ethylene glycol, choline chloride:1,4-butanediol), the ranking positions decrease with
260	changing ratios towards the growing presence of hydrogen bond donors in the compounds.
261	Based on values of similarities to ideal solution of HBA and HBD, DES consisting of any
262	combination of constituents, can be assessed in this way. Traditional organic solvents are
263	found along the entire list of compounds with similar order as in case of individual assessment
264	of HBA and HBD. Location of DES next to solvents of rather green character (alcohols, esters
265	or aliphatic hydrocarbons) indicates that DES are also not so problematic. On the other hand,
266	ILs are in the second half of the list.

267	Table 3. Results of environmental assessment for DES mixtures using toxicological model
268	and TOPSIS analysis and comparison with traditional organic solvents and ionic liquids

	DES/IL/traditional organic solvents name	Combined greenness effect
1	citric acid:D-sucrose (1:3)	0.2855
2	heptane	0.1730
3	citric acid:D-maltose (4:1)	0.1201
4	methanol	0.0944
5	glycerol:L-proline:D-sucrose (9:4:1)	0.0766
6	betaine:1,2-butanediol (1:3)	0.0574
7	betaine:ethylene glycol (1:4)	0.0474
8	ethyl acetate	0.0283
9	glycerol:xylitol:D-fructose (3:3:3)	0.0218
10	potassium carbonate:glycerol (1:7)	0.0205
11	hexane	0.0198
12	choline chloride:1,2-propanediol (1:4)	0.0194
13	choline chloride:1,2-butanediol (1:5)	0.0178
14	choline chloride:1,2-propanediol (1:2)	0.0175
15	choline chloride:polyethylene glycol (1:20)	0.0166
16	zirconyl chloride octahydrate:urea (1:5)	0.0157
17	choline chloride:1,2-propanediol (1:1)	0.0154
18	lactic acid:1,2-propanediol (1:1)	0.0154
19	choline chloride:1,4-butanediol (1:5)	0.0146
20	choline chloride:ethylene glycol (1:3)	0.0146
21	toluene	0.0144

22	choline chloride:urea (1:2)	0.0142
23	cyclohexane	0.0141
24	choline chloride:ethylene glycol (1:2)	0.0138
25	glycine:lactic acid (1:5)	0.0136
26	acetic acid	0.0135
27	choline chloride:glycerol (1:2)	0.0134
28	choline chloride:1,4-butanediol (1:2)	0.0133
29	choline chloride:p-toluenesulfonic acid (1:4)	0.0132
30	L-menthol:acetic acid (1:1)	0.0130
31	choline chloride:glycerol (1:1)	0.0123
32	choline chloride:lactic acid (1:2)	0.0123
33	choline chloride:levulinic acid (1:2)	0.0122
34	anisole	0.0122
35	choline chloride:malic acid (1:1)	0.0119
36	1-butyl-3-methylimidazolium nitrate	0.0118
37	1-butyl-3-methylimidazolium bromide	0.0116
38	choline chloride:phenol (1:4)	0.0116
39	choline chloride:tin(II) chloride (1:2)	0.0116
40	cyclohexanone	0.0115
41	1-butyl-3-methylimidazolium hexafluorophosphate	0.0115
42	choline chloride:oxalic acid (1:1)	0.0115
43	lactic acid:D-glucose (5:1)	0.0114
44	tetrabutylammonium chloride:decanoic acid (1:2)	0.0113
45	lactic acid:D-fructose (5:1)	0.0113
46	methyltrioctylammonium chloride:decanoic acid (1:2)	0.0112
47	tert-butanol	0.0111
48	1-butyl-3-methylimidazolium chloride	0.0111
49	iron(III) chloride hexahydrate:ethylene glycol (2:1)	0.0111
50	1-butyl-3-methylimidazolium trifluoromethanesulfonate	0.0111
51	n-butanol	0.0110
52	1-ethyl-3-methylimidazolium acetate	0.0108
53	choline chloride:zinc chloride (1:1.2)	0.0107
54	xylenes	0.0107
55	tetrabutylphosphonium bromide	0.0103
56	1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide	0.0103
57	1-butyl-3-methylimidazolium tetrafluoroborate	0.0102
58	phenol	0.0099
59	chlorobenzene	0.0094
60	tetrabutylammonium bromide:formic acid (1:1)	0.0081
61	tetrahydrofuran	0.0042
62	diethyl ether	0.0016

# 3.4. Results of sensitivity analysis and comprehensive ranking

Sensitivity analysis allows to assess the reliability of conducted analysis based on reliability of input data. Results of sensitivity analysis rankings are presented in **Tables 2** and **3**. In both cases, the changes of input data within  $\pm 10\%$  of original values are insignificant, as they do not affect the ranking. Therefore, the ranking results can be considered as reliable. There are some shifts in HDB positions in the middle of ranking results, where the differences in values of similarities to ideal solution are very low.

#### 277

## **3.5.Discussion - Comparison of obtained results**

HBD taken into evaluation are chemicals of a variety of characteristics, because they belong
to different groups of compounds. However, it can be seen that in the first part sugars alcohols
and straight-chain alcohols appear, they gradually pass through sugars and amides to organic
acids. These groups do not create a clear boundaries but interpenetrate gradually increasing
the predominance. Poor ecotoxicological profile of organic acids as a HBD is also reported by
Radošević et al. in *in vitro* study of cholinium-based IL and DES towards fish cell line [26].

Similar results are presented by Halder et al. [27] in in silico modeling study of HDB 284 toxicity. They divide evaluated chemicals into three groups, based on their toxicity level -285 low, intermediate and high. Their findings are marked in **Table 3** with green (low toxicity), 286 yellow (moderate toxicity) and red (high toxicity) colours, respectively. The reason for some 287 differences in comparison to this study may be fact, that Hadler's et al. assessment involves 288 only toxicity criteria measured for different organisms (11 different mammalian cell lines -289 and 12 different microbial organisms) what results in poor coverage of this study assessment 290 291 criteria. Hadler et al. also evaluate some HBA as preliminary studies, as they claim more experimental data is needed: choline chloride, menthol, N,N-diethylethanol ammonium 292 293 chloride (DEAC), and methyltriphenyl phosphonium bromide (MTPB). MTPB and DEAC, 294 are found to impart toxicity towards the most of the organisms, while N,N-diethylethanol ammonium chloride followed by choline chloride were found to be less toxic DES components. However, it is difficult to compare both results due to fact that our evaluation includes only choline chloride and MTPB. Nevertheless, ChCl and MTPB are ranked on 45<sup>th</sup> and 63<sup>rd</sup> place in the HBA list (out of 125 positions). The majority of evaluated HBA and HBD that are metalorganic compounds are ranked lower. The reason is that in our assessment toxicities are the most significant criteria and metal-containing DES are generally toxic to different organisms [28].

302 Perales et al. (2017) evaluated toxicity endpoints in combination with some physicochemical data (volatility and boiling point, flashpoint, biodegradability, bioconcentration factor, etc.) 303 using the Environmental Health and Safety Approach (EHSA) used for identification of risks 304 related to the environment and the human health) [29]. Using both types of information, each 305 chemical compound receives a score for the categories health, safety and environment, then 306 the best candidates considered as least dangerous for a short exposure time may be found. 307 308 Herein, glycerol (rank 17 in HBA ranking) - derived solvents as 3-ethoxy-1,2-propanediol, 3-butoxy-1,2-propanediol and 1,3-diethoxy-2-propanol 309 are the most favourable (1,2-propanediol ranked 23 and 1,3-propanediol ranked 57 but ethoxy derivatives are not 310 311 included in ranking).

DES mixtures may show some effects between the DES constituents (HBA and HBD) – the interactions, such as synergism and antagonism. More often synergistic effects are described due greater toxicity level of a mixture than toxicity level of its constituents. However, these two effects occur, which has also been discussed in the literature [30, 31]. In our study the synergistic or antagonistic effects are neglected, because still little is known on these types of interactions. In other words, only independent actions of the HBA and HBD are considered.

318 We also conduct evaluation of DES applications where authors claim their solvent is green 319 and these results are summarized in **Table S17**. The number of publications that describe

choline chloride-based DES application is significantly higher than the others (30 out of 46 320 321 examples). Then, betaine, citric acid, glycerol and lactic acid as HBA are of great interest, probably due to the natural origin. NADES generally belong to plant-based primary 322 metabolites, i.e. organic acids, sugars, alcohols, amines and amino acids. Often they are 323 324 considered as those with lower environmental impact and low toxicity than other DES. It has been reported in many papers, for instance in comparison of cytotoxicity profile of choline 325 326 chloride:fructose and choline chloride:glucose as NADES and N,N-diethyl ethanolammonium chloride:triethylene glycol as DES towards different hepatic cell lines [32]. 327

328 The problem with DES greenness assessment is that reports usually refer to physicochemical properties, such as density, viscosity, electrical conductivity, surface tension, solvatochromic 329 parameters or refractive index [33]. Unfortunately, there is still lack of data on toxicological 330 and environmental fate parameters (biodegradability, octanol-water partition coefficients, 331 etc.). In this area DES as poorly characterized as ILs. The comparison of results on the 332 333 cytotoxic effects on Channel Catfish Ovary cell line indicate that the cytotoxicity of cholinium-based IL and DES is generally lower than that of imidazolium- and pyridinium-334 335 based IL [26]. It is an implication that cholinium-based DES are promising and beneficial 336 class of solvents in terms of ecotoxicological impact. However, it only refers to this specific type of DES and single of species of tested organism. Our results show that selected ionic 337 338 liquids, mainly imidazolium salts, are placed in second part of list. Moreover, some cholinebased DES as choline chloride with oxalic acid (1:1) or zinc chloride (1:1.2) are ranked 339 between ILs. 340

All of the above-mentioned issues explain that it is not possible to unambiguously resolve the dispute, which of the solvents are more green - ILs or DES. DES properties depend on the specific case, criteria taken into evaluation, including tested organisms, etc. Therefore, the terms as non-toxic, biodegradable, environmentally friendly must be carefully used. Each of the mixtures should be tested and evaluated individually. Naming the solvent green because it belongs to DES group is an abuse. The interpretation of data gathered in Table S18 shows that only very few of authors claims about the greenness of the used DES mixture is presented without justification. This is a significant improvement in a reference to greenness evaluation of ionic liquids [20]. In case of DES solvents, more authors explain the use of the term "green" extensively, giving solid justifications.

### **4. Conclusions**

In this study, the TOPSIS algorithm combined with calculation of additive effects is applied 352 for DES components and DES ranking by their greenness. The comprehensive assessments 353 354 that includes simultaneously safety, biodegradability and toxicological criteria indicate that 355 DES formed by mixing sugars alcohols, straight-chain alcohol, sugars and amides may be promising green solvents, in contrary to those that include metal ions and organic acids. 356 357 Those ranked first are more environmentally advantageous than some of the selected imidazolium ionic liquids, which makes them a potential alternative solvents for many 358 applications. However, according to our results, due insufficient characteristics, especially 359 concerning toxicity level, a general flat assertion of DES mixtures as a green solvent is 360 inappropriate. Moreover, lack of data of some physiochemical properties may limit the 361 number of fields for they usage in chemical practice or industry. Therefore, additional studies 362 measuring environmental impact are required to understand the nature of DES mixtures 363 including properties and biological effects between their components. 364

Although the described approach provides general information about solvent greenness and allows for ease comparison of variety of solvents in terms of greenness performance, the proposed assessment procedure may be only treated as a screening tool for preliminary selection of a green alternative, due to simplified model of additivity that is used for DES

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369 mixtures calculations. More targeted evaluation for specific purpose is also possible, but need 370 providing more newly obtained data (variety of properties and environmental fate of 371 particular chemical) that may be easily incorporated into the performed algorithm.

## **372 Conflict of interests**

373 There are no conflicts of interests to declare.

# 374 Supplementary Information

- 375 Supplementary Information 1 Summary of different authors claims on DES being green,
- 376 numerical transformation involved criteria and alternative substances (objects) taken into
- 377 consideration in case of lack of data.
- 378 Supplementary Information 2 Gathered data concerning physiochemical and environmental
- 379 properties as a evaluated criteria of DES components and their mixtures.

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