Postprint of: Makoś-Chełstowska P., VOCs absorption from gas streams using deep eutectic solvents – A review, JOURNAL OF HAZARDOUS MATERIALS, Vol. 448 (2023), 130957, DOI: 10.1016/j.jhazmat.2023.130957

© 2023. This manuscript version is made available under the CC-BY-NC-ND 4.0 license https://creativecommons.org/licenses/by-nc-nd/4.0/

1	
2	
3	VOCs absorption from gas streams using deep eutectic solvents – a
4	review
5	Patrycja Makoś-Chełstowska ^{1,2,*}
6	
7	
8 9	¹ Department of Process Engineering and Chemical Technology, Faculty of Chemistry, Gdansk University of Technology, 80-233 Gdansk, Poland
10	² EcoTech Center, Gdańsk University of Technology, 80-233 Gdańsk, Poland
11	
12	
13	*corresponding author: patrycja.makos@pg.edu.pl
14	
15	
16 17 18 19 20 21 22 23 24 25 26 27 28 29	Abstract: Volatile organic compounds (VOCs) are one of the most severe atmospheric pollutants. They are mainly emitted into the atmosphere from anthropogenic sources such as automobile exhaust, incomplete fuel combustion, and various industrial processes. VOCs not only cause hazards to human health or the environment but also adversely affect industrial installation components due to their specific properties, i.e., corrosive and reactivity. Therefore, much attention is being paid to developing new methods for capturing VOCs from gaseous streams, i.e., air, process streams, waste streams, or gaseous fuels. Among the available technologies, absorption based on deep eutectic solvents (DES) is widely studied as a green alternative to other commercial processes. This literature review presents a critical summary of the achievements in capturing individual VOCs using DES. The types of used DES and their physicochemical properties affecting absorption efficiency, available methods for evaluating the effectiveness of new technologies, and the possibility of regeneration of DES are described. In addition, critical comments on the new gas purification methods and future perspectives are included.
30	Keywords: deep eutectic solvents, volatile organic compounds, absorption, gas purification, air
31	
32	



34

35 **1. Introduction**

36 Volatile organic compounds (VOCs) are considered one of the most important chemical 37 compounds that cause severe air pollution. According to the definition introduced by the World 38 Health Organization (WHO), VOCs are organic compounds whose boiling points (BP) range from 50 to 39 260 °C. In addition, they are characterized by high vapor pressure at room temperature. VOCs can 40 react with other substances in the atmosphere and affect the formation of photochemical fog, acid 41 rain, ozone depletion, etc. In addition, some VOCs are harmful to the environment, human health, 42 animals, and industrial installations. Particularly unfavorable VOCs include compounds from the groups of volatile oxygen-, sulfur-, halogen-, and silicon-organic compounds, as well as 43 44 monoaromatic and aliphatic hydrocarbons. They can be emitted into the atmosphere from both 45 natural and anthropogenic sources. However, the most severe risk is caused by VOCs that are 46 released from automobile exhaust, incomplete combustion of domestic fuel, and industrial sources 47 such as process vessels, venting, leaks from piping and other process equipment, wastewater 48 streams, heat exchange systems, breathing and loading losses from storage tanks, and transport of 49 raw materials and final products [1–7]. Therefore, it is essential to effectively capture VOCs from the 50 air, fuels, and industrial gas streams.

There are various methods to treat gaseous streams, e.g., catalytic and thermal oxidation, adsorption, physical and chemical absorption, adsorption, pressure swing adsorption, membrane separation, and cryogenic and biological separation [8–15]. Among available methods, absorption is widely used due to its simplicity, high efficiency, low operation, investment cost, and ability to regenerate the absorbent. However, to achieve high absorption efficiency while meeting the principles of green chemistry and green engineering, it is essential to select the appropriate absorbent [16–20]. Commercially available and widely used absorbents include water, silicon, minerals, vegetable and petroleum oils, polyethylene glycols, amines and other traditional organic

51

52

53

54

55

56

57

solvents with high BP [21–24]. Most of these absorbents are characterized by low sorption capacity
of VOCs (mainly hydrophobic ones), solvent degradation, and corrosion of installation equipment. In
addition, some absorbents require a distillation process for regeneration. This process involves high
energy requirements, and secondary contaminants can form during solvent regeneration [25,26].
Therefore, new alternative absorbents are still being sought.

64 Until recently, ionic liquids (ILs) were considered ideal absorbents due to their non-volatile 65 nature, non-flammability, non-explosivity, and the ability to tune other physicochemical properties 66 based on the selection of appropriate cation and anion [27]. However, expensive and complicated 67 synthesis, as well as proven toxicity and negligible biodegradability, have prevented them from being implemented in industrial processes [28,29]. To overcome the above limitations, in 2003 Abbott et al. 68 69 introduced a new type of green solvent called deep eutectic solvents (DES) [30]. According to the 70 definition, a DES is a mixture of two or more chemical compounds that bind to each other by specific 71 non-covalent interactions. In the DES structure, one of the components plays the role of a hydrogen 72 bond donor (HBD) and the second one an acceptor (HBA). Due to the HBA-HBD interaction (charge 73 delocalization), a significant decrease in the melting point of DES compared to pure components is 74 observed [31]. In addition, DES are characterized by similar unique physicochemical properties to ILs, 75 but they are "generally" less toxic, more biodegradable, and more cost-effective. The DES's ability to 76 interact with impurities molecules via hydrogen bonds or weaker electrostatic interactions, as well as 77 the ability to regenerate multiple times, can transform well-known technological processes into more 78 ecological ones. The favorable properties of DES have resulted in an increasing number of scientific 79 articles on their industrial application. DESs have been tested as extraction solvents for fuel 80 desulfurization and denitrification [32–35], separation of aromatic and aliphatic hydrocarbons [36], 81 biocatalysis [37], recycling of Li-ion batteries [38], and extraction of bioactive compounds [39]. To 82 date, the application of DES for the capture of inorganic harmful gaseous molecules, that is, carbon 83 dioxide, water, ammonia, hydrogen sulfide, or sulfur dioxide from the air, gaseous fuels, biogas, and 84 industrial gases, has been relatively well described in the literature [40-49]. However, there is still 85 little information on the capture of VOCs. Figure 1 shows the number of published papers on the 86 absorption of inorganic pollutants from gaseous streams compared to VOCs between 2013 and 2022.



Figure 1 a) Number of published papers between 2013 and 2022. The graphs were built using the Scopus database, from the topics deep eutectic solvents, absorption or capture, and volatile organic compounds; b) Percentage breakdown of the number of publications from 2013 to 2022 describing the use of DES to remove individual impurities from the gas phase. (Access date: 21.09.2022).

87

88

89

90

To the best of the author's knowledge, this is the first review article to critically summarize and compare the achievements in the application of DES for the absorption of various groups of VOCs from gaseous streams. In addition, the paper describes the influence of the physicochemical and structural properties of DES on the efficiency of VOCs captured from gas streams and methods of DES regeneration. Critical comments on the new gas treatment procedures and future perspectives are also included.

98 **2.** Characterization of deep eutectic solvents used for VOCs capture

99 2.1. Structures of DES

100 DES are a new generation of solvents that have become an alternative to non-aqueous and 101 organic solvents because of their unique properties. DES are also known as tailor-made solvents 102 because of the ability to tune their parameters for specific applications by selecting appropriate HBAs 103 and HBDs. Currently, there are several classifications of DES [50-54]. However, we can distinguish 104 four types of DES tested as new absorbents. They can be classified according to the HBA component 105 in the structure of the eutectic mixture. The first group includes the most popular and well-known 106 ionic DES, which consists of quaternary ammonium salts (QAS) or phosphonium salts (QPS). The 107 second group includes non-ionic DES, in which organic compounds containing active oxygen atoms 108 (=O, -O-) in their structure, including monoterpenes, polyphenols, or carboxylic acids, are used for 109 preparation [55]. The third group is the recently discovered SUPRADES, which contain cyclodextrins 110 (CDs) in their structures [56,57]. The last group includes DES composed of ionic liquid and an organic 111 compound [58]. In all types of DES, the same substances, i.e., monoterpenes, phenols, polyphenols, 112 carbamides, sugars, carboxylic acids, and glycols, are present as the second component. Some HBDs 113 can also be used as HBAs due to several active groups or specific groups, i.e., a carboxyl group, which can combine through hydrogen bonds with another acid and form a DES. Examples of DES 114



116



118 2.2. DES properties

The main parameter determining the effective absorption of VOCs is their solubility in DES. However, in dynamic processes, other parameters of absorbents also define their usefulness in purifying gas streams [59]. These physicochemical properties include melting/freezing point, degradation temperature, rheological parameters (viscosity, density, and surface tension), and polarity. To meet the requirements of green chemistry and green engineering, it is also necessary to determine the toxicity, vapor pressure, and biodegradability of DES [60,61]. All physicochemical parameters of DES used so far in the absorption of VOCs are summarized in Table 1.

126 2.2.1. Liquid range of DES

127 In the absorption process, the use of liquid sorption media is crucial. The liquid range of DES 128 depends on the lower (melting (MP), freezing (FP), and glass transition temperature (Tg)) and the upper-temperature limit (degradation temperature (T_{deg})) [62]. Physical absorption is a highly 129 130 exothermic process. To achieve high VOCs absorption efficiency, it is necessary to use low 131 temperatures in the process. MP/FP is the parameter to classify eutectic complexes as solvents. The 132 main difference between conventional solvents, solvent mixtures, and DES is the sharp drop in the 133 MP/FP of the complex compared to the pure components [63]. The decrease in melting/freezing point is related to the strength of the non-covalent interactions between HBA and HBD. The stronger 134 the interactions between DES components, the lower the MP/FP. The types and strength of 135 136 interactions depend on the chemicals and stoichiometry used to prepare DES. The melting point of ionic DES used in the absorption of VOCs ranges from -68.9 to 12 °C, while non-ionic DES range from 48 to 21.9 °C. For SUPRADES and IL-based DES, only glass transition temperature in the range from 51 to -87 C can be found. Tg is the temperature at which a hard glassy state of an amorphous
material is converted to a rubbery state, and it is much lower than MP or FP.

141 The degradation temperature affects the ability of DES to regenerate. Typically, regeneration 142 processes are conducted at elevated temperatures (60-125 °C) to ensure high desorption efficiency, 143 and to reduce process time. At high temperatures, the phase and significant changes in the deep 144 eutectic solvent structures and the breakdown of non-covalent interaction between HBA and HBD 145 may occur [64]. Therefore, DES used in the absorption/desorption process should exhibit high T_{deg}. 146 The degradation temperatures of ionic DES are relatively high. T_{deg} values range from 107.2 to 396 °C. 147 High degradation temperatures can also be observed for SUPRADES (117–137 °C).

This indicates that they could potentially be suitable absorbents for capturing VOCs and their subsequent desorption. However, information on the degradation temperatures of the other two DES groups is missed. However, due to the tendency of monoterpenes to sublimate, the degradation temperature of most non-ionic DES can be expected to be much lower [65]. Therefore, these substances are not a suitable choice as absorption media. On the other hand, ILs-based DES should probably have similar or higher degradation temperatures to ionic DES due to the high T_{deg} values of pure ionic liquids [65,66]. Nevertheless, still more research is needed.

155

156 2.2.2. Rheological parameters

157 Viscosity

158 Dynamic viscosity (η) is a crucial rheological parameter that affects absorption efficiency. Most 159 DES are characterized by relatively high viscosity (>100 mPas) at room temperature (RT) and under atmospheric pressure [53,67,68]. However, the high viscosity of the absorbents is unfavorable 160 161 because it hinders the mass transfer process. During absorption process the high dynamic viscosity of 162 DES can lead to slow gas diffusion through the gas-liquid interface. Large gas bubbles are formed in the barbotage column instead of tiny gas bubbles, which decreases the gas-liquid contact area. 163 Consequently, at high DES viscosities, local hydrodynamics are modified by generating a more 164 165 stabilized DES liquid. In addition, applying low viscous solvents in gas purification can reduce energy costs associated with pumping, heating, or desorption. The dynamic viscosity values of deep eutectic 166 167 solvents depend mainly on the substrates used to prepare DES and their stoichiometry.

Ionic DES composed of QAS or QPS and various HBDs have the highest viscosity. Their viscosities range from 15 to 3451.35 mPas [69,70]. The high values of solvent dynamic viscosity are attributable to the large ion size in the HBA structure and relatively small empty volumes (steric effect) [56]. In addition, the length of the alkyl chain in HBA and HBD significantly affects the viscosity of DES. As the chain length decreases, solvent viscosity decreases. Slightly lower viscosities have SUPRADES, whose viscosities at 30 °C range from 212.9 to 1300 mPas [71]. The addition of cyclodextrins to the eutectic mixtures increases the viscosity of DES. However, the increase is relatively small due to the low amount of CD in DES structures [57]. IL-based DES also exhibits relatively high viscosities (150-470 mPas at 25 °C) [72]. Their high viscosity is mainly due to the very high η of ionic liquids [73]. The lowest viscosities are characterized by non-ionic DES (4.2–31.1 mPas at 20 °C) [61,74].

DES viscosity is also affected by the strength and type of interactions between the HBA and HBD. Stronger non-covalent interactions, i.e., hydrogen bonds, electrostatic bonds, van der Waals, or

168 169

170

171

172

173

174

175

176

177

178

 π - π , reduce the mobility of free species within the eutectic molecule and cause an increase in 180 181 viscosity [75]. One possibility to lower the viscosity of DES is to add water. However, many DES are 182 highly hydrophobic. Therefore, the addition of water is only possible for selected absorbents. The water addition can significantly modify other physicochemical properties, causing a reduction in the 183 184 solubility of VOCs in DES. The viscosity of DES can also be reduced by raising the temperature of the 185 absorption process, which is consistent with the Arrhenius or Vogel-Fulcher-Tammann model. This is 186 because an increase in temperature causes an increase in the average velocity of HBA and HBD in the 187 liquid phase, resulting in a decrease in intermolecular forces. This results in a reduction in fluid flow 188 resistance and a change in dynamic viscosity [20]. However, increasing the temperature of the 189 absorption process is unfavorable due to the exothermic nature of the absorption process [76]. 190 Therefore, it is more advantageous to select DES, which has a lower viscosity at low temperatures.

- 191
- 192 Density

Another important rheological parameter of solvents is density (ρ). However, in the absorption process, the importance of this parameter is minor. DES density values can determine the selection of the DES regeneration process. Deep eutectic solvents, whose densities differ significantly from conventional solvents, i.e., water, can be regenerated by extraction.

197 Most ionic DES have a higher density than water, within the range of 1000 to 1350 kg/m³ 198 [51,68]. Similar to the viscosity parameter, the exact value of DES density strongly depends on the 199 type of ingredients used in DES preparation. IL-based DES have the highest density. Their density values range from 1040 to 1689.3 kg/m³. This is due to the high density of ILs. SUPRADES have 200 viscosities in the range of 1184.5 to 1234.3 kg/m³. Non-ionic DES have the lowest viscosity (898 – 201 202 943.7 kg/m³). Only those non-ionic DES composed of levulinic acid and terpenes have a slightly 203 higher viscosity than water. The density of DES can be controlled by mixing water or another organic 204 solvent with DES, or by decreasing/ increasing the temperature [77]. The strong temperature 205 dependence on DES density is because of a change in the kinetic energy of the molecules. At a high 206 temperature, the increase in the movement of the deep eutectic solvent molecules occurs. This 207 evokes an increase in the molar volume of DES [78,79].

208 Surface tension

209 The surface tension (ST) of DES also affects the mass transfer process [80]. According to the 210 definition, surface tension is the solvent's tendency to obtain the minimum surface area. The value of 211 surface tension mainly depends on the type and hydrophilic or hydrophobic nature of HBA and HBD, the strength of the intermolecular interactions between DES components, and temperature [81]. 212 Typically, the surface tension of DES is in the range of 40–65 mN \cdot m⁻¹ at room temperature [82,83], 213 and they are higher than surface tension of most ionic liquids [84]. However, only ionic DES are 214 215 characterized by high surface tension (45.8 – 75.3 mN/m). Values of surface tension in ILs and ionic 216 DES correspond to the strength of H-bonding between molecules [85]. Non-ionic DES have much 217 lower surface tension. The surface tension values are comparable to conventional organic solvents 218 (25-36.5 mN/m). However, there is no data on surface tension of SUPRADES and ILs-based DES. Low 219 surface tension values favorably affect the efficiency of VOCs absorption. To reduce the surface 220 tension of absorbents, HBA or HBD with a longer alkyl chain should be used to synthesize DES. This 221 contributes to lowering the charge density and decreasing the importance of electrostatic 222 interactions between DES components [61]. Likewise, the QAS or QPS content of the DES structure can be increased, which destroys the hydrogen bond network [81]. In addition, increasing the temperature of DES reduces surface tension. This is due to an increase in the movement of molecules and the average kinetic energy, as well as a decrease in cohesion forces between DES components [81,86,87].

227 2.2.3. Polarity

228 The polarity of the absorbents is an important parameter characterizing the ability of DES to 229 dissolve VOCs. This parameter corresponds to the intermolecular interactions between DES and 230 solutes that do not lead to chemical reactions [88]. The exact value of the DES polarity can be 231 determined using Betaine Dye 30 on a scale of $E_T(30)$, Betaine Dye 33 on a scale of $E_T(33)$ normalized 232 polarity scale (E_TN), and Nile red polarity scale ($E_T(NR)$). [89–91]. All these parameters allow for 233 determining the electronic transition energy in DES-VOC complexes. DES exact polarity values may 234 differ depending on the method used. Because of the numerous available ways, it isn't easy to 235 compare the polarity of the new DES with literature data. Published data indicate that most DES are 236 relatively polar. The polarity values of DES are similar to popular organic solvents i.e., methanol 237 $(E_T(33)=63.9 \text{ kcal/mol}; E_T(30)=55.5 \text{ kcal/mol}; E_TN=0.76)$, ethanol $(E_T(33)=60.5 \text{ kcal/mol}; E_T(30)=52.1 \text{ kcal/m$ 238 kcal/mol; $E_TN=0.66$), acetonitrile ($E_T(33)=54.8$ kcal/mol; $E_T(30)=46.6$ kcal/mol; $E_TN=0.49$), and water 239 $(E_{T}(33)=71.5 \text{ kcal/mol}; E_{T}(30)=63.1 \text{ kcal/mol}; E_{T}N=1.0)$, and dimethylsulfoxide $(E_{T}(33)=53.9 \text{ kcal/mol};$ 240 $E_{T}(30)=45.5$ kcal/mol; $E_{T}N=0.46$) [92,93]. The $E_{T}(33)$, $E_{T}(30)$, $E_{T}(NR)$ and $E_{T}N$ values of the ionic DES 241 and DES-based ILs are slightly lower than water and higher than the popular organic solvents. The 242 ranges of $E_T(33)$, $E_T(30)$, $E_T(NR)$, and E_TN values for DES are 65.7-67.59, 47.75-57.3, 45.5, and 44.88-58.07 kcal/mol, and 0.81-0.87, respectively. This means that ionic DES are medium-polar. To reduce 243 244 the polarity of DES, HBDs containing longer hydrocarbon chains should be used for their synthesis 245 [93]. There is no data about the polarity of SUPRADES and non-ionic DES. Some published papers also 246 describe the Kamlet-Taft parameters of deep eutectic solvents [94]. The π^* , α , and β values for ionic 247 DES are in ranges of 0.85 - 1.14, 0.421 - 1.85, and 0.27 - 1.05, respectively. Data are missing for 248 most non-ionic DES, SUPRADES, and DES based on ILs. Kamlet-Taft parameters were calculated only 249 for Th:DA (1:1) (α =1.11; β =0.05; π *=0.71). DES have similar dipolarity values to water (π *=1.09), 250 while they are higher than the rest of conventional solvents (0-58). In addition, the π^* value 251 increases with decreasing hydrocarbon chain length in HBDs structures. The occurrence of 252 permanent dipoles, delocalized bonds, and DES structures can explain this phenomenon [90,95]. 253 Most DES show a higher donation capacity of protons in DES-to-solute hydrogen bonding than pure 254 alcohols and ILs. On the other hand, DES show only slightly lower α values compared to water and 255 pure acids [95-98]. Therefore, these compounds may be more suitable for the absorption of 256 chlorinated or oxygenated organic compounds due to their potential ability to form hydrogen bonds 257 such as -OH…Cl, -COOH…Cl, -NH2…Cl, -OH…O=, -COOH…O=, -NH2…O=. On the other hand, most DES 258 are characterized by β values lower than 0.7. This means that the DES commonly used for VOC 259 capture are weak hydrogen bond acceptors and show less alkaline properties [95]. Only TBPCI: Lev (1:2), TBABr:DA (1:2), and ChCl:Res (1:2) show a higher potential to be a hydrogen bond acceptor 260 261 than conventional solvents. Therefore, they can absorb more efficiently VOCs such as alcohols and 262 amines. The polarity can be modified by increasing or decreasing the DES temperature. The 263 decreasing of the temperature generally increases the DES polarity. This is due to an increase in the 264 absorbent's hydrogen-bond donating acidity and the formation of stronger interaction between HBA 265 and HBD [99]. However, most absorption processes are carried out at room temperature or lower.

Therefore, the selection of DES for removing specific VOC groups should be driven by the structures of HBA and HBD.

268 2.2.4. DES volatility

269 From an industrial and environmental point of view, the volatility of DES is a crucial 270 parameter. The application of absorbents characterized by high vapor pressure can cause the 271 evaporation of DES components during the absorption and desorption processes. This can lead to the 272 loss of DES and the need for frequent replacement, which significantly increases the cost of the gas 273 purification process. It can also result in the contamination of treated gas and atmospheric air. [100]. 274 Therefore, only non-volatile sorption media should be used in the absorption process. Fortunately, 275 deep eutectic solvents are considered non-volatile. However, compared to the numerous reports on 276 the volatility of ILs, only limited information on the volatilization of DES can be found in the literature 277 [101–104]. The vapor pressure (Vp) of DES depends strongly on the type of HBA and HBD. Ionic DES 278 are mostly non-volatile. The total vapor pressures of the most popular DES, i.e., ChCl:U (1:2) and 279 ChCl:Gly (1:2), are 2.94 and 46.16 Pa at 393K, respectively [105,106]. The vapors pressure of ChCl:EG 280 (1:2) is about two orders of magnitude higher than that of ChCl:Gly (1:2). This is because the vapor 281 pressure of pure EG is much higher (6148.6 Pa at 393 K) compared to Gly (97.9 Pa at 393 K). This 282 indicates that the type of HBD and its stoichiometry plays a crucial role in the volatility of DES 283 because the vapor pressure of most quaternary ammonium and phosphonium salts is negligibly low. 284 Non-ionic DES, which consist of monoterpenes (i.e., menthol, thymol, lidocaine), has a higher vapor 285 pressure. Vapor pressure values at 40 °C typically range from 0.44 to 15.84 Pa. This is due to the 286 ability of monoterpenes to sublimate [65]. Replacing one of the monoterpenes with a carboxylic acid 287 significantly reduces the vapor pressure of DES [107]. Currently, there is no information on the 288 volatility of SUPRADES and DES based on ILs. However, a comparison of available literature values of 289 the volatility of DES with conventional organic solvents and ILs, indicates that DES have much lower 290 vapor pressures than organic solvents and higher than ionic liquids [108]. In addition, the vapor 291 pressure of all absorbent groups increases with increasing temperature [109]. At elevated 292 temperatures, in the first stage, the interactions between HBA and HBD are weakened, and 293 evaporation of the individual components occurs in the next step [106,110]. However, due to the 294 limited volatility data of DES, before the selection of the most suitable absorbent, it is necessary to 295 examine the vapor pressure of DES in both absorption and desorption process temperatures.

296 2.2.5. Toxicity

297 Apart from the physicochemical properties of DES that have a decisive impact on the 298 absorption efficiency of VOCs, it is essential to determine their ecological footprint. Most published 299 articles describe DES as non-toxic and environmentally friendly solvents. However, there are still few 300 papers that confirm this assumption. The literature provides information on the toxicity of the 301 individual components of DES (HBA and HBD) [111,112]. For instance, Morrison et al. examined the 302 toxicity profiles of ChCl and U for rats and mice (oral LD 50), which were 3400 and 3900 mg/kg for 303 ChCl and 8471 and 11000 mg/kg for U. The results suggest that these substances are 304 pharmaceutically acceptable [113]. Since DES are composed of at least two components, a synergy 305 effect between HBA and HBD may occur. This effect may increase or decrease the toxicity of eutectic 306 complexes compared to pure DES components [114]. However, only a few DES have been studied in 307 detail. Hayyan et al. demonstrated, based on toxicity tests on two Gram-positive bacteria (Bacillus 308 subtilis and Staphylococcus aureus) and two Gram-negative bacteria (Escherichia coli and Pseudomonas aeruginosa), as well as brine shrimp (Artemia saliva), that four DES (ChCl:Gly, ChCl:EG, 309 310 ChCl:TEG i ChCl:U) do not have toxic effects. On the other hand, they found that the cytotoxicity of all tested DES was higher than their individual components [114]. The same conclusions were also 311 suggested in other works [115,116]. In contrast, in another study, the authors obtained contradictory 312 313 findings. The authors observed that DES showed an antagonistic effect against Allivibrio fischeri. This 314 indicates that DES are less toxic than separate substances [117]. Based on in vitro toxicity data on cell lines (fish COO and human MCF cancer cell lines), the authors indicated that ChCl:Gly (1:2) has low 315 316 cytotoxicity (EC 50 > 2000 mg/L), and the ChCl:Ox (1:2) has moderate cytotoxicity (EC 50=218.7 and 559 mg/L, respectively for COO and MCF cells). On the other hand, phytotoxicity results indicate that 317 318 both DES are non-toxic at seed germination (EC50 > 5000 mg/L) [118]. Similar results were obtained 319 for HEK293T, MCF-7, and HeLa 7 cell lines [70]. This suggests that DES containing organic acids in 320 their structure have toxic properties and cannot be considered green absorbents. Other studies have 321 shown that DES toxicity increases with alkyl chain length in QAS and QPS [119]. In addition, it has also 322 been shown that the molar ratio of HBA components: HBD can positively or negatively affect the 323 toxicity of DES [120]. Current studies suggest that the toxicity of DES depends on several variables. 324 Some of the DES are not toxic, so they can successfully be used as green solvents. However, only a 325 few DES have been studied. For most DES, information on their toxicities is lacking. However, further 326 cytotoxicity studies are crucial to enable their large-scale utilization.

327 2.2.6. Biodegradability

328 New absorbents should be biodegradable to meet the requirements of green chemistry and 329 engineering. This is a significant parameter because it allows an understanding of the environmental impact of solvents. According to the most common biodegradability test (No. 301) of the OECD 330 Guidelines, solvents are considered readily biodegradable if a minimum of 70% of dissolved organic 331 332 carbon is removed [121]. In addition, 60% of CO_2 should be generated by the respirometry method 333 within ten days in a 28-d period of the aerobic test. Most of the DES-based absorbents used to date 334 are readily biodegradable. After 28 days of experiments, the biodegradability of DES composed of 335 QAS is above 67.2% [70,118,122,123]. This means that DES are more biodegradable than ILs [124]. 336 Only TBABr:DA (1:2) does not exhibit biodegradability after a 14-day process, which suggests that 337 DES does not meet the requirements for green solvents. This is because the process of degradation 338 of hydrophobic DES is very slow. Therefore, a significant amount of water should be added to dilute 339 the absorbents and accelerate their biodegradation. This significantly increases the cost of DES 340 degradation. Moreover, substances with long alkyl chains in structures are less susceptible to 341 transmembrane transport, resulting in relatively low biodegradation. In theory, DES that contains the 342 hydroxyl, carboxyl, and amino groups may be readily biodegradable due to potential sites for enzyme 343 reactions [125]. However, there is still very little data on the biodegradability of DES. There is a lack 344 of biodegradability results for SUPRADES, non-ionic DES, and DES based on ILs. In addition, the direct 345 mechanisms of DES biodegradation are also poorly understood. The chemical mechanism may be 346 related to the ability of HBA and HBD to cross cell walls or to degrade on their own [126,127]. 347 However, further studies are needed.

2.2.7. Price of DES

350 From an economical and industrial point of view, the price of DES is crucial. Since DES are not commercially available, their cost can only be estimated by the cost of individual HBAs and HBDs on a 351 352 laboratory scale. Therefore, their prices are relatively high. Prices per kilogram of ionic, non-ionic, DES based on ILs and SUPRADES range from 29.9–1165.7 €, 18.0–533.0 €, 55.9–246.9 €; 2521.4– 353 354 15482.0 €, respectively (Table 1). The costs of the selected DES were estimated from the original 355 articles. These values, in unchanged form, are included in the manuscript. For the remaining DES, prices were determined by averaging the market prices (per kilogram) of popular chemical sellers. 356 The cost of DES was subsequently calculated based on the stoichiometry of the individual 357 358 components. The presented prices were estimated for high-purity (above 98%) DES components. The 359 results indicate that the average cost of non-ionic DES is lower than other DES. This is due to the 360 relatively low price of monoterpenes, carboxylic acids, and polyphenols, which are usually used to 361 prepare DES. The high costs of the other groups of DES are influenced by the relatively high prices of QASs, QPSs, cyclodextrins, and ionic liquids [128]. Nevertheless, the price is lower for large-scale 362 sales. It is generally considered that the cost of absorbents on an industrial scale is 10% of the price 363 364 of absorbents sold on a laboratory scale [129]. In addition, it is possible to reduce costs by decreasing 365 the purity of HBA and HBD. However, additional impurities can affect the efficiency of removing VOCs from the gas and influence the physicochemical properties of DES. Therefore, further research 366 367 is needed before using this approach. The unit price per kilogram of DES is lower than ILs but higher 368 than conventional organic solvents [130]. However, due to the low volatility of DES, they can 369 potentially be regenerated many times without significant loss (this is a common occurrence with the 370 use of organic solvents). This means that despite the higher purchase price of DES compared to 371 conventional absorbents, the total cost of the VOCs absorption process can be comparable to or 372 lower than the price for other gas treatment methods [131].

373 Table 1 Physicochemical properties of DES used for VOCs absorption

	DES (HBA:HBD molar ratio)	Abbreviation	Viscosity at 20°C (mPa·s)	Density at 20°C (g/cm3)	Surface tension at 20 °C [mN/m]	MP/FP /TG [°C]	Decomp osition temperat ure [°C]	Vp [Pa]	Polarity	Toxicity EC₅o	Biodegrada bility [%]	Hydrophob icity	Price per 1 kg	Literat ure
								Ionic DE	S					
zy.pl	Choline chloride : urea (1:2)	ChCl:U (1:2)	1618.3	1.17	63.76	12	134.5	0.336 ^{e)} ; 2.941 ^{f)} ; 6.6 ^{h)}	E _T (33)=65.4 kcal/mol; E _T (30)=57.0 kcal/mol; E _T (RN)=49.25 kcal/mol E _T N=0.81 α =1.42; β=0.5; π *=1.14	4500 mg/L (Allivibro fischeri) 7.098 % v/v (Allivibro fischeri) >2000 mg/L (Hela cells) >2000 mg/L (HEK293T cells) >2000 mg/L (MCF-7 cells) 8532 mg/L (R. subcapitata) 1099 mg/L (D. magna) 26346 mg/L (A. fischeri) 295.9 mM E. coli	97.1 %(28 days) 64.6 (28 days)	No	44.6€	[70,88, 122,12 3,126,1 32– 136]
stwied	Choline chloride : resorcinol (1:2)	ChCl:Res (1:2)	326 2218	1.1869	61.56	-43.9	n.d.	n.d.	α_{pred} =1.85; β_{pred} =1.0	n.d.	n.d.	No	71€	[69,13 5,137,1 38]
aded from mos	Choline chloride : levulinic acid (1:2)	ChCl:Lev (1:2)	206 ^{c)}	1.1371 ^{b)} 1.1345 ^{c)}	n.d.	-11.9 ⁱ⁾	159	n.d.	$E_{T}(NR)=49.79$ kcal/mol; $E_{T}(33)=50.26$ kcal/mol; $E_{T}N=0.35$ α=0.51; β=0.57; π*=1.0	n.d.	67.2 (28 days)	No	42.5€	[72,13 2,135,1 39,140]
IIEDZY Bownly	oline chloride : lactic acid (1:2)	ChCl:Lac (1:2)	305 ^{c)}	1.176 ^{c)}	47.4	-63.9	196.83	n.d.	E _T (30)=48.02 kcal/mol; E _T (33)=67.59; kcal/mol; E _T (NR)=44.88 kcal/mol; E _T N=0.87; α =1.34; β=0.5; π *=0.85	33.6 (A. fischeri)	n.d.	No	35.5€	[81,14 1]
OST W	oline chloride : Oxalic acid (1:2)	ChCl:OxA (1:2)	5363 ^{c)}	n.d.	75.30 ^{b)}	-21 ⁱ⁾	134.81	n.d.	E _T (30)=47.78 kcal/mol; E _T (33)=66.19 kcal/mol;	330.9 mg/L (Hela cells) > 2000 mg/L (HEK293T cells) 558.98 mg/L (MCF-7	73.4 (28 days)	No	50.3€	[70,13 5,139]
Ž														

									E _⊤ N=0.828;	cells)				
									α_{pred} =1.19; β_{pred}					
									=0.27					
	Choline Chloride : phenol (1:2)	ChCl:Ph (1:2)	122.51 ^{b)}	1.0989 ^{b)}	35.46 ^{b)}	-68.9	n.d.	n.d.	n.d.	1.54 % v/v (Allivibro fischeri)	79 (14 days)	No	50.6€	[134,1 42]
	Choline chloride : ethylene glycol (1:2)	ChCl:EG (1:2)	207.14	1.1168	49.4; 48.91	-66	107.2	790 ^{e)} ; 5600 ^{g)}	$\begin{array}{c} {\sf E}_{\sf T}({\sf NR}){=}57.3\\ {\sf kcal/mol}\\ {\sf E}_{\sf T}(33){=}65.7\\ {\sf kcal/mol};\\ {\sf E}_{\sf T}(30){=}57.3\\ {\sf kcal/mol}; {\sf E}_{\sf T}{\sf N}{=}0.82\\ {\alpha}{=}1.47; {\beta}{=}0.57;\\ {\pi}^{*}{=}1.07 \end{array}$	4000 mg/L (Allivibro fischeri) 9196 mg/L (R. subcapitata) 1868 mg/L (D. magna) 108526 mg/L (A. fischeri) 532.0 E. Coli	81.9 (28 days) 73.4 (28 days)	No	37.5€	[64,81, 82,88,1 22,123, 135,13 6]
C	Choline chloride : diethylene glycol (1:2)	ChCl:DEG (1:2)	52.5	1.1143 ^{b)} 1.1216	48.49	-13	n.d.	n.d.	ENR=50.8 kcal/mol	n.d	n.d.	No	56.9€	[132,1 43,144]
stwiedzy.pl	Choline chloride : glycerol (1:2)	ChCl:Gly (1:2)	237; 136.1 ^{c)}	1.1920	57.24; 57.8	-36	184	2.141 ^{e)} ; 46.16 ^{g)}	$E_{T}(NR)=58.1 \\ kcal/mol; \\ E_{T}(33)=66.4 \\ kcal/mol; \\ E_{T}(30)=58.0 \\ kcal/mol; E_{T}N=0.84 \\ \alpha=1.49; \beta=0.52; \\ \pi^{*}=1.11$	9000 mg/L (Allivibro fischeri) 7080 mg/L (R. subcapitata) 2528 mg/L (D. magna) 86726 mg/L (A. fischeri) 434.4 mM (E.Coli)	95.9 (28 days)	No	40.1€	[64,81, 82,88,1 22,123, 135,13 6]
	Choline chloride : 1,2-propanediol : water (1:1:1)	ChCl:PC:H ₂ O (1:1:1)	114.5	1.08	n.d.	n.d.	134.0	n.d.	E _τ (NR)=50.2 kcal/mol; α=0.421; β=0.531; π*=1.05	1.541 %, v/v (Allivibro fischeri)	n.d.	No	38.9€	[70]
<u>Downloaded frq</u>	Choline chloride : glucose : water (5:2:5)	ChCl:Glu:H2O (5:2:5)	3451.3	1.41	n.d.	n.d.	154.4	n.d.	E _T (NR)=53.3 kcal/mol	8.448 %, v/v (Allivibro fischeri) 182 mM (Hela S3) 139 mM (CoOV3), 186 mM (MCF-7) 211 mM (B16F10)	92 (28 days) 83 (14 days)	No	38.2€	[70,13 4]
DZY	oline chloride : xylose : water (2:1:3)	ChCl:Xyl:H ₂ O (2:1:3)	400.3	1.17	n.d.	n.d.	207.9	n.d.	E⊤(NR)=50.4 kcal/mol	n.d.	89.7 (28 days) 80 (14 days)	No	29.9€	[70,13 4]
	traethylammonium chloride : phenol (1:2)	TEACI:Ph (1:2)	15	1.04	n.d.	1.9	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	406.8€	[69]
≤ ⊢	trabutylammonium bromide: decanoic acid (2:1)	TBABr:DA (2:1)	1784 ^{d)}	0.9158 ^{d)}	n.d.	-60	185	n.d.	n.d.	n.d.	n.d.	Yes	706€	[145]
0S	trabutylammonium bromide: decanoic acid (1:1)	TBABr:DA (1:1)	1100 ^{d)}	0.9108 ^{d)}	n.d.	-63	197	n.d.	n.d.	n.d.	n.d.	Yes	534€	[145]

Tetrabutylammonium bromide: decanoic acid (1:1.5)	TBABr:DA (1:1.5)	600 ^{d)}	0.9071 ^{d)}	n.d.	-72	205	n.d.	n.d.	n.d.	n.d.	Yes	432 €	[145]
Tetrabutylammonium bromide: decanoic acid (1:2)	TBABr:DA (1:2)	548	0.9045 ^{d)}	n.d.	-9	204	n.d.	E _T (NR)==51.4 kcal/mol α =0.95; β=1.05; π *=0.71	0.123 %, v/v (Allivibro fischeri)	0% (14 days)	Yes	361.9€	[95,13 5,145]
Tetrabutylammonium bromide: decanoic acid (1:3)	TBABr:DA (1:3)	102.4 ^{d)}	0.8964 ^{d)}	n.d.	-4	197	n.d.	n.d.	n.d.	n.d.	Yes	281€	[145]
Tetrabutylphosphonium chloride : Levulinic acid (1:1)	TBPCI:Lev (1:1)	480	0.99	n.d.	n.d.	367	n.d.	n.d.	n.d.	n.d.	No	1165.7 €	[146]
Tetrabutylphosphonium chloride : Levulinic acid (1:2)	TBPCI:Lev (1:2)	229.3	1.0228	n.d.	n.d.	369	n.d.	β=0.82; π*=1.06	n.d.	n.d.	No	777.9€	[146]
Tetrabutylphosphonium chloride : Levulinic acid (1:3)	TBPCI:Lev (1:3)	175	1.04	n.d.	n.d.	369	n.d.	n.d.	n.d.	n.d.	No	595€	[146]
Tetrabutylphosphonium chloride : Levulinic acid (1:4)	TBPCI:Lev (1:4)	138	1.06	n.d.	n.d.	369	n.d.	n.d.	n.d.	n.d.	No	481.5€	[146]
Tetrabutylphosphonium bromide : Levulinic acid (1:6)	TBPBr:Lev (1:6)	118.2	1.09	n.d.	n.d.	118.95	n.d.	E _T (NR)=49.2 kcal/mol	0.12 %, v∕v (Allivibro fischeri)	n.d.	No	76.1€	[147,1 48]
Tetrabutylphosponium bromide : decanoic acid (1:2)	TBABr:DA (1:2)	85	0.95	n.d.	n.d.	126.7	n.d.	E _T (NR)=51.4 kcal/mol	n.d.	n.d.	Yes	183€	[137]
Tetrabutylphosphonium bromide: glycerol (1:1)	TBPB:Gly (1:1)	n.d.	n.d.	45.77	< RT	n.d.	n.d.	n.d.	n.d.	n.d.	No	199.9€	[147,1 48]
Tetrapropylammonium bromide: Tetraethylene glycol (1:2)	TPABr:TEG (1:3)	84.6 ^{c)}	1.552	n.d.	-48	n.d.	n.d.	n.d.	n.d.	n.d.	No	66.1€	[149]
Trimethylallyl ammonium chloride : phenol (1:2)	TAACI:Ph (1:2)	45	1.06	n.d.	< RT	n.d.	n.d.	n.d.	n.d.	n.d.	No	414€	[25]
Triethyl benzyl ammonium chloride : levulinic acid (1:2)	TEBACI:Lev (1:2)	1850	1.11	n.d.	< RT	n.d.	n.d.	n.d.	n.d.	n.d.	No	77.1€	[25]
Triethyl benzyl ammonium chloride : Ethylene glycol	TEBACI:EG (1:2)	420	1.10	n.d.	< RT	n.d.	n.d.	n.d.	n.d.	n.d.	No	91.7€	[25]
Triethyl benzyl ammonium chloride : phenol (1:2)	TEBACI:Ph (1:2)	2150	1.088	n.d.	< RT	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	83.4€	[25]
Triethyl benzyl ammonium chloride : phenol (1:3)	TEBACI:Ph (1:3)	325	1.085	n.d.	< RT	n.d.	n.d.	n.d.	n.d.	n.d.	No	64.5€	[25]
Tetraethylammonium chloride : phenol (1:2)	TEACI:Ph (1:2)	170	1.05	n.d.	< RT	n.d.	n.d.	n.d.	n.d.	n.d.	No	406.8€	[25]
etraethylammonium chloride :oleic acid (1:3)	TEACI:OA (1:3)	203	0.91	n.d.	< RT	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	304.7€	[150]
							Non-ionic	DES					
iicaol : Camphor: Levulinic acid (1:1:3)	Gu:C:Lev (1:1:3)	n.d.	1.1123 ^{b)}	n.d.	< RT	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	33€	[132]
Camphor: Guaiacol (1:1)	C:Gu (1:1)	10.9	1.0284	n.d.	-48	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	32.78€	[74]
Syringol : Levulinic acid (1:1)	Syr:Lev (1:1)	31.1	1.1675	n.d.	-23	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	263.5€	[74]
Suaiacol : Levulinic acid (1:1)	Gu:Lev (1:1)	30	1.1382	n.d.	-43	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	36.01€	[74]

<

Camphor : Levulinic acid (1:2)	C:Lev (1:2)	26.2	1.0597	n.d.	8	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	24.02€	[74]
Eucalyptol : octanoic acid (1:1)	E:OA (1:1)	5.25	0.9157	30	-18.9	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	43€	[61,15 1]
Camphor : octanoic acid (1:1)	C:OA (1:1)	9.42	0.9397	30.9	-1.4	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	29.9€	[61,15 1]
Camphor : decanoic acid (1:1)	C:DA (1:1)	11.2	0.9437	28.1	17.0	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	35.5€	[61,15 1]
Camphor : undecanoic acid (1:1)	C:UDA (1:1)	13.4	0.8985	n.d.	18.1	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	95.1€	[61,15 1]
Camphor : dodecanoic acid (3:1)	C:DDA (3:1)	4.2 ^{b)}	0.925	n.d.	-18.8	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	44€	[61,15 2]
Carvone : levulinic acid (1:1)	Car:Lev (1:1)	7	1.04	36.5	-25	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	62.4€	[61]
Carvone : octanoic acid (1:1)	Car:OA (1:1)	4.4	0.95	31	-22	n.d.	n.d.	E _⊤ (NR)=52.5 kcal/mol	n.d.	n.d.	Yes	58.4€	[61] 131]
Carvone : nonanoic acid	Car:NA (1:1)	4.6	0.94	29.8	-21	n.d.	n.d.	E _⊤ (NR)=52.5 kcal/mol	n.d.	n.d.	Yes	61.1€	[61] 131]
Carvone : decanoic acid (1:1)	Car:DA (1:1)	5	0.93	29	-19	n.d.	n.d.	E _T (NR)=52.7 kcal/mol	n.d.	n.d.	Yes	63.8€	[151] [61] 131]
Thymol : decanoic acid (1:1)	Th:DA (1:1)	11.8	0.9281	30.02	11.5	n.d.	n.d.	α=1.11; β=0.05; π*=0.71	n.d.	n.d.	Yes	41€	[61,13 5,151,1 53,154]
Lidocaine : decanoic acid (1:2)	Lid:DA (1:2)	55 ^{a)}	0.96	n.d.	n.d.	192	55 ^{f)}	n.d.	n.d.	n.d.	Yes	533€	[137]
Dodecanoic acid : decanoic acid (1:2)	DDA:DA (1:2)	4.7 ^{c)} ; 12.9	0.898	n.d.	21.9; 18	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	27€	[153,1 55,156]
Dodecanoic acid : decanoic acid (1:3)	DDA:DA (1:3)	10.8	0.9	n.d.	21.2	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	33.1€	[137]
Octanoic acid : dodecanoic acid (3:1)	OA:DDA (3:1)	6 ^{c)} ; 8.2	0.91	25	9	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	25.1€	[155,1 56]
Octanoic acid : decanoic acid (2:1)	OA:DA (2:1)	4.9	0.904	n.d.	< RT	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	18€	[137]
Nonanoic acid : dodecanoic acid (3:1)	NA:DDA (3:1)	7.5 °; 10.1	0.901	n.d.	9	n.d.	n.d.	n.d.	n.d.	n.d.	Yes	29.1€	[155,1 56]
							SUPRAD	ES					
lfobutylether-β-CD : Levulinic acid (1:44)	Captisol:Lev (1:44)	1300 ^{c)}	1.2343 ^{c)}	n.d.	-67.8 ⁱ⁾	127.6	n.d.	n.d.	n.d.	n.d.	n.d.	55.93€	[71]
w methylated-β-CD : Levulinic acid (1:25)	CRYSMEB:Lev (1:25)	480 ^{c)}	1.2075 ^{c)}	n.d.	-73.5 ⁱ⁾	137.7	n.d.	n.d.	n.d.	n.d.	n.d.	246.94 €	[71]
ydroxypropyl-β-CD : Levulinic acid (1:32)	HP-β-CD:Lev (1:32)	600 ^{c)}	1.2047 ^{c)}	n.d.	-73.3 ⁱ⁾	130.4	n.d.	n.d.	n.d.	n.d.	n.d.	130.4€	[71]
landomly methylated-β-CD : Levulinic acid (1:27)	RAMEB:Lev (1:27)	212.9 ^{c)}	1.1845 ^{c)}	n.d.	-74.3 ⁱ⁾	117.6	n.d.	n.d.	n.d.	n.d.	n.d.	71.4€	[71]
						I	DES based	on ILs					

Hexylcholinium levulinate	Chol-C6-Lev	300 ^{b)}	1.08 ^{b)}	n.d.	-79.8 ⁱ⁾	n.d.	n.d.	E _T (NR)=52.9 kcal/mol	n.d.	n.d.	n.d.	n.d.	
Octylcholinium levulinate	Chol-C8-Lev	470 ^{b)}	1.06 ^{b)}	n.d.	-82.6 ⁱ⁾	n.d.	n.d.	E _⊤ (NR)=53.9 kcal/mol	n.d.	n.d.	n.d.	n.d.	[72]
Hexylcholinium lactate	Chol-C6-Lac	150 ^{b)}	1.10 ^{b)}	n.d.	-73.1 ⁱ⁾	n.d.	n.d.	E _⊤ (NR)=52.5 kcal/mol	n.d.	n.d.	n.d.	n.d.	[/2]
Octylcholinium lactate	Chol-C8-Lac	460 ^{b)}	1.04 ^{b)}	n.d.	-68.7 ⁱ⁾	n.d.	n.d.	E _⊤ (NR)=53.0 kcal/mol	n.d.	n.d.	n.d.	n.d.	
Tetrabutylammonium perfluorobutanesulfonate : perfluoropentanoic acid (1:1)	[N ₄₄₄₄][C ₄ F ₉ SO ₃]:C ₄ F ₉ CO ₂ H (1:1)	n.d.	1.3517	n.d.	-61 ⁱ⁾	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	15482 €	
Tetrabutylammonium perfluorobutanesulfonate : perfluoropentanoic acid (2:1)	[N ₄₄₄₄][C ₄ F ₉ SO ₃]:C ₄ F ₉ CO ₂ H (2:1)	n.d.	1.3066	n.d.	-51 ⁱ⁾	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	19874 €	
Tetrabutylammonium perfluorobutanesulfonate : perfluoropentanoic acid (1:2)	[N ₄₄₄₄][C ₄ F ₉ SO ₃]:C ₄ F ₉ CO ₂ H (1:2)	n.d.	1.4191	n.d.	-82 ⁱ⁾	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	11089 €	
(2- Hydroxyethyl)trimethylammonium perfluorobutanesulfonate : Derfluoropentanoic acid (1:1)	[N ₁₁₁₂ (OH)][C ₄ F ₉ SO ₃]: C ₄ F ₉ CO ₂ H (1:1)	n.d.	1.6336	n.d.	-79 ⁱ⁾ (MP=0° C)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3826€	
(2-Hydroxyethyl)- trimethylammonium perfluoropentanoate : perfluoropentanoic acid (1:1)	[N ₁₁₁₂ (OH)][C ₄ F ₉ CO ₂] :C ₄ F ₉ SO ₃ H (1:1)	n.d.	1.6291	n.d.	-75 ⁱ⁾	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3671€	[157]
(2-Hydroxyethyl)- trimethylammonium perfluorooctanesulfonate : perfluoropentanoic acid (1:1)	[N ₁₁₁₂ (OH)][C ₈ F ₁₇ SO ₃]:C ₄ F ₉ CO ₂ H (1:1)	n.d.	1.6841	n.d.	-87 ⁱ⁾	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3496€	
1-Ethyl-3-methylimidazolium perfluorooctanesulfonate : perfluoropentanoic acid (1:1)	[C ₂ C ₁ Im][C ₈ F ₁₇ SO ₃]:C ₄ F ₉ CO ₂ H (1:1)	n.d.	1.6721	n.d.	-84 ⁱ⁾ (MP=- 4°C)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2790€	
1-Ethyl-3-methylimidazolium perfluorooctanesulfonate : perfluoropentanoic acid (2:1)	[C ₂ C ₁ Im][C ₈ F ₁₇ SO ₃]:C ₄ F ₉ CO ₂ H (2:1)	n.d.	1.6875	n.d.	-84 ⁱ⁾	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3058.6 €	
-Ethyl-3-methylimidazolium perfluorooctanesulfonate : verfluoropentanoic acid (1:2)	[C ₂ C ₁ Im][C ₈ F ₁₇ SO ₃]:C ₄ F ₉ CO ₂ H (1:2)	n.d.	1.6893	n.d.	-80 ⁱ⁾	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2521.4 €	

374 a) measurements at 0°C; b) measurements at 25°C; c) measurements at 30°C; d) measurements at 40°C; e) measurements at 70°C; f) measurements at 100°C;g) measurements at 120°C; h) measurements at 160°C; i) solid-liquid transition 375 temperatures.

376 3. VOCs absorption using DES

In the published works, the authors mainly focused on the absorption of VOCs, which have particularly adverse effects on the environment, human health, and industrial installations. Therefore, the following section presents the achievements in the absorption of particular groups of pollutants, including volatile aliphatic and monoaromatic hydrocarbons, volatile organosulfur-, oxygen-, sulfur-, halogen-, and silicon-organic compounds using DES. The detailed processes condition and obtained results are compared in Table 2.

383 **2.1. Volatile hydrocarbons**

384 Volatile aliphatic, cyclic, and monoaromatic hydrocarbons are one of the most commonly studied 385 contaminants of air, gaseous fuels, biofuels, and industrial, natural, and waste gasses [158–160]. 386 They come from anthropogenic sources such as coal combustion, automobile engines, petroleum 387 refineries, and architectural materials. The group of monoaromatic hydrocarbons includes benzene, 388 ethylbenzene, toluene, xylenes (BTEX), and styrene. The group of aliphatic hydrocarbons consists of 389 linear hydrocarbons from C2 to C10. From the ecological, public health, and industrial perspectives, 390 the presence of hydrocarbons in air and waste gas streams is unfavorable [161,162]. High toxicity 391 and proven carcinogenic effects on organisms characterize them. They undergo photochemical 392 reactions with ozone [163–167]. In addition, the presence of selected aromatic hydrocarbons in 393 biogas and natural gas streams during fuel combustion can affect corrosion, contamination, and 394 clogging of engine systems [168,169].

395 Several works have demonstrated the high DES absorption efficiency of monoaromatic and 396 aliphatic hydrocarbons from biogas and exhaust gas. In most published works, researchers have 397 focused on removing only toluene as a representative of the monoaromatic hydrocarbons. In these 398 studies, the authors determined vapor-liquid partition coefficients (K) using the static headspace 399 technique to evaluate the effectiveness of the new DES [147,170,171]. According to the definition, K 400 is a parameter that describes the tendency of VOCs to distribute between two phases, liquid, and 401 gas, at equilibrium. It can be calculated as the ratio of the VOCs concentration in the vapor phase in 402 equilibrium to the VOCs concentration in the liquid DES in the equilibrium state [172,173]. In 403 practice, the Headspace procedure involves placing 0.5 - 2 ml of DES in a 20 ml vial and adding a 404 small amount of carefully weighed VOCs. The vial is then sealed with a cap with a membrane and 405 shaken at the specified temperature. After 24 hours, the headspace is drawn and injected into a gas 406 chromatograph. The smaller peaks obtained on the chromatogram indicate lower concentrations of 407 VOCs in the gas phase and their potentially better absorption in DES. In one of the first studies, 408 Moura et al. tested several popular ionic eutectic mixtures based on quaternary ammonium and 409 phosphonium salts such as ChCl:U (1:2), ChCl:EG (1:2), ChCl:Gly (1:2), ChCl:Lev (1:2), TBPB:Gly (1:1), TBPB:Lev (1:6), and TBAB:DA (1:2). They found that the higher ability to absorb volatile 410 411 monoaromatic hydrocarbons has DES, consisting of tetrabutylammonium bromide and decanoic acid 412 in a 1:2 molar ratio. The K value of toluene in DES was similar to other common solvents, i.e., ionic 413 liquids or silicone oil (K=0.001) and 251-fold at 30 °C and 654-fold lower at 60 °C than water 414 [147,170,171]. In addition, they observed that there is no difference in vapor-liquid partition 415 coefficients at different temperatures. This can be an advantage due to the instability of process 416 gases' temperature. Thus, the lack of difference in absorption capacity may benefit the economics of 417 the process, as it may prevent additional energy expenses used to control the temperature of the gas 418 stream before the purification process [147]. Similar results were obtained by Moufawad et al. They 419 determined vapor-liquid partition coefficients for toluene, n-heptane, and 1-decene in the same ionic 420 DES. This work confirmed that the highest affinity for both monoaromatic and aliphatic hydrocarbons 421 has TBAB:DA (1:2) [148]. The K value for toluene in TBAB:DA (1:2) was comparable to common 422 organic solvents and silicone oils [174,175]. The experimental toluene absorption results were in line 423 with theoretical studies determined using the conductor-like screening model segment activity 424 coefficient (COSMO-SAC). Calculation studies indicated that as the length of the alkyl chain in the salt 425 increases, the absorption capacity of DES increases [150]. In addition, the significant effect of alkyl 426 chain length in carboxylic acids (HBD) on absorption efficiency was shown. The K-value results 427 indicated the same trend as for the HBA component of DES. The longer the alkyl chain of the acid, 428 the better hydrocarbon solubility in DES. The same conclusions were obtained in another 429 experimental study [137]. The lowest value of the vapor-liquid partition coefficient was obtained for 430 1-decene. The K value was, 60000-fold lower than water. The aliphatic hydrocarbons such as n-431 heptane and 1-decene indicate a similar affinity profile as monoaromatic hydrocarbons for the 432 studied ionic DES. As the authors observed, the absorption capacity of aliphatic hydrocarbons in DES 433 decreases as the number of hydroxyl groups in HBD increases. However, the authors did not explain 434 the reason for this phenomenon [148]. In a study of the removal of styrene from the gas, the authors 435 observed that the crucial parameter determining solubility, and thus absorption capacity, is the 436 general principle of chemistry. This indicates that polar substances dissolve more easily in polar 437 solvents and vice versa. The DES absorption capacity of styrene was ranked as follows: TBABr:DA 438 (1:2) >> TBPBr:Lev (1:6) > ChCl:Xyl:H₂O (2:1:3) > ChCl:PCH:H₂O (1:1:1) > ChCl:Urea (1:2) > 439 ChCl:Glu:H₂O (5:2:5) [134]. Significantly lower values of partition coefficients of toluene were 440 obtained for DES containing cyclodextrins (CD) in their composition. The K values were 0.003, 0.002, 441 0.002, and 0.001 for Captisol:Lev (1:44), CRYSMEB:Lev (1:25), HP-β-CD:Lev (1:32), and RAMEB:Lev 442 (1:27), respectively. The authors demonstrated the affinity DES to toluene is due to the formation of 443 the CD/toluene complex during the absorption process [176–178]. In another paper, the authors 444 proved by 1D ¹H and ROESY spectra with diffusion and relaxation NMR experiments that the water 445 addition to SUPRADES can improve the inclusion of toluene [179]. However, there is a lack of 446 experimental studies to confirm this theory. The results are similar to those obtained for non-ionic 447 DES composed of guaiacol, camphor, and levulinic acid in a 1:1:3 molar ratio [132]. In this system, the 448 driving force of the toluene removal process is most likely π - π and electrostatic interactions. Also, Chen et al. showed high efficiency in removing low concentrations of BTEX from the gas phase with 449 450 non-ionic DES. The lowest value of Henry's constant was obtained for DDA: DA (1:3). This 451 corresponds with the equilibrium capacity of BTEX absorption equal to 9.94 mg/g at an inlet 452 concentration of 800 ppm v/v [137]. On the other hand, based on COSMO-RS modeling, among 39 453 new absorbents, DES composed of monoterpenes and carboxylic acids such as C:OA (1:1), C:DA (1:1), 454 Car:OA (1:1), Car:NA (1:1), Car:DA (1:1), Car:Lev (1:1), and Eu:OA (1:1) was shown to have the highest 455 affinity for BTEX. The authors suggested that the coexistence of two types of interactions between 456 DES and monoaromatic hydrocarbons (π - π and van der Waals interactions) cause this phenomenon 457 [61]. The structure of monoaromatic hydrocarbons also affects absorption efficiency. The study 458 showed that the absorption capacity of all DES increases in the following order, benzene < toluene < 459 xylene < ethylbenzene. This indicates that the alkyl groups form stronger non-covalent bonds with 460 DES compared to π - π interactions [180]. All obtained data suggest that non-ionic DES or SUPRADES can be better media for volatile hydrocarbon removal from the gas phase. The lowest affinity of 461 462 hydrocarbons for ionic DES is due to the presence in DES of a strong non-bonded interaction between cation and anion, which is stronger than the electrostatic interactions formed betweenabsorbents and hydrocarbons [181].

465 To fully assess the suitability of DES as absorbents for removing VOCs from gaseous streams, it is 466 necessary to consider both the affinity of DES to pollutants and other absorption process 467 parameters. For this purpose, it is essential to conduct research in a dynamic system, which is a 468 miniaturized version of industrial installations. In such studies, the effects of gas mixture 469 composition, temperature, water addition to DES, gas flow, and pressure on absorption efficiency are 470 commonly investigated. In addition, it is possible to determine the absorption capacity of individual 471 DES [182–184]. So far, several papers have presented the results of BTEX removal using DES in a 472 dynamic system [61,155,185]. All the papers reached similar conclusions about the effect of process 473 parameters on the efficiency of hydrocarbon capture from gas mixtures. The authors showed that 474 the absorption capacity of hydrocarbons gradually decreases with the increase of the DES 475 temperature. This is in line with typical absorbents' behavior (ILs, glycols, and oils) due to the 476 exothermic character of the physical absorption process [183]. Theoretically, an increase in DES 477 temperature decreases viscosity, which can positively affect mass transfer between phases. 478 However, this can't counterbalance the decrease in affinity between hydrocarbons and DES. 479 Therefore, in all works, it was shown that the optimal temperature for the absorption of hydrocarbons was between 10 and 30 °C [25,61,72,132,134,137,147,148,153,155,186-188]. The 480 481 water addition to DES is advantageous from an industrial point of view because it reduces the cost of 482 the absorbents. However, published work has shown a decrease in the absorption capacity of both 483 linear and aromatic hydrocarbons. This is due to their limited solubility in water. In addition, too 484 much water in DES structures breaks the hydrogen bonds between HBA and HBD [189,190]. From an 485 industrial point of view, the gas flow rate should be relatively high to purify a significant amount of 486 gas within a short period. However, too high a flow rate of contaminated gas reduces the absorption 487 efficiency of DES. This is because as the contaminated gas flow rate increase, the contact time of the 488 gas phase with liquid DES decreases [191]. Another crucial physical absorption parameter is the 489 composition of inlet gas. Most research has focused only on the VOCs removal from an inert gas (N_2) . 490 This method only enables the study of interactions between specific contaminants and DES. Nitrogen 491 as an inert gas should not affect the efficiency of absorption. Therefore, it is possible to identify in 492 detail the types and strengths of interactions between DES and hydrocarbons. However, industrial 493 gases, fuels, air, or waste gases contain a wide range of organic and inorganic contaminants. The 494 presence of other impurities can negatively affect the process of hydrocarbon absorption by blocking 495 active groups to which hydrocarbons can potentially attach [61]. However, in some cases, there may 496 be a temporary improvement in the absorption capacity of DES due to incorporating other impurities 497 into DES structures that contain active groups capable of attaching hydrocarbons. Such a 498 phenomenon was observed during biogas purification. Absorbed carbon dioxide created additional 499 active sites that formed hydrogen bonds with -CH···O= hydrocarbons. However, due to the relatively 500 high CO₂ content of the biogas, which causes rapid supersaturation of DES, enhancement of 501 absorption efficiency is observed only for a short period. Then a rapid decrease in process efficiency 502 is observed [61]. Therefore, before using DES in the biogas treatment process, carbon dioxide should be preliminarily removed by other methods [192,193]. The concentration of the absorbed substance 503 504 is also a crucial parameter. Most of the presented works concern the removal of volatile 505 hydrocarbons at low concentrations from the gas phase. Xu et al. proved the utility of DES in the 506 separation of gaseous hydrocarbons, i.e., C_2H_4/C_2H_6 . Due to the similar boiling points of ethane and 507 ethylene, the use of the traditional method of distillation is inefficient and energy-consuming. The authors in the study demonstrated that by selecting the proper molar ratio of TBACI: DA, it is possible to tune the selective solubility of hydrocarbons in DES. They also indicated significantly higher solubility of C_2H_4 in DES than in ionic liquids [145].

Among the DES tested to date, the highest absorption efficiency for monoaromatic hydrocarbons 511 512 was observed for ionic DES composed of guaternary ammonium salts and phenol. The solubility of 513 toluene in DES ranged from 227 to 304 mg/g. The dominant role in the absorption efficiency 514 belonged to phenol (HBD), as well as the benzyl group in HBA that formed π - π , O-H \cdots π , 515 π ···H···Cl⁻ and C-H··· π interactions with toluene. The results showed that DES that contained more 516 phenol molecules in the structure better-absorbed toluene from the gas. The absorption efficiency 517 for TEBAC:Ph (1:3) was significantly higher than that of the ionic liquid [EMIM][Tf2N] (223 mg/g) and 518 TEG (163 mg/g) under the same process conditions [25]. Slightly lower efficiencies were found for 519 TEBACI:LA (1:2), TEBACI:LA (1:2), and non-ionic DES in the form of E:OA (1:1). Absorption capacities 520 were 218, 78, and 56 mg/g for toluene and sum of BTEX, respectively [61]. For other DES, the 521 efficiency values ranged from 0.23 to 4.04 mg/g. Absorption efficiencies for the rest group of 522 hydrocarbons were much lower. The highest absorption capacities for cyclohexane (0.058 mg/g), 523 ethylene (0.066 mol/kg), ethane (0.074 mol/kg), n-hexane (0.75 mg/g), n-heptane (2.37 mg/g), 1decene (0. 51 mg/g), and limonene (2.6 mg/g) were observed for ChCl:U (1:1), TBACI:DA (1:1.5), 524 525 TBACI:DA (1:3), Th:DA (1:1), TBABr:DA (1:2), TBABr:DA (1:2), and NA:DDA (3:1), respectively 526 [25,145,147,148,155]. However, a solid comparison of DES is difficult due to the different conditions 527 of the dynamic absorption process and different methods of evaluating DES effectiveness. In 528 published works, absorption efficiency factors are expressed as Henry's constants, activity 529 coefficients, or solubility of hydrocarbons in DES.

All the described studies were performed on a laboratory scale. Only one paper has presented results obtained on an enlarged 20-fold scale. The authors showed that it is possible to scale up the process and receive similar absorption efficiencies to the laboratory process. [61]. However, industrial or semipreparative scale tests are needed to prove the applicability of DES. In addition, no tests have been reported on real waste gas streams or gaseous fuels. All tests that have been performed have been on model streams.

2.2. Volatile organosulfur compounds

Volatile organosulfur compounds (VOSCs) are common contaminants in the off-gases of oil refineries, pulp mills, manure and sewer systems, rayon production, and wastewater treatment plants [194–196]. In addition, these compounds can be found in landfill, natural and petroleum gas, and biogas produced from agri-food waste [191,197,198]. Their concentrations strictly depend on the biogas production process. They can vary from a few ppb levels in agricultural emissions to ppm levels in industrial gases [199]. The VOSCs group includes thiols, sulfides, disulfides, and thiophenes. They are characterized by unpleasant smells, even at low concentrations. Typically, the odor threshold values of VOSCs are between 0.07 and 5.9 ppb (v/v). At higher concentration levels (0.5 to 20 ppm, v/v), some VOSCs compounds can evoke human health problems such as eye irritation, dizziness, vomiting, and headaches [200–202].

536

537

538

539

540

541 542

543

544 545

546

547

- 551
- 552

555

553

In addition, VOSCs can cause many technological problems due to their corrosive and reactive activity. For example, during biogas or natural gas combustion, VOSCs can be converted into SOx. In the next stage, SOx can react with water or oxygen and form highly corrosive H₂SO₄. As a 554 result, corrosion of installation equipment, including combustion chamber components, occurs [191]. Therefore, the absorption of VOSCs from industrial or waste gas streams is crucial [191].

556 A comparison of three DES composed of choline chloride as HBA and three different HBDs 557 such as phenol (Ph), ethylene glycol (EG), and levulinic acid in a molar ratio of 1:2 showed that it is 558 possible to efficiently capture dimethyldisulfide (DMDS) from a model biogas stream. The authors 559 observed that as the viscosity of DES increased, the absorption efficiency of DMDS decreased. This 560 was due to the hindrance of the mass transfer process. Investigations of the integration mechanisms 561 between DES and DMDS revealed the absence of strong bonds between the sulfur atom and the 562 active groups of DES, including S-H··· π , O-H···S and C-H···S. Density functional analysis (DFT) indicated 563 that weaker van der Waals interactions were the main driving force for DMDS absorption. The calculated theoretical DES-DMDS interaction energy showed the same trend as the experimental 564 565 study ChCl:Ph (1:2) > ChCl:EG (1:2) > ChCl:Lev (1:2) [191]. Other process parameters, such as 566 temperature, the flow rate of contaminated gas, initial concentration of contaminants, or pressure, 567 also affect absorption efficiency. The study showed typical correlations of the absorption process. It 568 has been proven that as the temperature increases, the process efficiency decreases. This is due to 569 the decrease in the solubility of DMDS in DES because the absorption processes are exothermic. The 570 increase in gas flow rate reduces absorption efficiency, which is caused by too short contact between 571 the impurities and the absorbent. In addition, increasing the volume of DES improves absorption due 572 to the prolongation of contact time between the gas and liquid phases, which increases the 573 supersaturation time [21,191,203–205]. Theoretically, the increase of DMDS concentration in inlet 574 gas should result in a linear decrease in the partition coefficients and an increase in the amount of 575 VOCs soluble in DES. However, no changes were observed in the study, which was most likely due to 576 the saturation of DES and reaching the solubility limit of DMDS in the absorbent [148,191]. Another 577 paper also demonstrated the possibility of absorbing DMDS from a model biogas mixture (75% v/v 578 CH_4 and 25% v/v CO_2) using two DES. The authors showed that higher absorption efficiency was 579 obtained with non-ionic DES (C:Gu 1:1) than with ionic ChCl:U (1:1). However, the authors did not 580 explain why such results were obtained, and other parameters affecting DMDS uptake were not 581 studied [187]. Panda et al. investigated the possibility of using supramolecular low-melting eutectic 582 mixtures for thiophene absorption through the static headspace technique. Based on the K-factor 583 results, they showed that DES have about 30 times better thiophene absorption capacity than water, 584 and twice better compared to conventional non-cyclodextrin DES i.e., ChCl:Lev (1:2). The vapor-liquid 585 partition coefficient was 0.139, 0.009, 0.006, 0.005, 0.006, 0.009 for water Captisol:Lev (1:44), 586 CRYSMEB:Lev (1:25), HP-β-CD:Lev (1:32), RAMEB:Lev (1:27), ChCl:Lev (1:2), respectively. However, 587 the authors did not explain what mechanisms determine the high uptake of thiophene. The paper also does not present studies in a dynamic system [177]. 588

2.2. Volatile methyl siloxanes

Volatile methyl siloxanes (VMS) named siloxanes are commonly used in personal care products, household cleaning, and many branches of industries as solvents or lubricants. Therefore, VMS can easily migrate into the atmosphere [206]. The group of volatile siloxanes that are most commonly identified in air gaseous fuels and include cyclic VMS such as

589 590

591

592 593

595 hexamethylcyclopentasiloxane (D3), octamethylcyclotetrasiloxane (D4), decamethylcyclopentasiloxane (D5), dodecamethylcyclohexasiloxane (D6), and aliphatic siloxanes 596 597 including hexamethyldisiloxane (L2), octamethyltrisiloxane (L3), decamethyltetrasiloxane (L4) and 598 dodecamethylpentasiloxane (L5). The impact on human health and the environment is currently 599 quite controversial. Some studies show the possibility of VMS bioaccumulation in biota, endocrine-600 disrupting effects of D4, and immunosuppressant and carcinogenic effects of D5. While other studies 601 prove the absence of negative impact on the environment and organisms [207–209]. The presence 602 of VMS in biogas has unfavorable effects on combustion equipment components. The combustion of 603 VMS-rich biogas in burners results in the formation of solid silicon dioxide (SiO₂) particles. SiO₂ can 604 deposit on turbine blades and heat exchangers, shortening their lifespan and increasing plant 605 maintenance costs, reducing energy efficiency, and causing numerous malfunctions. [210,211].

606 In one of the published papers, the authors performed calculations of the ability of selected 607 ionic DES to absorb 200 ppm v/v of VMS (L2, L3, and D4) from a model biogas mixture composed of 608 CH₄:CO₂:H₂S (68:31:1 % v/v). The authors divided the studied DES into three groups. The first group 609 included absorbents that effectively captured all impurities, including CO₂ siloxanes and H2S. The 610 second group consisted of DES that selectively captured only siloxanes, while the third group 611 included other DES that showed no absorption efficiency for any pollutants. ChCl: U (1:2) and ChCl: OA (1:2) were selected as the most effective DES. The study proved that the type of HBA has the 612 613 main effect on the efficiency of contaminant capture. The application of DES that contains ChCl is 614 favorable due to lower viscosity than DES composed of QAS and QPS with long alkyl chain lengths. 615 [68,131]. However, the paper did not include an experimental study. All conclusions were based on 616 theoretical studies using the COSMO-RS model. The COSMO-RS is a fully predictive model because no 617 experimental data, functional group parameters, or system-specific adjustments are needed to 618 predict thermodynamic properties and the calculation of interactions between molecules. This is an 619 advantage of the model, but it can also affect the lower accuracy compared to locally adapted 620 methods. [212]. Authors carried out more reliable experimental studies of VMS uptake for glycols 621 such as ethylene glycol (EG), glycerol (Gly), triethylene glycol (TriEG), tetraethylene glycol (TEG), 622 diethylene glycol (DEG), and DES composed of glycols and QAS. From an economic point of view, 623 pure glycols application is preferable due to the relatively high price of QAS. However, as the authors observed, the solubility of VMS in DES is much higher than in glycols. In addition, VMS capture 624 625 efficiency decreases as the glycol content of the DES structure increases. The addition of TPABr 626 lowers the polarity of the DES molecule, which increasingly adopts a similar character to pure VMS. 627 Among the DES tested, TPABr:TEG (1:3) had the highest solubility due to the content of more -O-628 active groups in the glycol structure, which can form weak hydrogen bonds with -CH₃ groups in VMS 629 structures. [149]. Nevertheless, a comparison of ionic and non-ionic DES showed higher efficiency of 630 VMS capture by eutectic complexes composed of non-ionic components [132]. In another work, 631 authors tested 90 non-ionic hydrophobic DES composed of terpenes, carboxylic acids, and 632 polyphenols as potential green absorbents for L2, L3, L4, D3, and D5 removal from model biogas, 633 using COSMO-RS model. The authors compared the logarithmic activity coefficients of individual 634 siloxanes in DES. The eutectic complexes composed of carvone and carboxylic acids, i.e., DA, UDA, and DDA in a 1:1 molar ratio, showed the highest affinity for VMS. This is due to the simple structure 635 636 of DES components. Carvone has one carbonyl group, which acts as a hydrogen bond acceptor, while DA, UDA, and DDA contain a carboxyl group, which is a hydrogen bond donor. The absence of active 637 638 groups, i.e., =0, -0-CH₃, $-CH_3$, increases the access of the oxygen atom from the Si-O-Si to the 639 carboxyl group to which it could attach. On the other hand, the presence of these groups reduces the strength of interactions between siloxanes and DES and reduces their solubility in DES. The paper demonstrated that cyclic siloxanes absorb significantly better in DES than linear siloxanes. This is due to the higher number of Si-O bonds, which tend to form stronger bonds between siloxanes and DES. The lowest absorption efficiency was observed for L2. The lowest absorption efficiency was observed for L2 because of its high vapor pressure, and polarity. An additional advantage of Car:DA (1:1) is the low solubility of methane. Methane was captured below 1% by DES. This value is within the acceptable range [152].

647 **2.4. Oxygenated volatile organic compounds**

648 Oxygenated volatile organic compounds (O-VOCs) are a specific group of VOCs that contain 649 at least one atom of oxygen, i.e., aldehydes, ketones, alcohols, phenols, esters, ethers, and carboxylic 650 acids. They are characterized by relatively high toxicity and vapor pressure, mutagenic, and 651 malodorous properties. In addition, they are highly reactive. O-VOCs play an active role in 652 tropospheric ozone formation [7,213–215]. The source of O-VOCs in the environment is primarily 653 industrial installations due to the widespread use of solvents in paints [216,217], pharmaceuticals 654 [218], polymer processing, and the refinery industry [219]. They can harm the human respiratory 655 system, skin, and eyes. Therefore, it is crucial to eliminate O-VOCs emissions from various industrial 656 sources.

657 Due to the presence of active groups in O-VOC, such as -OH, =O, -O-, -COOH, they can be 658 absorbed by DES with high efficiency. During the absorption, active O-VOCs groups can form strong 659 hydrogen bonds with DES components. However, there are only a few reports in the literature on the 660 removal of O-VOCs from gas streams by absorption using DES. The authors mainly focused on 661 determining the vapor-liquid partition coefficients of O-VOCs between DES and the gas phase. In one 662 work, a preliminary preselection based on the determined K values showed that non-ionic DES could slightly better capture propionaldehyde compared to ionic DES, i.e., ChCl:U (1:2), ChCl:Lev (1:2); 663 664 ChCl:DEG (1:2). The results were comparable to conventional absorbents based on n-hexadecane. On 665 the other hand, the results demonstrated that water is characterized by the higher absorption 666 efficiency of O-VOCs than most DES [132]. Similar results were obtained for SUPRADES. The authors 667 in their study showed that there is no significant difference in the absorption efficiency of 668 acetaldehyde and butanone between different SUPRADES and water. The high polarity of O-VOCs 669 hinders their incorporation into the hydrophobic cavity of the CD molecule in the SUPRADES 670 structure [177]. Methyl ethyl ketone (MEK) also shows a higher affinity for water than ionic DES. On 671 the other hand, the authors obtained lower K values of acetaldehyde in ionic DES (i.e., ChCl: U, 672 ChCl:EG, ChCl:G, ChCl:Lev, TBPBr:EG, TBPBr:G, TBPBr:Lev, and TBABr:DA) compared to water, which 673 contradicts the previous studies [132,185]. Indra et al. compared the acetaldehyde uptake potential 674 of two popular DES (ChCl:U (1:2) and ChCl:Lev (1:2)) using the molecular dynamics (MD) simulation 675 analysis. The authors demonstrated that acetaldehyde absorbs better in ChCl:U (1:2). This is due to 676 the occurrence of non-polar interactions at the liquid-vapor interface, which increases the absorption 677 of acetaldehyde. The authors obtained similar results of partition coefficients to those obtained by 678 the experimental method [147,220]. In addition, they showed that DES has a twofold higher 679 absorption capacity compared to ionic liquid in the form of [BMIM]PF6 [221].

Chen et al. researched acetone removal using hydrophobic and hydrophilic DES. Acetone is hydrophilic due to its high polarity (2.88 D). Therefore, it should dissolve better in hydrophilic DES [222]. However, hydrophobic DES composed of Th and DA (1:1) showed a higher absorption capacity

680

681

than hydrophilic ChCl:Res (1:2). The absorption capacities were 2.66 and 0.76 mg/g for hydrophobic and hydrophilic DES, respectively. The results indicate that the polar nature of DES does not guarantee the high absorption efficiency of polar VOCs. The efficiency is more affected by the low viscosity and the presence of specific active groups in the DES structures capable of H-bonding formation [153].

688 689

2.6. Volatile organochlorine compounds

690 Volatile organochlorine compounds (VOX) are commonly present in waste gas streams from 691 paint manufacturing, plastic manufacturing, foam, and electronic industries [223-225]. In addition, 692 they can be identified in landfill gas or biogas produced from sewage sludge [226]. Some of these 693 compounds have been recognized by the United States Environmental Protection Agency (US EPA) 694 and the European Environment Agency (EEA) as extremely hazardous gaseous pollutants that 695 adversely affect both human health and the environment [227]. Uncontrolled emissions of VOX to 696 the atmosphere can cause the formation of photochemical smog and global warming. Exposure of 697 humans to organochlorine substances can cause irritation symptoms, cancer, allergies, asthma, and 698 neurological and liver toxicity. These compounds are also technologically disadvantageous due to 699 their highly corrosive properties, which can shorten the lifespan of many industrial installation 700 components. [228].

701 Most scientific papers describe the removal of only dichloromethane (DCM) from the gas 702 phase. Moura et al. observed that from seven ionic DES, the TBABr:DA and TBPBr:Lev were the most 703 effective absorbents for DCM removal. The absorption capacity was 28- and 23-fold higher than 704 water at 30 °C [147]. However, the paper does not explain which interactions contributed to the 705 selection of mentioned DES. In another study, the same DES were applied to the absorption of DCM. 706 The authors confirmed that DES, composed of alkylphosphonium or alkylammonium salts with long 707 alkyl chains, promotes the removal of DCM from the gas phase. This is because the longer alkyl 708 chains in HBA affect the increasing hydrophobic nature of DES [148]. Similar conclusions were 709 obtained for other absorbents, i.e., silicone oil or ionic liquids [174,229,230]. Mu et al. explained that 710 this is due to the steric hindrance in DES structures. This hindrance increases the distance between 711 the anion and the cation. The authors also showed that DES composed of non-cyclic cation HBAs 712 (QAS and QPS) have a higher absorption capacity than cyclic HBAs (i.e., pyridinium and imidazolium-713 based) due to the low polarity of non-cyclic cations. Among the 28 DES examined, TBPCI:Lev (1:2) 714 showed the highest DCM absorption capacity (899 mg/g) comparable to traditional organic solvents. 715 This is due to the formation of relatively strong non-covalent interactions between DCM and Lev (C-716 H…O) [146]. Another group of scientists tested four SUPRADES as green absorbents for DCM removal 717 from the gas phase. The absorption capacities ranged from 0.274 to 0.3 mg/g. This indicates that the 718 type of cyclodextrin has only a minor effect on the absorption capacity of DCM [177].

However, due to the strong influence of CD type on the physicochemical properties of SUPRADES, they can play a crucial role in dynamic absorption processes. However, no such studies have been performed to date. Inferior DCM partition coefficient results were obtained for G:C:Lev (1:1:3) compared to SUPRADES and ionic DES. The lower absorption capacity of G:C:Lev (1:1:3) may be due to the competitiveness of interactions formed with toluene, propionaldehyde, or hexamethyldisiloxane [132]. In other studies, experiments were conducted on a single impurity removal from an inert gas (nitrogen). Only one paper has described research on the application of DES to the dynamic absorption of other VOX substances such as 1,1,2,2-tetrachloroethane (TCE),

719

720

721

722

723

724

725

727 2,2,2-trichloroethanol (TCEtOH), chloroform (CF), and carbon tetrachloride (TCM) from model gaseous fuels. In these studies, the authors tested four DES such as Syr : Lev (1:1), C: Gu (1:1), C: Lev 728 729 (1:2), and Gu: Lev (1:1). They showed that the highest absorption capacity was found in Syr:Lev (1:1) 730 due to the formation of van der Waals interactions between DES and most VOX. Only between DES 731 and TCEtOH authors identified the coexistence of van der Waals interactions and hydrogen bonds between the hydroxyl groups of Syr, Lev, and TCEtOH (OH···HO). The bond lengths were 1.79 and 1.8 732 733 Å, respectively. The ability to form relatively strong non-covalent interactions is the reason for the 734 high absorption capacity of DES, which was 420 ± 22 , 360 ± 16 , 304 ± 11 , 292 ± 8 , and 661 ± 34 mg g-735 1 for DCM, CF, TCM, TCE, and TCEtOH, respectively. These values are 100 times higher than for ILs 736 and ionic DES composed of quaternary ammonium salts (i.e., ChCl, TBABr, or TPABr) [147,231]. Only 737 for the metal-organic framework (UiO-66) was it possible to achieve a higher absorption capacity [232]. However, as the authors observed, the price of UiO-66 was about 300 times higher than DES. 738 739 On the other hand, such a high price makes it impossible to use the sorption medium in industrial 740 processes. The effect of the rest of the parameters on absorption efficiency was similar to the other 741 VOCs groups [226].

742 **2.7. Volatile fluorinated gases**

Volatile fluorinated gases (VFG) such as sulfur hexafluoride, perfluorocarbons, and hydrofluorocarbons are dangerous greenhouse gaseous. They are mainly used in refrigeration and air conditioning. VFGs are responsible for climate change and ozone depletion. The global warming potential (GWP) of VFG is up to 23 000 times higher than that of CO₂. Many countries have introduced legislation to limit VFG emissions into the atmosphere. However, capturing VFG from the air remains a challenge [233–235].

749 Only one study has examined the possibility of using DES to capture VFG from the air. The 750 authors tested a DES composed of fluorinated ionic liquids and perfluorinated acids for 751 difluoromethane (R-32), pentafluoroethane (R-125), and 1,1,1,2-tetrafluoroethane (R-134a) 752 absorption. The authors selected two DES including $[N_{4444}][C_4F_9SO_3]/C_4F_9CO_2H$ and 753 $[C_2C_1Im][C_8F_{17}SO_3]/C_4F_9CO_2H$ as the most efficient absorbents.

The authors observed that the cationic nature of fluorinated ionic liquids has a major effect on the solubility of VFG in DES. On the other hand, the type of anion did not affect the absorption process. In addition, they observed that DES has high selectivity toward R-134a in binary gas mixtures at pressures above 0.2 MPa. Therefore, new absorbents can also be used to recover commercial refrigerants for re-use. However, only one paper has been published so far. Therefore, it is challenging to assess whether other types of DES would be preferable for VFG absorption [157].

760 **Table 2** Summary of studies on VOCs absorption from gas streams using DES.

voc	DES (HBA:HBD molar ratio)	Gas matrix	Absorptio n capacity / solubility [mg/g]	Saturati on time [min]	Vapor– liquid partition coefficients (K)/ Henry's Law Constant*	Absorption process conditions	Desorption process conditions	The absorptio n/ desorptio n cycles	Ref.
					VOLATILE HYD	ROCARBONS			
	Captisol:Lev (1:44)	n.d.	0.282	n.d.	0.003	Static headspace analysis:		5	
	CRYSMEB:Lev (1:25)	n.d.	0.287	n.d.	0.002	Initial concentration: 59 g m ^{-3}		5	[4 7 7]
toluene	HP-β-CD:Lev (1:32)	n.d.	0.285	n.d.	0.002	Temperature: 30°C	Thermal desorption at	5	[1//]
	RAMEB:Lev (1:27)	n.d.	0.287	n.d.	0.001	Time of equilibrium: 24 h	60 C, 48 h	5	
	ChCl: Lev (1:2)	n.d.	0.280	n.d.	0.004	DES volume: n.d.		5	
	ChCl:DEG (1:2)	N ₂	n.d.	> 100	n.d.	Dynamic absorption:	n.d.	n.d.	
	ChCl:U (1:2)	N ₂	n.d.	65	n.d.	Initial concentration: 2000 ppm v/v	n.d.	n.d.	
toluene	ChCl:U:TEG (1:2)	N ₂	n.d.	> 100	n.d.	Temperature: 30°C Flow rate: 25 mL/min Pressure: 10 kPa DES volume: 30 mL	n.d.	n.d.	[186]
	ChCl:U (1:2)	Air	0.275 n.d. n.d.	n.d.	0.25 11 1.2			5	
	ChCl:EG (1:2)	Air	0.26 n.d. n.d.	n.d.	0.096 0.018 0.64	Static headspace analysis: Initial concentration: 59 g m ⁻³	Thermal decorption at	5	
toluene n-heptane	ChCl:Gly (1:2)	Air	0.23 n.d. n.d.	n.d.	0.022 0.018 1,1	Time of equilibrium: 24 h		5	[147,14
n-heptane 1-decene	ChCl:Lev (1:2)	Air	0.55 0.01 n.d.	n.d.	0.054 0.27 0.029	Dynamic absorption: Initial concentration: n-heptane: 885 g/m ³ ; 1-decene: 4720 g/m ³	60°C, 48 h	5	8]
	TBPB:Gly (1:1)	Air	0.28 n.d. n.d.	n.d.	0.005 0.11 0.0011	Pressure: n.d. DES mass: 30 g		5	
	TBPB:Lev (1:6)	Air	1.42 0.1 n.d.	n.d.	0.0013 0.034 0.0015			5	

	TBAB:DA (1:2)	Air	0.32	n.d.	0.0009 0.0033			5	
	G:C:Lev (1:1:3)	N ₂	0.51 n.d.	1800	<0.0004	<u>Static headspace analysis:</u> Initial concentration: 50 ppm v/v		5	
	ChCl:U (1:2)	N ₂	n.d.	n.d.	0.026	Temperature: 25°C Volume of absorbent: 1 mL Time of equilibrium: 48 h		5	
toluene	ChCl:Lev (1:2)	N ₂	n.d.	n.d.	0.035	<u>Dynamic absorption:</u> Initial concentration: 50 ppm y/y	Adsorption with activated carbon	5	[132]
	ChCl:DEG (1:2)	N ₂	n.d.	n.d.	0.076	Temperature: 25°C Flow rate: 50 mL/min Pressure: 10 kPa DES volume: 50 mL		5	
	DDA:DA (1:2)	N ₂	3.54	n.d.	n.d.			5	
	DDA:DA (1:3)	N ₂	4.04	120	0.79 (Pa× m3)/mol	Dynamic absorption:	thermal distillation 80	5	
	DDA:DA (1:4)	N ₂	3.3	120	n.d.	Initial concentration: 400 ppm v/v	∘C in continuously	5	
toluene	Lid:DA (1:2)	N ₂	2.26	45	n.d.	Temperature: 30°C	flowing nitrogen at a	5	[137]
	Th:DA (1:1)	N ₂	2.2	60	n.d.	Flow rate: 150 mL min	flow rate of 90 mL min-	5	
	TBPBr:DA (1:2)	N ₂	0.8	70	n.d.	Pressure: 10 kPa	1 for 3 h	5	
	OA:DA (2:1)	N ₂	0.68	30	n.d.	DES mass: 3 g		5	
	ChCl:Res (1:2)	N ₂	0.51	25	n.d.			5	
	TEACI:Ph (1:2)	N ₂	227	n.d.	n.d.	Dynamic absorption:		10	
	TAACI:Ph(1:2)	N ₂	198	n.d.	n.d.	Initial concentration: 20000 ppm v/v	Vacuum drver:	10	
toluene	TEBACI:LA (1:2)	N ₂	219	n.d.	n.d.	Temperature: 25°C	pressure: 0.05 bar;	10	[0-]
	TEBACI:EG (1:2)	N ₂	78	n.d.	n.d.	Flow rate: 100 mL min ⁻¹	Temperature: 60°C	10	[25]
	TEBACI:Ph (1:2)	N ₂	257	n.d.	n.d.	Pressure: 101.3 kPa	Time 2 h	10	
	TEBACI:Ph (1:3)	N ₂	304	n.d.	n.d.	DES mass: 2 g		10	
	ChCl:Lev (1:2)	n.d.	n.d.	n.d.	0.0045			n.d.	
	ChCl:Lac (1:2)	n.d.	n.d.	n.d.	0.0101	Static headspace analysis:		n.d.	
toluene	Chol-C6-Lev	n.d.	n.d.	n.d.	0.0021	Tomporature: 20 °C	cosc 48 b	n.d.	[72]
	Chol-C8-Lev	n.d.	n.d.	n.d.	0.0016	Mass of absorbant: 2.4 g	60 C, 48 h	n.d.	[/2]
	Chol-C6-Lac	n.d.	n.d.	n.d.	0.0028	Time of equilibrium: 48 h		n.d.	
	Chol-C8-Lac	n.d.	n.d.	n.d.	0.0020			n.d.	
toluono	ChCl:U (1:2)	n.d.	n.d.	n.d.	0.002	Molecular dynamics (MD) simulation	nd	n.d.	[220]
toluene	ChCl:Lev (1:2)	n.d.	n.d.	n.d.	0.002	technique (30°C)	11.u.	n.d.	[220]
benzene	E:OA (1:1)	CH ₄ :CO ₂ :N	Sum of	3118	0.027	Dynamic absorption:	Nitrogen barbotage at	10	[61]

ethylbenzene		2	BTEX: 56	4319	0.018	Initial concentration: 2000 mg/m ³	120°C for 3 h		
toluene		(50%:30%:		5731	0.013	Temperature: 10°C			
xylene		20% v/v)		5859	0.013	Flow rate: 500 mL/min			
						Pressure: 1 atm			
						DES volume: 1L			
				1536	0.035				
	Cam·DA (1·1)	Na	nd	3221	0.024			10	
		142	1.0.	4452	0.02			10	
				4562	0.019				-
				2365	0.034				
	Cam:OA (1:1)	Na	n.d.	3251	0.027			10	
				4571	0.021				
				4579	0.02	Dynamic absorption:			-
				2103	0.038	Initial concentration: 2000 mg/m ³			
	C-one:Lev (1:1)	N ₂	n.d.	3065	0.028	Temperature: 25°C		10	
		_		4498	0.026	Flow rate: 50 mL/min			
benzene				4507	0.025	Pressure: 10 kPa			-
ethylbenzene				3108	0.031	DES volume: 50 mL			
toluene	C-one:OA (1:1)	N ₂	n.d.	3215	0.029	Ctatia haadaaa ay ah wix	Nitrogen barbotage at	10	[61]
xylene				4105	0.021	Static fieldspace analysis:	120 C 101 3 11		
				4007	0.019				-
				1256	0.033	Volume of absorbent: 0.5 ml			
	C-one:NA (1:1)	N ₂	n.d.	4250	0.023	Time of equilibrium: 24 h		10	
				4255	0.022	nine of equilibrium. 24 m			
				1997	0.02				-
				4984	0.026				
	C-one:DA (1:1)	N ₂	n.d.	5845	0.016			10	
				5856	0.015				
				2789	0.027				-
				5898	0.018				
	E:OA (1:1)	N ₂	n.d.	5926	0.013			10	
				5946	0.013				
	ChCl:U (1:2)	n.d.	n.d.	n.d.	0.12			n.d.	
	TBPBr:Lev (1:6)	n.d.	n.d.	n.d.	0.02	Static headspace analysis:		n.d.	
	TBABr:DA (1:2)	n.d.	n.d.	n.d.	0.001	Initial concentration: 0.5 – 5 µL/mL		n.d.	
styrene	ChCl:PCH:H2O (1:1:1)	n.d.	n.d.	n.d.	0.06	Volume of absorbent: 0.5 mL	n.d.	n.d.	[134]
	ChCl:Glu:H2O (5:2:5)	n.d.	n.d.	n.d.	0.13	Time of equilibrium: 72 h		n.d.	

	ChCl:Xyl:H2O (2:1:3)	n.d.	n.d.	n.d.	0.04			n.d.	
	OA:DDA (3:1)	N ₂	n.d.	n.d.	0.00048 0.00012	Static headspace analysis: Initial concentration: 59 mg/g		5	
	NA:DDA (3:1)	N ₂	0.29 - 2.6	n.d.	0.00046 0.00012	Mass of absorbent: 3.5 g	Nitrogen barbotage	5	
toluene limonene	DA:DDA (2:1)	N ₂	0.7	n.d.	0.00051 0.00011	Dynamic absorption:	(flow rate: 40 L/h) at 30°C for 5 h.	5	[155]
	Rameb:Lev (7:3)	N ₂	n.d.	n.d.	0.0018 0.00062	Initial concentration: 59 -531 ppm Flow rate: 15µL/h		5	
	ChCl:Lev (2:1)	N ₂	n.d.	n.d.	0.0042 n.d.	Pressure: 10 kPa Temperature: 30°C DES mass: 20 g		5	
Benzene hexane	Th:DA (1:1)	N ₂	1.98 0.75	n.d.	n.d.	Dynamic absorption: Initial concentration: 1480 ppm v/v Temperature: 30°C Flow rate: 150 mL/min Pressure: 10 kPa DES mass: 3 g	Nitrogen barbotage (flow rate: 150 mL min ⁻¹) at 80°C.	5	[153]
С ₂ Н ₄ С ₂ Н ₆	TBACI:DA (1:3)	$C_2H_4:C_2H_6$	0.0636 mol/kg 0.0741	n.d.	15.7 13.5 100kPa·kg/ mol	<u>Dynamic absorption:</u> Initial concentration: 50:50 %, v/v Temperature: 40°C Flow rate: n.d.		10	
C ₂ H ₄ C ₂ H ₆	TBACI:DA (1:2)	C ₂ H ₄ :C ₂ H ₆	0.0646 mol/kg 0.0719	n.d.	15.5 13.9 100kPa·kg/ mol	Pressure: 1.0 bar DES mass: 2 g		10	[1/15]
C₂H₄ C₂H ₆	TBACI:DA (1:1.5)	C ₂ H ₄ :C ₂ H ₆	0.0661 mol/kg 0.0665	n.d.	15.1 15.0 100kPa·kg/ mol		Depressurizing method (pressure: 0.1 kPa, temperature: 313 K, time 1h.	10	[143]
C₂H₄ C₂H ₆	TBACI:DA (1:1)	C ₂ H ₄ :C ₂ H ₆	0.0632 mol/kg 0.0568	n.d.	15.8 17.6 100kPa·kg/ mol			10	
C₂H₄ C₂H ₆	TBACI:DA (2:1)	C ₂ H ₄ :C ₂ H ₆	0.0651 mol/kg 0.0497	n.d.	15.4 20.1 100kPa·kg/ mol			10	[145]
cyclohexane	ChCl:U (1:2)	CH ₄ :CO ₂	n.d.	n.d.	n.d.	Dynamic absorption:	n.d.	n.d.	[187]

		/75.050/							
		(75:25%				Initial concentration: 16 ppm			
		V/V)				Temperature:			-
	C.C. (1.1)	CH ₄ :CO ₂				Flow rate: 300 cm min			
	C:GU (1:1)	(75:25%	n.a.	n.a.	n.a.	Pressure: n.d.	n.a.	n.a.	
		v/v)			72.6 har (20	DLS Volume. n.d.			
	ChCl:EG (1:1)	N ₂	0.01465	n.d.	72.0 bar (30	Dynamic absorption:		10	
	$Ch(l) \in C(1,2)$	N	0.002820	nd	260.4*	Initial concentration: 400 ppm	Description	10	-
avalah awaya		IN ₂	0.003820	11.U.	200.4	Temperature: 30°C	Regeneration in	10	[100]
cyclonexane		IN ₂	0.00178	n.u.		Flow rate: 15 mi min-1	(0.1 kpc 2 h, 222 2 K)	10	[188]
	ChCl:U (1:1)	N ₂	0.05812	n.a.	14.4	DES volumo: n d	(0.1 KPa 2 fl, 333.2 K)	10	-
	ChCl:U (1:2)	N ₂	0.04682	n.a.	15.0	DES volume. n.u.		10	-
	ChCI:0 (1:3)	N ₂	0.04749		19.3			10	
	Continelyl av (1, 1, 1)			VULA				F	
		n.a.	n.d.	n.a.	0.009	Static headspace analysis:		5	-
	CRYSIVIEB:Lev (1:25)	n.d.	n.a.	n.a.	0.006	Initial concentration: 59 g m	Inermal desorption at	5	[477]
Thiophene	HP-β-CD:Lev (1:32)	n.d.	n.d.	n.d.	0.005	Temperature: 30°C	60°C, 48 h	5	[1//]
	RAMEB:Lev (1:27)	n.d.	n.d.	n.d.	0.006	Time of equilibrium: 24 h		5	
	ChCl: Lev (1:2)	n.d.	n.d.	n.d.	0.009	DES Volume: n.d.		5	
	ChCl:Ph (1:2)	N ₂	n.d.	1050	n.d.	Dynamic absorption:		5	-
	ChCl:Lev (1:2)	N ₂	n.d.	800	n.d.	Initial concentration: 1 mg/Nm ²	Nitrogen barbotage at	5	-
DMDS						Temperature: 25°C	RT for 5 h.		[191]
	ChCl:EG (1:2)	N_2	n.d.	600	n.d.	Flow rate: 50 mL/min		5	
						Pressure: 10 kPa			
						DES VOIUTILE: 50 TIL			
	C·Gu (1·1)		nd	nd	nd	Dynamic absorption:	nd	nd	
	0.00 (1.1)	CH ₄ :CO ₂	ind.	1	, indi	Tomporature: PT		ind.	
DMDS		(75:25%				Flow rate: $300 \text{ cm}^3 \text{ min}^{-1}$			[187]
	ChCl:U (1:2)	v/v)	n.d.	n.d.	n.d.	Pressure: n d	n.d.	n.d.	
						DES volume: n.d.			
				Volat	ile organochlo	prine compounds			1
	ChCl:U (1:2)	Air	0.2	n.d.	0.055	•		5	
	ChCl:EG (1:2)	Air	0.26	n.d.	0.034	Static headspace analysis:		5	
	ChCl:Gly (1:2)	Air	0.24	n.d.	0.037	Initial concentration: 59 g m ^{-3}		5	[147][14
DCM	ChCl:Lev (1:2)	Air	0.27	n.d.	0.008	Temperature: 30°C	Thermal desorption at	5	8]
	TBPB:Gly (1:1)	Air	0.28	n.d.	0.0053	Time of equilibrium: 24 h	60°C, 48 h	5	1
	TBPB:Lev (1:6)	Air	0.29	n.d.	0.006	·		5	1
	TBAB:DA (1:2)	Air	0.3	n.d.	0.005			5	1
DCM	Captisol:Lev (1:44)	n.d.	0.27	n.d.	0.013	Static headspace analysis:	Thermal desorption at	5	[177]
	,		1	1		· · · · · · · · · · · · · · · · · · ·		1	

	CRYSMEB:Lev (1:25)	n.d.	0.275	n.d.	0.010	Initial concentration: 59 g m ^{-3}	60°C, 48 h	5	
	HP-β-CD:Lev (1:32)	n.d.	0.275	n.d.	0.010	Temperature: 30°C		5	-
	RAMEB:Lev (1:27)	n.d.	0.279	n.d.	0.009	Time of equilibrium: 24 h		5	1
	ChCl: Lev (1:2)	n.d.	0.274	n.d.	0.011	DES volume: n.d.		5	-
	TBPCI:Lev (1:2)	N ₂	899 mg/g (5.58 mol/mol)	40	n.d.			10	
	TBPCI:Lev (1:1)	N ₂	988 mg/g	n.d.	n.d.	Dynamic absorption:		10	1
	TBPCI:Lev (1:3)	N ₂	860 mg/g	n.d.	n.d.	initial DCM partial pressure 5.53 kPa	Heating under vacuum	10	1
DCM	TBPCI:Lev (1:4)	N ₂	843 mg/g	n.d.	n.d.	Temperature: 30°C	at 100 °C and 0.5 kPa	10	[146]
	TEACI:Lev (1:2)	N ₂	800	n.d.	n.d.	Flow rate: 100 mL/min	for 8 h.	10	
	TEACI:Ph (1:2)	N ₂	541	n.d.	n.d.	DES mass: 2g		10	-
	TEACI:EG (1:2)	N ₂	498	n.d.	n.d.			10	-
	BPYCI:Lev (1:2)	N ₂	758	n.d.	n.d.			10	
	TBACI:Lev (1:2)	N ₂	867	n.d.	n.d.			10	-
	G:C:Lev (1:1:3)	N ₂	n.d.	1000	0.057	Static headspace analysis: Initial concentration: 50 ppm v/v Temperature: 25°C		5	
DCM	ChCl:U (1:2)	N ₂	n.d.	n.d.	0.052	Volume of absorbent: 1 mL Time of equilibrium: 48 h	Adsorption with	5	[132]
	ChCl:Lev (1:2)	N ₂	n.d.	n.d.	0.075	Initial concentration: 50 ppm v/v Temperature: 25°C Elow rate: 50 ml /min	activated carbon	5	
	ChCl:DEG (1:2)	N ₂	n.d.	n.d.	0.038	Pressure: 10 kPa DES volume: 50 mL		5	-
	ChCl:Lev (1:2)	n.d.	n.d.	n.d.	0.0105	Chatia haa dagaa ay ah siya		n.d.	
	ChCl:Lac (1:2)	n.d.	n.d.	n.d.	0.0211	Static neadspace analysis:	The survey of the second time of	n.d.	
DOM	Chol-C6-Lev	n.d.	n.d.	n.d.	0.009	Initial concentration: 3000 g/m3	I nermal desorption at	n.d.	[70]
DCIVI	Chol-C8-Lev	n.d.	n.d.	n.d.	0.0071	Mass of absorbant: 2.4 g	60 C, 48 N	n.d.	[/2]
	Chol-C6-Lac	n.d.	n.d.	n.d.	0.0141	Time of equilibrium: 48 b		n.d.	
	Chol-C8-Lac	n.d.	n.d.	n.d.	0.0105	Time of equilibrium. 46 fr		n.d.	
DCM		CH ₄ :CO ₂ :H	304	800		Dynamic absorption:			
CF		₂ O:N ₂	420	700		Initial concentration: 0.5 mg cm $^{-3}$	Nitrogen barbotage		
тсм	Syr:Lev (1:1)	(58:38:2:2	360	450	n.d.	Temperature: 25°C	(flow rate: 70 mL min ^{-1})	10	[74]
TCE		% v/v)	292	580		Flow rate: 50 mL/min	at 100°C for 1 h.		[[/]]
TCEtOH			661	1200		Pressure: 10 kPa			
	C:Gu (1:1)	CH ₄ :CO ₂ :H	215	500	n.d.	DES volume: 50 mL		10	

	C:Lev (1:2)	20:N2 (58:38:2:2 % v/v) CH ₄ :CO ₂ :H 20:N2 (58:38:2:2 % v/v) CH ₄ :CO ₂ :H	561.5 320 262.4 275.3 181 401.5 143.5 248 198.15 130.7	620 400 600 1200 275 220 225 280 650 200	n.d.			10	
	Gu:Lev (1:1)	20:N2 (58:38:2:2 % v/v)	399.5 115.8 154 161.2	250 250 350 800	n.d.			10	
			OX	YGENATED	VOLATILE ORGA	ANIC COMPOUNDS (O-VOCS)			
	Captisol:Lev (1:44)	n.d.	0.275 0.281	n.d.	0.007 0.005			5	
	CRYSMEB:Lev (1:25)	n.d.	0.282 0.285	n.d.	0.005 0.003	Static headspace analysis:		5	
butanone	HP-β-CD:Lev (1:32)	n.d.	0.278 0.282	n.d.	0.006 0.004	Temperature: 30°C	60°C, 48 h	5	[177]
	RAMEB:Lev (1:27)	n.d.	0.278 0.283	n.d.	0.007 0.005	DES volume: n.d.		5	
	ChCl: Lev (1:2)	n.d.	0.283 0.277	n.d.	0.001 0.007			5	
	ChCl:U (1:2)	Air	0.28	n.d.	0.14.10-4	Static headspace analysis:		5	
	ChCl:EG (1:2)	Air	0.28	n.d.	$0.97 \cdot 10^{-4}$	Initial concentration: 59 g m ⁻³		5	
	ChCl:Gly (1:2)	Air	0.28	n.d.	0.39.10 ⁻⁴	Temperature: 30°C		5	
acetaidenyde	ChCl:Lev (1:2)	Air	0.28	n.d.	4.66·10 ⁻⁴	Volume of absorbent: n.d.	Thermal desorption at	5	[147]
	TBPBr:Gly (1:6)	Air	0.28	n.d.	0.37.10 ⁻⁴	Time of equilibrium: 24 h	60°C, 48 n	5	
	TBPBr:Lev (1:1)	Air	0.28	n.d.	1.65·10 ⁻⁴			5	
	TBABr:DA (1:2)	Air	0.29	n.d.	4.02·10 ⁻⁴			5	
acetaldehvde	ChCl:U (1:2)	n.d.	n.d.	n.d.	0.06	Molecular dynamics (MD) simulation	n.d.	n.d.	[220]
	ChCl:Lev (1:2)	n.d.	n.d.	n.d.	0.05	technique (30°C)	n.d.	n.d.	[220]
propionaldehyde (PA)	G:C:Lev (1:1:3)	N ₂	n.d.	1200	0.008	<u>Static headspace analysis:</u> Initial concentration: 50 ppm v/v Temperature: 25°C	Adsorption with activated carbon	5	[132]

						Volume of absorbent: 1 mL				
	ChCl:U (1:2)	N ₂	n.d.	n.d.	0.01	Time of equilibrium: 48 h		5		
		-								
						Dynamic absorption:			-	
	ChCl:Lev (1:2)	Na	n.d.	n.d.	0.011	Initial concentration: 50 ppm v/v		5		
	()	2				Temperature: 25°C				
						Flow rate: 50 mL/min				
	ChCl:DEG (1:2)	N ₂	n.d.	n.d.	0.01	Pressure: 10 kPa		5		
						DES volume: 50 mL				
						Dynamic absorption:				
						Initial concentration: MEK: 3540 g/m3;				
MEK			13 69		0.004	AA: 1180 g/m3	Thermal desorption at			
Acetaldehyde	TBABr:DA (1:2)	Air	4 49	n.d.	0 0004	Temperature: 30°C	60° C 48 hr	5	[185]	
(AA)						Flow rate: 73 µL.hr-1				
						Pressure: 10 kPa				
						DES mass: 30 g				
МЕК	ChCl:Lev (1:2)	n.d.	n.d.	n.d.	0.0066	Static headspace analysis: Initial concentration: 3000 g/m3 Temperature: 30 °C Mass of absorbent: 3.4 g Time of equilibrium: 48 h	Thermal desorption at	n.d.	[72]	
	ChCl:Lac (1:2)	n.d.	n.d.	n.d.	0.0098			n.d.		
	Chol-C6-Lev	n.d.	n.d.	n.d.	0.0055		60°C. 48 h	n.d.		
	Chol-C8-Lev	n.d.	n.d.	n.d.	0.0051			n.d.		
	Chol-C6-Lac	n.d.	n.d.	n.d.	0.0067			n.d.		
	Chol-C8-Lac	n.d.	n.d.	n.d.	0.0062	•		n.d.		
	Th:DA (1:1)	N ₂	2.66	60	8.58 kPa	Dynamic absorption: Initial concentration: 1480 ppm v/v Temperature: 30°C Flow rate: 150 mL/min Pressure: 10 kPa	Nitrogen barbotage	5		
acetone	ChCl:Re (1:2)	N ₂	0.76	40	n.d.		(flow rate: 150 mL min ^{−1}) at 80°C.	5	[153]	
	DDA:DA (1:2)	Na	0.49	18	n.d.			5		
			0110			DES mass: 3 g				
				5000		IYL SILOXANES	1		1	
		N ₂ :CH ₄ :		5000						
	C:DA (1:1)	C:DA (1:1) C:DA (1:1) C:DA (1:1) CO ₂ (66.7:33.3 % v/v)	ام مر	5500	n.d.			-		
L2 L3 L4 - D3 D5			n.d.	6000		Dynamic absorption:	Nitrogen barbotage	5		
				5200		Initial concentration: 30 g/m ³	(flow rate: 70 mL min ^{-1})			
		N ₂ :CH ₄ :		5500		Temperature: 25°C	at 150°C for 90 min.		[453]	
			J ₂ :CH ₄ : CO ₂	1000		Flow rate: 50 mL/min			[152]	
	C:UDA (1:1)	C:UDA (1:1) CO ₂ (66.7:33.3 % v/v)		1400	nd	Pressure: 10 kPa	_			
			(66.7:33.3	n.u.	1100	n.d.	DES volume: 50 mL	DES volume: 50 mL	5	
			% v/v)		1100					
			nd	400	nd			E	-	
		IN2.C⊓4.	n.u.	400	i.u.			J		

		CO ₂ (66.7:33.3 % v/v)		2000 1000 1000 1000					
L2	G:C:Lev (1:1:3)	N ₂	n.d.	2500	<0.001	<u>Static headspace analysis:</u> Initial concentration: 50 ppm v/v Temperature: 25°C		5	[132]
	ChCl:U (1:2)	N ₂	n.d.	n.d.	0.012	Time of equilibrium: 48 h	Adsorption with	5	
	ChCl:Lev (1:2)	N ₂	n.d.	n.d.	0.0085	Initial concentration: 50 ppm v/v Temperature: 25°C		5	
	ChCl:DEG (1:2)	N ₂	n.d.	n.d.	0.0096	Pressure: 10 kPa DES volume: 50 mL		5	
L2 L3 D4	ChCl:U (1:2)	CH ₄ :CO ₂ :H 2S (68:31:1 % v/v)	1.42 mol/L 0.99 1.09	1313.4 1245.6 1470.6	n.d.	<u>Dynamic absorption:</u> Initial concentration: 200 ppm v/v Temperature: 20°C	Stripper column, temperature of 115– 125 ∘C and air pressure	73	[404]
	ChCl:OA (1:2)	(68:31:1 % v/v)	0.24 mol/L 0.1 0.14	223.8 120.6 187.2	n.d.	Flow rate: 813 m ³ /h Pressure: 100 kPa DES volume: 2.35 m3	of 140–170 kPa. inlet air stream (403 m3 /h)	60	[131]
L2 L3 D4	TPABr:TEG (1:3)	N ₂ :CH ₄ (2:1% v/v)	380 g/L 230 g/L 5000 g/L	375 280 5300	n.d.	<u>Dynamic absorption:</u> Initial concentration: 50 mg/dm3 Flow rate: 50 mL/min. Pressure: 10 kPa Temperature: 25°C DES volume: 50 mL	Nitrogen barbotage (flow rate: 50 mL min ⁻¹) at 90°C for 3 h.	10	[149]
	OA:DDA (3:1)	N ₂	n.d.	n.d.	0.000297	Static headspace analysis:		5	
D4	NA:DDA (3:1)	N ₂	n.d.	n.d.	0.000292	Initial concentration: 59 mg/g		5	
	DA:DDA (2:1)	N ₂	n.d.	n.d.	0.000314	Temperature: 30°C	Nitrogen barbotage	5	
	Rameb:Lev (7:3)	N ₂	n.d.	n.d.	0.0136	Mass of absorbent: 3.5 g	(flow rate: 40 L/h) at	5	
	ChCl:Lev (2:1)	N ₂	n.d.	n.d.	n.d.	Dynamic absorption: Dynamic absorption: Initial concentration: 59 -531 ppm Flow rate: 15µL/h Pressure: 10 kPa	m: 24 n 30°C for 5 h. 59 -531 ppm ιL/h kPa	5	[155]

						Temperature: 30°C			
						DES mass: 20 g			
				`	OLATILE FLUOR	RINATED GASES			
R-32 R-125 R-134a	[N ₄₄₄₄][C ₄ F ₉ SO ₃]/C ₄ F ₉ CO ₂ H (1:1)	pure VFA	0.0951 0.1761 0.2659	n.d.	1.111 MPa 1.358 1.169		<u>m:</u> n.d.	n.d.	[157]
	[N ₄₄₄₄][C ₄ F ₉ SO ₃]/C ₄ F ₉ CO ₂ H (2:1)	pure VFA	0.0925 0.1861 0.2681	n.d.	1.040 0.916 0.975			n.d.	
	[N ₄₄₄₄][C ₄ F ₉ SO ₃]/C ₄ F ₉ CO ₂ H (1:2)	pure VFA	0.0673 0.2975 0.2567	n.d.	1.576 1.780 1.061	<u>Stainless steel volumetric system:</u> Temperature: 30°C Pressure: 0.6 MPa DES mass: 0.5 - 0.8 g		n.d.	
	[C ₂ C1Im][C ₈ F ₁₇ SO ₃]/ C ₄ F ₉ CO ₂ H (1:1)	pure VFA	0.0636 0.1449 0.2175	n.d.	1.707 2.177 1.271			n.d.	
	$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	pure VFA	0.0637 0.1582 0.1736	n.d.	1.759 1.469 0.881			n.d.	
	[C ₂ C ₁ Im][C ₈ F ₁₇ SO ₃]/ C ₄ F ₉ CO ₂ H (1:2)	pure VFA	0.0569 0.1280 0.2084	n.d.	2.4317 2.408 1.474			n.d.	

761 3. DES regeneration

762 The reversible use of absorbents for VOCs capture determines the cost and the sustainability 763 of the industrial processes. The cost of solvent replacement in an absorption column is relatively 764 high. In addition, the used absorbent, which does not ensure high gas purity, must be utilized. Thus, 765 frequent replacement of absorbents significantly increases the cost of the process and adversely 766 affects the environment [131]. Various absorbent regeneration processes are available, i.e., thermal 767 desorption, adsorption using common adsorbents, distillation, or barbotage using inert gas [236]. 768 The most commonly used regeneration methods are presented in Figure 3. All DES regeneration 769 processes usually require high temperatures to ensure high VOCs removal efficiency. Therefore, not 770 all well-studied DES can be used as absorbents. Some of them are characterized by low thermal 771 stability, low degradation temperature, and high vapor pressure, which can result in the degradation 772 and loss of DES during the regeneration process [64,237].

773 Among available regeneration processes, conventional thermal desorption is one of the most 774 common used. It involves continuous stirring of the DES at an elevated 60 °C for 48 hours. As a result 775 of heating the absorbent, the non-covalent bonds formed between DES and VOCs elongate and 776 become weaker. The VOCs then evaporate from the solvent and they are transferred to the gas 777 phase. The regeneration process allows efficient regeneration of absorbents based on quaternary 778 ammonium salts and cyclodextrins, as well as conventional DES. VOCs including toluene, DCM, 779 thiophene, acetaldehyde and butanone can be almost completely removed from DES without 780 noticeable loss of absorption capacity. After five cycles, the absorption capacity remains between 97 781 and 99%. In addition, no change in absorbent mass was observed before and after five absorption-782 desorption cycles [72,147,148,177]. From an industrial point of view, five cycles is not enough to 783 make the process economical. However, the authors did not specify after how many cycles the 784 decreases in DES uptake efficiency would be observed. Moreover, the absorbent regeneration time is 785 too long to ensure process continuity in a typical industrial system, which consists of one absorption 786 column and one desorption column. Increasing the process temperature is one approach to improve 787 efficiency and reduce DES regeneration time. However, this can lead to the evaporation of DES 788 components, changing the properties of the absorbents and leading to their loss. Therefore, the 789 regeneration temperature should be chosen according to the properties of the absorbent used [238].

Another method to ensure a shorter regeneration time for absorbents is the application of nitrogen barbotage. This is the reverse process of conventional absorption. Passing nitrogen through DES containing absorbed VOCs in contact with the gas captures the contaminants and transfers them from the liquid to the gas phase. This process can effectively remove DMDS, toluene, and limonene from ionic and non-ionic DES [155,191]. After five cycles of absorption-desorption, no significant changes are observed in the structure of DES and absorption capacity. In addition, the time of regeneration can be shortened to 5 hours [191]. However, only a combination of the above methods ensures almost 100% regeneration of DES within 1 hour [61,74,149,152,153].

The DES regeneration process can also be conducted under reduced pressure (0.05-0.5 kPa) without additional energy input. The application of reduced-pressure regeneration is favorable for unstable DES, which degrade at elevated temperatures. However, high regeneration efficiency can be achieved only for the most volatile VOCs. The evaporation under vacuum efficiency decreases as the boiling point of VOCs increases [239]. Increasing the process temperature reduces the time and increases the efficiency of the VOCs desorption [25,146,188]. Complete DES regeneration can be achieved within one hour at 40 °C [145].

790

791

792

793

794

795

796

797

798

799

800

801

802

803

805 Another method for DES regeneration after VOCs absorption is adsorption. The process uses 806 the equilibrium relationship between the adsorbent, DES, and adsorbate to break the adsorption 807 equilibrium by changing the temperature or pH value of the solvent [240,241]. To regenerate DES, an 808 adsorbent with a high affinity for VOCs must be appropriately selected. To date, activated carbon, 809 silica gel, and aluminum oxide (III) have been tested for VOCs adsorption from used DES [132,191]. 810 The highest DMDS desorption efficiency was demonstrated for silica gel. In addition, it was observed 811 that as the mass of adsorbent increases, the desorption efficiency of VOCs from DES increases. This is 812 due to the increased number of active sites in the adsorbent to which DMDS molecules can attach. 813 However, from an economic point of view, increasing the mass of adsorbent is disadvantageous due 814 to the cost of purchasing new sorbent and the necessity to regenerate or utilize a higher amount of 815 used adsorbent. In addition, it has been demonstrated that the desorption efficiency closely depends 816 on the type of DES. Some DES components can bind strongly to the adsorbent, blocking the active 817 sites. The adsorption efficiency ranged from 84.5 to 96.6% [191]. This indicates that it is not the most 818 favorable method for DES regeneration.

A back extraction method using common solvents, i.e., water [242], diethyl ether [142], or nheptane [243], can also be used to regenerate DES. However, a large amount of waste solvent remains after the process, which must be disposed of properly. Consequently, the cost of the process increases. In addition, most of the solvents used are volatile substances that can contaminate the atmosphere, and the gas purification process is no longer a "green" method. Therefore, this approach should not be used for the regeneration of DES.



Figure 3 DES regeneration methods a) nitrogen barbotage with heating; b) evaporation under vacuum; c) thermal regeneration; d) nitrogen barbotage; e) adsorption.

828 4. Critical remarks

Currently, published studies demonstrate the great potential of DES application in the industrial gas separation processes. Nevertheless, many problems and limitations can be observed in the presented works, which must be solved before using them on an industrial scale. The first major limitation is the lack of a large amount of data on the physicochemical properties of the developed DES. Most researchers limit their studies to basic physical parameters' determination, such as density, viscosity, and MP of DES. Crucial parameters are missed, including polarity, surface tension, volatility, and degradation temperature. In addition, only toxicity and biodegradability data are

826

827

829

830

831

832 833

834

available for the most popular DES. Therefore, it is hard to estimate the environmental impact of
DES. Many publications assume the green nature of DES, but any studies do not confirm this theory.
A systematic analysis of the mentioned parameters is necessary to conduct further studies on an
enlarged scale.

840 The cost of some DES is relatively high compared to commercially available absorbents, i.e., 841 glycols. Therefore, some of them are unsuitable for industrial applications. One possibility to reduce 842 the cost of the absorption process is regeneration. However, some well know DES are characterized 843 by relatively high vapor pressure. Despite their high efficiency of VOCs absorption, it is impractical to 844 use some DES in industrial conditions due to the introduction of additional pollutants into the 845 treated biogas. As a result, the purified gas may contain more contaminants than before the 846 purification process. The vapor pressure of most DES is still unknown. However, based on the DES 847 studied, it can be assumed that a large group of DES can be characterized by high vapor pressure. The 848 regeneration of such absorbents at high temperatures is almost impossible. At elevated 849 temperatures, volatile absorbents are vaporized, resulting in the loss of absorbents and the 850 transmission of DES vapors into the ambient air.

851 The main drawback of the published works is the lack of information on multiple DES 852 regeneration. Most DES were subjected to the regeneration stage only five times. After that, it was 853 proven that DES do not change their structural, physical, and functional properties. However, it is still 854 unclear after how many absorption-desorption cycles, DES significantly reduces its absorption 855 capacity. Without this information, it is impossible to fully estimate the economics of the process. In 856 addition, regeneration processes should reflect real conditions. However, most of the published 857 processes consisted only of heating the used absorbents. Such a process takes a very long time, 858 about 24 hours, and is uneconomical. Therefore, it is not suitable for industrial conditions. Typically, 859 the setup consists of absorption and desorption columns that work simultaneously. Therefore, 860 regeneration of the absorbent should not take longer than the absorption process. A much better 861 solution is to heat the DES and supply a stream of nitrogen, which accelerates the regeneration 862 process.

863 A comparison of DES with conventional and commercially available absorbents indicates that DES 864 can absorb hydrophobic VOCs better or comparably. In contrast, the absorption capacity of hydrophilic contaminants from the O-VOCs group is similar to or worse than water. Therefore, for 865 866 absorption of hydrophilic VOCs, it is better to consider using water, which is a more "green 867 absorbent." On the other hand, the evaluation of DES efficiency was usually done by examining the 868 partition coefficient of VOCs between the absorbent and the gas phase. However, this is not the best assessment of the new absorbents, as the applicability of the new solvents is affected by many more 869 870 parameters, i.e., gas flow rate, gas temperature, or composition of the purified stream. These are 871 parameters whose effect on the efficiency of VOCs capture can only be studied using a dynamic 872 absorption system. However, only a few works consider such studies. To date, only a few works have 873 examined the effect of the gas matrix on the absorption efficiency of VOCs. Most of the presented 874 studies were limited solely to the examination of VOC absorption from nitrogen. Due to the inert 875 nature of nitrogen, these studies contribute valuable information about the interaction of VOCs with 876 DES components, but they do not reflect real conditions. The presence of various pollutants, i.e., 877 carbon dioxide in high concentrations, can rapidly block DES active sites and significantly reduce 878 absorption efficiency. Most of the presented papers describe absorption experiments at room 879 temperature and atmospheric pressure. However, the waste or flue gas temperature is higher (50-80 °C). Therefore, more research is needed to fill the huge gap between laboratory studies andindustrial processes.

In addition, some studies presented the use of mathematical modeling to evaluate the utility of DES in absorption processes. Predictive models, i.e., COSMO-RS, or COSMO-SAC, are perfect for DES preselection because there is no need to introduce real data or to conduct long-term and expensive calculations. However, the main drawback of the models is the large error. Therefore, mathematical modeling should only be complementary to experimental studies.

Large-scale (preparative and semipreparative) studies are lacking in published papers. To consider the applicability of DES in an industrial setting, enlarged-scale studies should be conducted using real waste streams. To date, only one paper has considered increasing the scale of the process to 1 L of absorbent. Moreover, barbotage columns were used in all works dedicated to dynamic absorption with DES. Due to their low efficiency, they are not widely used in industry. Therefore, additional research should also be done on the application of other types of absorbers, i.e., spray towers, irrigated packed beds, and plate towers.

894

895 4. Conclusions and outlook

896 Currently, a limited number of studies can be found in the literature on the application of DES to 897 VOCs captured from gas streams. The available research is fundamental studies that mainly describe 898 the mechanism of VOCs absorption from the model gas by DES. However, there is still a lack of 899 information on the removal mechanisms of some VOC groups. Therefore, the depth of fundamental 900 and experimental studies (i.e., physicochemical data and molecular interactions between deep 901 eutectic solvent components) are still highly desirable. Published studies demonstrate the great 902 potential of DES as an alternative to commercially available absorbents. This is due to their high VOC 903 absorption efficiency, favorable physicochemical properties, regenerability, and simple and 904 inexpensive synthesis. However, the main advantage in the absorption of VOCs using DES is the 905 ability to tune their properties by selecting HBA and HBD. Therefore, an appropriately designed DES 906 can selectively capture specific contaminants by forming specific non-covalent interactions.

907 Shortly, we can expect to extend the research using more tailored DES to absorb the selected VOC 908 groups. Probably, future research will also be directed to the removal of multiple VOC groups 909 simultaneously from the model as well as real gas streams. There is still a lack of enlarged-scale 910 studies on industrial gas streams or gaseous fuels. However, because of increased scientific interest 911 in this topic, we can soon expect semi-preparative or industrial-scale studies. In addition, the 912 continued development of DES and the appearance of reports of new DES groups in the literature 913 will probably increase similar work using new DES with unique properties for absorbing VOCs. On the 914 other hand, greater awareness among scientists of the negative environmental impact of organic 915 compounds will prompt scientists to better test DES for biodegradability and toxicity.

917 Acknowledgements

This work was supported by Gdańsk University of Technology under the Argentum Triggering
Research Grants—EIRU program Grant (No. DEC-34/2020/IDUB/I.3.3) and the National Science
Centre, Poland within the grant project (No. UMO-2021/43/D/ST8/01791).

921 Abbreviations:

922 BP boiling point; BTEX benzene, ethylbenzene, toluene, xylenes; **BTPB** butyltriphenylphosphonium bromide; C – camphor; Car – carvone; Captisol - Sulfobutylether- β -CD; 923 924 CDs - cyclodextrins ; CF – chloroform; ChCl – choline chloride; Chol-C6-Lac - Hexylcholinium lactate; Chol-C6-Lev - Hexylcholinium levulinate; Chol-C8-Lac - Octylcholinium lactate; Chol-C8-Lev -925 Octylcholinium levulinate; COSMO-RS - conductor like screening model for real solvents; COSMO-926 927 SAC - conductor-like screening model segment activity coefficient; CRYSMEB - methylated beta 928 cyclodextrin; D3 – hexamethylcyclopentasiloxane; D4 – octamethylcyclotetrasiloxane; D5 – 929 decamethylcyclopentasiloxane; D6 – dodecamethylcyclohexasiloxane; DA – decanoic acid; DCM – 930 dichloromethane; DDA – dodecanoic acid; DEG – diethylene glycol; DES – deep eutectic solvents; DFT 931 - density functional theory; DMDS - dimethyldisulfide; E - eucalyptol; EC50 - half maximal effective 932 concentration; EEA - European Environment Agency; EG - ethyl glycol; FP - freezing point; G -933 guaiacol; Glu – glucose; Gly – glycerol; Gu – guaiacol; GWP - global warming potential; HBA -934 hydrogen bond acceptor; HBD - hydrogen bond donor; HP-β-CD - hydroxypropyl-β-CD; ILs - ionic 935 liquids; K - vapor-liquid partition coefficient; L2 – hexamethyldisiloxane; L3 – octamethyltrisiloxane; 936 L4 - decamethyltetrasiloxane; L5 – dodecamethylpentasiloxane; LA – lactic acid; LD50 - Lethal Dose, 937 50%; Lev – levulinic acid; Lid – lidocaine; MEK – Methylethylketone; MP - melting point; NA – 938 nonanoic acid; OA – octanoic acid; OECD - Organisation for Economic Cooperation and Development; 939 O-VOCs - Oxygenated volatile organic compounds; Ox - oxalic acid; PC - 1,2-propanediol; Ph -940 phenol; RAMEB - randomly methylated β-cyclodextrin; QAS - quaternary ammonium salts; QPS -941 quaternary phosphonium salts; R-32 – difluoromethane; R-125 – pentafluoroethane; R-134a -942 1,1,1,2-tetrafluoroethane; Res – resorcinol; RT – room temperature; ST - surface tension; SUPRADES 943 - supramolecular deep eutectic solvents; Syr - Syringol; TBABr - tetrabutylammonium bromide; 944 - tetrabutylammonium chloride; TBPBr - tetrabutylphosphonium bromide; TBPCl TBACI 945 tetrabutylphosphonium chloride; TCE – tetrachloroethane; TCEtOH - 2,2,2-trichloroethanol; TCM -946 carbon tetrachloride; Tdeg - degradation temperature; TEACl - Tetraethylammonium chloride; 947 TEBACI - Triethyl benzyl ammonium; TEG - tetraethylglycol; Tg - glass transition temperature; Th -948 thymol; TOABr - tetraoctylammonium bromide; TPABr - tetrabutylphosphonium bromide; TriEG -949 triethylene glycol; TTABr - tetradecyltrimethylammonium bromide; U – urea; UA – undecanoic acid; 950 US EPA - United States Environmental Protection Agency; WHO - World Health Organization; VFG -951 Volatile fluorinated gases; VMS - Volatile methyl siloxanes; VOCs - volatile organic compounds; 952 VOSCs - Volatile organosulfur compounds; VOX - Volatile organochlorine compounds; Vp - vapor 953 pressure; Xyl - xylose

955 Literature

954

962 963

- R. Hu, G. Liu, H. Zhang, H. Xue, X. Wang, P.K.S. Lam, Odor pollution due to industrial emission
 of volatile organic compounds: A case study in Hefei, China, J. Clean. Prod. 246 (2020) 119075.
 https://doi.org/10.1016/J.JCLEPRO.2019.119075.
- M. Mu, X. Zhang, G. Yu, C. Sun, R. Xu, N. Liu, N. Wang, B. Chen, C. Dai, Deep removal of
 chlorobenzene based volatile organic compounds from exhaust gas with ionic liquids, Sep.
 Purif. Technol. 298 (2022) 121610. https://doi.org/10.1016/J.SEPPUR.2022.121610.
 - [3] C.Y. Hsu, P.Y. Wu, Y.C. Chen, P.C. Chen, Y.L. Guo, Y.J. Lin, P. Lin, An integrated strategy by using long-term monitoring data to identify volatile organic compounds of high concern near petrochemical industrial parks, Sci. Total Environ. 821 (2022) 153345.

- 965 https://doi.org/10.1016/J.SCITOTENV.2022.153345.
- 966 [4] S. Xue, W. Ding, L. Li, J. Ma, F. Chai, J. Liu, Emission, dispersion, and potential risk of volatile
 967 organic and odorous compounds in the exhaust gas from two sludge thermal drying
 968 processes, Waste Manag. 138 (2022) 116–124.
 969 https://doi.org/10.1016/J.WASMAN.2021.11.040.
- 970 [5] Y. Lu, X. Pang, Y. Lyu, J. Li, B. Xing, J. Chen, Y. Mao, Q. Shang, H. Wu, Characteristics and
 971 sources analysis of ambient volatile organic compounds in a typical industrial park:
 972 Implications for ozone formation in 2022 Asian Games, Sci. Total Environ. 848 (2022) 157746.
 973 https://doi.org/10.1016/J.SCITOTENV.2022.157746.
- 974 [6] C. Liu, Y. Xin, C. Zhang, J. Liu, P. Liu, X. He, Y. Mu, Ambient volatile organic compounds in 975 urban and industrial regions in Beijing: Characteristics, source apportionment, secondary 976 transformation and health risk assessment, Sci. Total Environ. (2022) 158873.
 977 https://doi.org/10.1016/J.SCITOTENV.2022.158873.
- 978 [7] P. Makoś, A. Przyjazny, G. Boczkaj, Methods of assaying volatile oxygenated organic
 979 compounds in effluent samples by gas chromatography—A review, J. Chromatogr. A. 1592
 980 (2019) 143–160. https://doi.org/10.1016/j.chroma.2019.01.045.
- 981 [8] Y. Huang, S. Ho, Y. Lu, R. Niu, L. Xu, J. Cao, S. Lee, Removal of Indoor Volatile Organic
 982 Compounds via Photocatalytic Oxidation: A Short Review and Prospect, Molecules. 21 (2016)
 983 56. https://doi.org/10.3390/molecules21010056.
- 984[9]F.I. Khan, A. Kr. Ghoshal, Removal of Volatile Organic Compounds from polluted air, J. Loss985Prev. Process Ind. 13 (2000) 527–545. https://doi.org/10.1016/S0950-4230(00)00007-3.
- 986 [10] G. Gan, S. Fan, X. Li, Z. Zhang, Z. Hao, Adsorption and membrane separation for removal and
 987 recovery of volatile organic compounds, J. Environ. Sci. (2022).
 988 https://doi.org/10.1016/J.JES.2022.02.006.
- 989 [11] X. Gong, J. Yang, X. Feng, X. Yang, H. Zheng, Z. Wu, Q. Hu, Removal of thiophene in air stream
 990 by absorption combined with electrochemical oxidation, J. Taiwan Inst. Chem. Eng. 84 (2018)
 991 173–178. https://doi.org/10.1016/J.JTICE.2018.01.022.
- 992 [12] C. Li, L. He, X. Yao, Z. Yao, Recent advances in the chemical oxidation of gaseous volatile
 993 organic compounds (VOCs) in liquid phase, Chemosphere. 295 (2022) 133868.
 994 https://doi.org/10.1016/J.CHEMOSPHERE.2022.133868.
- [13] Z. Liang, J. Wang, Y. Zhang, C. Han, S. Ma, J. Chen, G. Li, T. An, Removal of volatile organic
 compounds (VOCs) emitted from a textile dyeing wastewater treatment plant and the
 attenuation of respiratory health risks using a pilot-scale biofilter, J. Clean. Prod. 253 (2020)
 120019. https://doi.org/10.1016/J.JCLEPRO.2020.120019.
- 999[14]M. Meena, P. Sonigra, G. Yadav, Biological-based methods for the removal of volatile organic1000compounds (VOCs) and heavy metals, (n.d.). https://doi.org/10.1007/s11356-020-11112-10014/Published.
- .002 [15] H. Zhang, X. Wang, X. Shen, X. Li, B. Wu, G. Li, H. Bai, X. Cao, X. Hao, Q. Zhou, Z. Yao, Chemical characterization of volatile organic compounds (VOCs) emitted from multiple cooking cuisines and purification efficiency assessments, J. Environ. Sci. (2022).
 .005 https://doi.org/10.1016/J.JES.2022.08.008.
 - [16] S. Zhang, H. He, Q. Zhou, X. Zhang, X. Lu, Y. Tian, Principles and strategies for green process

1007		engineering, Green Chem. Eng. 3 (2022) 1–4. https://doi.org/10.1016/J.GCE.2021.11.008.
1008 1009	[17]	K.L. Wasewar, Process intensification and green engineering in process industry, Environ. Sustain. Ind. (2022) 433–459. https://doi.org/10.1016/B978-0-323-90034-8.00019-1.
1010 1011	[18]	J.C. Warner, P.T. Anastas, Green Chemistry: Theory and Practice, Green Chem. Theory Pract. Oxford Univ. Press. New York. (1998) 7.
1012 1013 1014	[19]	D.J.C. Constable, Green and sustainable chemistry – The case for a systems-based, interdisciplinary approach, IScience. 24 (2021) 103489. https://doi.org/10.1016/j.isci.2021.103489.
1015 1016 1017	[20]	R. Haghbakhsh, K. Parvaneh, S. Raeissi, A. Shariati, A general viscosity model for deep eutectic solvents: The free volume theory coupled with association equations of state, Fluid Phase Equilib. 470 (2018) 193–202. https://doi.org/10.1016/j.fluid.2017.08.024.
1018 1019 1020	[21]	Y. Guo, Z. Niu, W. Lin, Comparison of removal efficiencies of carbon dioxide between aqueous ammonia and NaOH solution in a fine spray column, Energy Procedia. 4 (2011) 512–518. https://doi.org/10.1016/j.egypro.2011.01.082.
1021 1022 1023	[22]	C. Pirola, M. Mattia, Purification of air from volatile organic compounds by countercurrent liquid gas mass transfer absorption process, Int. J. Thermofluids. 9 (2021) 100060. https://doi.org/10.1016/j.ijft.2020.100060.
1024 1025 1026	[23]	M. Lhuissier, A. Couvert, A. Kane, A. Amrane, J.L. Audic, P.F. Biard, Volatile organic compounds absorption in a structured packing fed with waste oils: Experimental and modeling assessments, Chem. Eng. Sci. 238 (2021) 116598. https://doi.org/10.1016/J.CES.2021.116598.
1027 1028	[24]	N. HATCHER, C. JONES, R. WEILAND, Solubility of hydrocarbons and light ends in amines, Pet. Technol. Q. (2013).
1029 1030 1031	[25]	C. Dai, M. Chen, W. Mu, B. Peng, G. Yu, N. Liu, R. Xu, N. Wang, B. Chen, Highly efficient toluene absorption with π-electron donor-based deep eutectic solvents, Sep. Purif. Technol. 298 (2022) 121618. https://doi.org/10.1016/J.SEPPUR.2022.121618.
1032 1033 1034 1035	[26]	Y. Li, H. Chang, H. Yan, S. Tian, P.G. Jessop, Reversible Absorption of Volatile Organic Compounds by Switchable-Hydrophilicity Solvents: A Case Study of Toluene with N, N- Dimethylcyclohexylamine, ACS Omega. 6 (2021) 253–264. https://doi.org/10.1021/acsomega.0c04443.
1036 1037 1038 1039	[27]	C. Zhang, J. Wu, R. Wang, E. Ma, L. Wu, J. Bai, J. Wang, Study of the toluene absorption capacity and mechanism of ionic liquids using COSMO-RS prediction and experimental verification, Green Energy Environ. 6 (2021) 339–349. https://doi.org/10.1016/J.GEE.2020.08.001.
1040 1041 1042	[28]	Y. Zhao, J. Zhao, Y. Huang, Q. Zhou, X. Zhang, S. Zhang, Toxicity of ionic liquids: Database and prediction via quantitative structure-activity relationship method, J. Hazard. Mater. 278 (2014) 320–329. https://doi.org/10.1016/j.jhazmat.2014.06.018.
.043 .044 .045	[29]	A. Romero, A., Santos, A., Tojo, J. & Rodríguez, Toxicity and biodegradability of imidazolium ionic liquids, J. Hazard. Mater. 151 (2008) 268–273. https://doi.org/10.1016/J.JHAZMAT.2007.10.079.
.046 .047	[30]	V. Abbott, A.P., Capper, G., Davies, D.L., Rasheed, R.K. & Tambyrajah, Novel Solvent Properties of Choline Chloride /Urea Mixtures, Chem. Commun. 0 (2003) 70–71.
		42

- 1048 https://doi.org/https://doi.org/10.1021/ja048266j.
- 1049 [31] W. Tang, Y. An, K.H. Row, Emerging applications of (micro) extraction phase from hydrophilic 1050 to hydrophobic deep eutectic solvents: opportunities and trends, TrAC - Trends Anal. Chem. 1051 136 (2021) 116187. https://doi.org/10.1016/j.trac.2021.116187.
- 1052 [32] W. Jiang, H. Jia, H. Li, L. Zhu, R. Tao, W. Zhu, H. Li, S. Dai, Boric acid-based ternary deep 1053 eutectic solvent for extraction and oxidative desulfurization of diesel fuel, Green Chem. 21 1054 (2019) 3074–3080. https://doi.org/10.1039/c9gc01004a.
- 1055 L. Xu, Y. Luo, H. Liu, J. Yin, H. Li, W. Jiang, W. Zhu, H. Li, H. Ji, Extractive desulfurization of [33] 1056 diesel fuel by amide-based type IV deep eutectic solvents, J. Mol. Lig. 338 (2021) 116620. 1057 https://doi.org/10.1016/J.MOLLIQ.2021.116620.
- 1058 L. Xu, H. Jia, D. Zhu, F. Huan, R. Liu, W. Jiang, W. Zhu, H. Li, Hydrogen bonding boosted [34] 1059 oxidative desulfurization by ZnCl2/boric acid/polyethylene glycol-based ternary deep eutectic solvents, J. Mol. Liq. 368 (2022) 120725. https://doi.org/10.1016/J.MOLLIQ.2022.120725. 1060
- 1061 [35] L. Xu, J. Yin, Y. Luo, H. Liu, H. Li, L. Zhu, J. He, W. Jiang, W. Zhu, H. Li, Rational Design of 1062 Caprolactam-Based Deep Eutectic Solvents for Extractive Desulfurization of Diesel Fuel and 1063 Mechanism Study, ACS Sustain. Chem. Eng. 10 (2022) 4551-4560. 1064 https://doi.org/10.1021/acssuschemeng.1c08413.
- 1065 [36] M.K. Hadj-Kali, Z. Salleh, E. Ali, R. Khan, M.A. Hashim, Separation of aromatic and aliphatic 1066 hydrocarbons using deep eutectic solvents: A critical review, Fluid Phase Equilib. 448 (2017) 1067 152–167. https://doi.org/10.1016/J.FLUID.2017.05.011.
- 1068 [37] M. Pätzold, S. Siebenhaller, S. Kara, A. Liese, C. Syldatk, D. Holtmann, Deep Eutectic Solvents 1069 as Efficient Solvents in Biocatalysis, Trends Biotechnol. 37 (2019) 943–959. 1070 https://doi.org/10.1016/j.tibtech.2019.03.007.
- 1071 [38] C. Padwal, H.D. Pham, S. Jadhav, T.T. Do, J. Nerkar, L.T.M. Hoang, A. Kumar Nanjundan, S.G. 1072 Mundree, D.P. Dubal, Deep Eutectic Solvents: Green Approach for Cathode Recycling of Li-Ion 1073 Batteries, Adv. Energy Sustain. Res. 3 (2022) 2100133. 1074 https://doi.org/10.1002/aesr.202100133.
- 1075 [39] D. Rente, M. Cvjetko Bubalo, M. Panić, A. Paiva, B. Caprin, I. Radojčić Redovniković, A.R.C. 1076 Duarte, Review of deep eutectic systems from laboratory to industry, taking the application in 1077 the cosmetics industry as an example, J. Clean. Prod. 380 (2022) 135147. 1078 https://doi.org/10.1016/J.JCLEPRO.2022.135147.
- [40] 1079 F. Paludetto Pelaquim, A. Marinho Barbosa Neto, I. Angela Lucini Dalmolin, M. Conceição da 1080 Costa, Gas Solubility Using Deep Eutectic Solvents: Review and Analysis, Ind. & amp; Eng. 1081 Chem. Res. 60 (2021) 8607–8620. https://doi.org/10.1021/acs.iecr.1c00947.
- 1082 [41] K. Chandran, C.F. Kait, C.D. Wilfred, H.F.M. Zaid, A review on deep eutectic solvents: 1083 Physiochemical properties and its application as an absorbent for sulfur dioxide, J. Mol. Liq. .084 338 (2021) 117021. https://doi.org/10.1016/J.MOLLIQ.2021.117021.
- .085 [42] R.J. Isaifan, A. Amhamed, Review on Carbon Dioxide Absorption by Choline Chloride/Urea .086 Deep Eutectic Solvents, Adv. Chem. 2018 (2018) 1–6. https://doi.org/10.1155/2018/2675659.
- .087 [43] I. Wazeer, M.K. Hadj-Kali, I.M. Al-Nashef, Utilization of Deep Eutectic Solvents to Reduce the Release of Hazardous Gases to the Atmosphere: A Critical Review, Molecules. 26 (2021) 1–34. .089 https://doi.org/10.3390/MOLECULES26010075.

1090 [44] Z. Yan, S.Y. Lai, C.L. Ngan, H. Li, A.R. Mohamed, Recent advances in energy-efficient and 1091 regenerative SO2 absorption over deep eutectic solvents, J. Environ. Chem. Eng. 10 (2022) 1092 108967. https://doi.org/10.1016/J.JECE.2022.108967. 1093 [45] Y. Marcus, Gas solubilities in deep eutectic solvents, Monatshefte Fur Chemie. 149 (2018) 1094 211-217. https://doi.org/10.1007/s00706-017-2031-8. 1095 [46] Y. Wang, S. Ren, Y. Hou, W. Wu, Capture of acidic gases from flue gas by deep eutectic 1096 solvents, Processes. 9 (2021) 1–27. https://doi.org/10.3390/pr9081268. 1097 [47] F. Soltanmohammadi, A. Jouyban, A. Shayanfar, New aspects of deep eutectic solvents: 1098 extraction, pharmaceutical applications, as catalyst and gas capture, Chem. Pap. 75 (2021) 1099 439–453. https://doi.org/10.1007/s11696-020-01316-w. 1100 [48] P. Janicka, J. Płotka-Wasylka, J. Gębicki, Deep Eutectic Solvents and Their Uses for Air 1101 Purification, J. Ecol. Eng. 23 (2022) 181–190. https://doi.org/10.12911/22998993/152459. 1102 [49] Y. Chen, X. Han, Z. Liu, D. Yu, W. Guo, T. Mu, Capture of Toxic Gases by Deep Eutectic 1103 Solvents, ACS Sustain. Chem. Eng. 8 (2020) 5410–5430. 1104 https://doi.org/10.1021/acssuschemeng.0c01493. 1105 [50] L.S. Bobrova, F.I. Danilov, V.S. Protsenko, Effects of temperature and water content on 1106 physicochemical properties of ionic liquids containing CrCl3·xH2O and choline chloride, J. Mol. 1107 Liq. 223 (2016) 48–53. https://doi.org/10.1016/J.MOLLIQ.2016.08.027. 1108 [51] T. El Achkar, H. Greige-Gerges, S. Fourmentin, Basics and properties of deep eutectic solvents: 1109 a review, Environ. Chem. Lett. 19 (2021) 3397–3408. https://doi.org/10.1007/s10311-021-1110 01225-8. [52] 1111 P. Makoś, E. Słupek, J. Gębicki, Hydrophobic deep eutectic solvents in microextraction 1112 techniques-A review, Microchem. J. 152 (2020) 104384-10400. 1113 https://doi.org/10.1016/j.microc.2019.104384. 1114 [53] E.L. Smith, A.P. Abbott, K.S. Ryder, Deep Eutectic Solvents (DESs) and Their Applications, 1115 Chem. Rev. 114 (2014) 11060–11082. https://doi.org/10.1021/cr300162p. 1116 [54] P. Makoś-Chełstowska, M. Kaykhaii, J. Płotka-Wasylka, M. de la Guardia, Magnetic deep 1117 eutectic solvents – Fundamentals and applications, J. Mol. Liq. 365 (2022) 120158. 1118 https://doi.org/10.1016/J.MOLLIQ.2022.120158. 1119 [55] D.K. Panda, B.L. Bhargava, Molecular dynamics investigation of non-ionic deep eutectic 1120 solvents, J. Mol. Graph. Model. 113 (2022) 108152. 1121 https://doi.org/10.1016/J.JMGM.2022.108152. 1122 [56] T. El Achkar, T. Moufawad, S. Ruellan, D. Landy, H. Greige-Gerges, S. Fourmentin, 1123 Cyclodextrins: From solute to solvent, Chem. Commun. 56 (2020) 3385–3388. https://doi.org/10.1039/d0cc00460j. 1124 .125 [57] P. Janicka, M. Kaykhaii, J. Płotka-Wasylka, J. Gębicki, Supramolecular deep eutectic solvents .126 and their applications, Green Chem. 24 (2022) 5035–5045. .127 https://doi.org/10.1039/d2gc00906d. .128 [58] H. Wu, X. Zhang, W. Xiong, J. Liang, S. Zhang, X. Hu, Y. Wu, Deep eutectic behavior in binary .129 mixtures of protic ionic liquids, J. Mol. Liq. 366 (2022) 120251. .130 https://doi.org/10.1016/J.MOLLIQ.2022.120251. 44

- 1131
 [59]
 J.R. Fair, H.Z. Kister, Absorption (Chemical Engineering), Encycl. Phys. Sci. Technol. (2003) 1–

 1132
 25. https://doi.org/10.1016/B0-12-227410-5/00001-6.
- 1133 [60] V.M. Nagulapati, H.M. Raza Ur Rehman, J. Haider, M. Abdul Qyyum, G.S. Choi, H. Lim, Hybrid
 1134 machine learning-based model for solubilities prediction of various gases in deep eutectic
 1135 solvent for rigorous process design of hydrogen purification, Sep. Purif. Technol. 298 (2022)
 1136 121651. https://doi.org/10.1016/J.SEPPUR.2022.121651.
- 1137 [61] P. Makoś-Chełstowska, E. Słupek, A. Kramarz, D. Dobrzyniewski, B. Szulczyński, J. Gębicki,
 1138 Green monoterpenes based deep eutectic solvents for effective BTEX absorption from biogas,
 1139 Chem. Eng. Res. Des. 188 (2022) 179–196. https://doi.org/10.1016/J.CHERD.2022.09.047.
- 1140 [62] L.J.B.M. Kollau, M. Vis, A. Van Den Bruinhorst, A.C.C. Esteves, R. Tuinier, Quantification of the
 1141 liquid window of deep eutectic solvents, Chem. Commun. 54 (2018) 13351–13354.
 1142 https://doi.org/10.1039/c8cc05815f.
- 1143 [63] V. Andruch, P. Makoś-Chełstowska, J. Płotka-Wasylka, Remarks on use of the term "deep 1144 eutectic solvent" in analytical chemistry, Microchem. J. 179 (2022) 107498.
 1145 https://doi.org/10.1016/J.MICROC.2022.107498.
- 1146 [64] N. Delgado-Mellado, M. Larriba, P. Navarro, V. Rigual, M. Ayuso, J. García, F. Rodríguez,
 1147 Thermal stability of choline chloride deep eutectic solvents by TGA/FTIR-ATR analysis, J. Mol.
 1148 Liq. 260 (2018) 37–43. https://doi.org/10.1016/J.MOLLIQ.2018.03.076.
- 1149 [65] M.A.R. Martins, L.P. Silva, N. Schaeffer, D.O. Abranches, G.J. Maximo, S.P. Pinho, J.A.P.
 1150 Coutinho, Greener Terpene-Terpene Eutectic Mixtures as Hydrophobic Solvents, ACS Sustain.
 1151 Chem. Eng. 7 (2019) 17414–17423. https://doi.org/10.1021/acssuschemeng.9b04614.
- 1152[66]C. YUANYUAN, M. Tiancheng, cOMPREHENSIVE INVESTIGATION ON THE THERMAL STABILITY1153OF 66 IONIC LIQUIDS BY THERMOGRAVIMETRIC ANALYSIS, Ind. Eng. Chem. Res. (2014) 8651–11548664.
- 1155 [67] A.P. Abbott, G. Capper, D.L. Davies, R.K. Rasheed, V. Tambyrajah, Novel solvent properties of
 1156 choline chloride/urea mixtures, Chem. Commun. (2003) 70–71.
 1157 https://doi.org/10.1039/b210714g.
- 1158 [68] P. Makoś, E. Słupek, J. Gębicki, Hydrophobic deep eutectic solvents in microextraction
 1159 techniques–A review, Microchem. J. 152 (2020).
 1160 https://doi.org/10.1016/j.microc.2019.104384.
- 1161[69]Y. Ma, Q. Wang, T. Zhu, Comparison of hydrophilic and hydrophobic deep eutectic solvents for1162pretreatment determination of sulfonamides from aqueous environments, Anal. Methods. 111163(2019) 5901–5909. https://doi.org/10.1039/c9ay02244a.
- K. Radošević, I. Čanak, M. Panić, K. Markov, M.C. Bubalo, J. Frece, V.G. Srček, I.R.
 Redovniković, Antimicrobial, cytotoxic and antioxidative evaluation of natural deep eutectic
 solvents, Environ. Sci. Pollut. Res. 25 (2018) 14188–14196. https://doi.org/10.1007/s11356018-1669-z.
- [71] T. El Achkar, L. Moura, T. Moufawad, S. Ruellan, S. Panda, S. Longuemart, F.X. Legrand, M.
 Costa Gomes, D. Landy, H. Greige-Gerges, S. Fourmentin, New generation of supramolecular
 mixtures: Characterization and solubilization studies, Int. J. Pharm. 584 (2020) 119443.
 https://doi.org/10.1016/J.IJPHARM.2020.119443.
 - [72] F. Fahri, K. Bacha, F.F. Chiki, J.P. Mbakidi, S. Panda, S. Bouquillon, S. Fourmentin, Air pollution:

- 1173new bio-based ionic liquids absorb both hydrophobic and hydrophilic volatile organic1174compounds with high efficiency, Environ. Chem. Lett. 18 (2020) 1403–1411.1175https://doi.org/10.1007/s10311-020-01007-8.
- 1176 [73] K. Paduszyński, U. Domańska, Viscosity of ionic liquids: An extensive database and a new
 1177 group contribution model based on a feed-forward artificial neural network, J. Chem. Inf.
 1178 Model. 54 (2014) 1311–1324. https://doi.org/10.1021/ci500206u.
- 1179 [74] P. Makoś-Chełstowska, E. Słupek, J. Gębicki, Deep eutectic solvent-based green absorbents for 1180 the effective removal of volatile organochlorine compounds from biogas, Green Chem. (2021)
 1181 4814–4827. https://doi.org/10.1039/d1gc01735g.
- 1182[75]A.P. Abbott, G. Capper, S. Gray, Design of improved deep eutectic solvents using hole theory,1183ChemPhysChem. 7 (2006) 803–806. https://doi.org/10.1002/cphc.200500489.
- 1184 [76] V. Muresan, M.L. Unguresan, C. Varodi, J.Z. Szucs-Balazs, Temperature influence over the absorption process of CO2 in octane, Proc. - 2015 8th Rom. Tier 2 Fed. Grid, Cloud High
 1186 Perform. Comput. Sci. ROLCG 2015. (2015) 1–5.
 1187 https://doi.org/10.1109/ROLCG.2015.7367420.
- 1188[77]V.S. Protsenko, L.S. Bobrova, F.I. Danilov, Physicochemical properties of ionic liquid mixtures1189containing choline chloride, chromium (III) chloride and water: effects of temperature and1190water content, Ionics (Kiel). 23 (2017) 637–643. https://doi.org/10.1007/s11581-016-1826-7.
- 1191 [78] F. Chemat, H. Anjum, A.M. Shariff, P. Kumar, T. Murugesan, Thermal and physical properties
 of (Choline chloride + urea + l-arginine) deep eutectic solvents, J. Mol. Liq. 218 (2016) 301–
 1193 308. https://doi.org/10.1016/J.MOLLIQ.2016.02.062.
- 1194 [79] A. Hayyan, F.S. Mjalli, I.M. Alnashef, T. Al-Wahaibi, Y.M. Al-Wahaibi, M.A. Hashim, Fruit sugar1195 based deep eutectic solvents and their physical properties, Thermochim. Acta. 541 (2012) 70–
 1196 75. https://doi.org/10.1016/J.TCA.2012.04.030.
- E. Jiménez, M. Cabanas, L. Segade, S. García-Garabal, H. Casas, Excess volume, changes of refractive index and surface tension of binary 1,2-ethanediol + 1-propanol or 1-butanol mixtures at several temperatures, Fluid Phase Equilib. 180 (2001) 151–164.
 https://doi.org/10.1016/S0378-3812(00)00519-7.
- [81] Y. Chen, W. Chen, L. Fu, Y. Yang, Y. Wang, X. Hu, F. Wang, T. Mu, Surface Tension of 50 Deep
 Eutectic Solvents: Effect of Hydrogen-Bonding Donors, Hydrogen-Bonding Acceptors, Other
 Solvents, and Temperature, Ind. Eng. Chem. Res. 58 (2019) 12741–12750.
 https://doi.org/10.1021/acs.iecr.9b00867.
- 1205 [82] K. Shahbaz, F.S. Mjalli, M.A. Hashim, I.M. AlNashef, Prediction of the surface tension of deep
 1206 eutectic solvents, Fluid Phase Equilib. 319 (2012) 48–54.
 1207 https://doi.org/10.1016/j.fluid.2012.01.025.
- 1208[83]K.A. Kurnia, M.I.A. Mutalib, Z. Man, M.A. Bustam, Density and Surface Tension of Ionic Liquids.209[H2N–C2mim][PF6] and [H2N–C3mim][PF6], J. Chem. Eng. Data. (2012) 17025–17036.
- .210 [84] M. Tariq, M.G. Freire, B. Saramago, J.A.P. Coutinho, J.N.C. Lopes, L.P.N. Rebelo, Surface
 .211 tension of ionic liquids and ionic liquid solutions, Chem. Soc. Rev. 41 (2012) 829–868.
 .212 https://doi.org/10.1039/c1cs15146k.
 - [85] G. García, S. Aparicio, R. Ullah, M. Atilhan, Deep eutectic solvents: Physicochemical properties and gas separation applications, Energy and Fuels. 29 (2015) 2616–2644.

- 1215 https://doi.org/10.1021/ef5028873.
- 1216 [86] A.P. Abbott, R.C. Harris, K.S. Ryder, C. D'Agostino, L.F. Gladden, M.D. Mantle, Glycerol eutectics as sustainable solvent systems, Green Chem. 13 (2011) 82–90.
 1218 https://doi.org/10.1039/c0gc00395f.
- 1219 [87] F.S. Mjalli, J. Naser, B. Jibril, V. Alizadeh, Z. Gano, Tetrabutylammonium chloride based ionic
 1220 liquid analogues and their physical properties, J. Chem. Eng. Data. 59 (2014) 2242–2251.
 1221 https://doi.org/10.1021/je5002126.
- 1222 [88] K.A. Omar, R. Sadeghi, Physicochemical properties of deep eutectic solvents: A review, J. Mol.
 1223 Liq. 360 (2022) 119524. https://doi.org/10.1016/J.MOLLIQ.2022.119524.
- 1224[89]H. Acceptor, The solvatochromic comparison method. I. The .beta.-scale of solvent hydrogen-1225bond acceptor (HBA) basicities, J. Am. Chem. Soc. 98 (1975) 377–383.
- 1226 [90] M.Q. Farooq, N.M. Abbasi, J.L. Anderson, Deep eutectic solvents in separations: Methods of
 preparation, polarity, and applications in extractions and capillary electrochromatography, J.
 1228 Chromatogr. A. 1633 (2020) 461613. https://doi.org/10.1016/J.CHROMA.2020.461613.
- 1229[91]C. Reichardt, Solvatochromic dyes as solvent polarity indicators, Chem. Rev. 94 (1994) 2319–12302358. https://doi.org/10.1021/cr00032a005.
- 1231 [92] Y. Dai, J. van Spronsen, G.J. Witkamp, R. Verpoorte, Y.H. Choi, Natural deep eutectic solvents
 1232 as new potential media for green technology, Anal. Chim. Acta. 766 (2013) 61–68.
 1233 https://doi.org/10.1016/J.ACA.2012.12.019.
- 1234 [93] A. Pandey, R. Rai, M. Pal, S. Pandey, How polar are choline chloride-based deep eutectic
 1235 solvents?, Phys. Chem. Chem. Phys. 16 (2014) 1559–1568.
 1236 https://doi.org/10.1039/c3cp53456a.
- 1237 [94] M. Zhang, X. Zhao, S. Tang, K. Wu, B. Wang, Y. Liu, Y. Zhu, H. Lu, B. Liang, Structure–properties
 1238 relationships of deep eutectic solvents formed between choline chloride and carboxylic acids:
 1239 Experimental and computational study, J. Mol. Struct. 1273 (2023).
 1240 https://doi.org/10.1016/j.molstruc.2022.134283.
- [95] A.R.R. Teles, E. V. Capela, R.S. Carmo, J.A.P. Coutinho, A.J.D. Silvestre, M.G. Freire,
 Solvatochromic parameters of deep eutectic solvents formed by ammonium-based salts and
 carboxylic acids, Fluid Phase Equilib. 448 (2017) 15–21.
 https://doi.org/10.1016/J.FLUID.2017.04.020.
- 1245[96]Y. Marcus, The properties of organic liquids that are relevant to their use as solvating solvents,1246Chem. Soc. Rev. 22 (1993) 409–416. https://doi.org/10.1039/CS9932200409.
- 1247 [97] K.A. Kurnia, F. Lima, A.F.M. Cláudio, J.A.P. Coutinho, M.G. Freire, Hydrogen-bond acidity of
 1248 ionic liquids: an extended scale, Phys. Chem. Chem. Phys. 17 (2015) 18980–18990.
 1249 https://doi.org/10.1039/c5cp03094c.
- U. Buhvestov, F. Rived, C. Ràfols, E. Bosch, M. Rosés, Solute-solvent and solvent-solvent
 interactions in binary solvent mixtures. Part 7. Comparison of the enhancement of the water
 structure in alcohol-water mixtures measured by solvatochromic indicators, J. Phys. Org.
 Chem. 11 (1998) 185–192. https://doi.org/10.1002/(SICI)1099-1395(199803)11:3<185::AID-
 POC993>3.0.CO;2-5.
 - [99] Y. Liu, J.B. Friesen, J.B. McAlpine, D.C. Lankin, S.N. Chen, G.F. Pauli, Natural Deep Eutectic

- 1256Solvents: Properties, Applications, and Perspectives, J. Nat. Prod. 81 (2018) 679–690.1257https://doi.org/10.1021/acs.jnatprod.7b00945.
- [100] K. Shahbaz, F.S. Mjalli, G. Vakili-Nezhaad, I.M. AlNashef, A. Asadov, M.M. Farid,
 Thermogravimetric measurement of deep eutectic solvents vapor pressure, J. Mol. Liq. 222
 (2016) 61–66. https://doi.org/10.1016/j.molliq.2016.06.106.
- 1261 [101] M.S. Najafabadi, E.N. Lay, An empirical correlation for predicting vapor pressure of ionic 1262 liquids, J. Ion. Liq. 2 (2022) 100035. https://doi.org/10.1016/J.JIL.2022.100035.
- [102] H. Shekaari, M.T. Zafarani-Moattar, S. Faraji, M. Mokhtarpour, Prediction of vapor pressure
 and density for nonaqueous solutions of the ionic liquid 1-ethyl-3-methylimidazolium ethyl
 sulfate using PC-SAFT equation of state, Fluid Phase Equilib. 506 (2020) 112320.
 https://doi.org/10.1016/J.FLUID.2019.112320.
- 1267 [103] S. Huang, Z. Wang, S. Liu, R. Zhu, Z. Lei, Measurement and prediction of vapor pressure in binary systems containing the ionic liquid [EMIM][DCA], J. Mol. Liq. 309 (2020) 113126.
 https://doi.org/10.1016/J.MOLLIQ.2020.113126.
- 1270 [104] O. Aschenbrenner, S. Supasitmongkol, M. Taylor, P. Styring, Measurement of vapour
 1271 pressures of ionic liquids and other low vapour pressure solvents +, (2009) 1217–1221.
 1272 https://doi.org/10.1039/b904407h.
- 1273 [105] H.S. Salehi, H.M. Polat, F. de Meyer, C. Houriez, C. Coquelet, T.J.H. Vlugt, O.A. Moultos, Vapor
 1274 pressures and vapor phase compositions of choline chloride urea and choline chloride
 1275 ethylene glycol deep eutectic solvents from molecular simulation, J. Chem. Phys. 155 (2021).
 1276 https://doi.org/10.1063/5.0062408.
- 1277 [106] S.H. Wu, A.R. Caparanga, R.B. Leron, M.H. Li, Vapor pressure of aqueous choline chloride based deep eutectic solvents (ethaline, glyceline, maline and reline) at 30–70 °C, Thermochim.
 1279 Acta. 544 (2012) 1–5. https://doi.org/10.1016/J.TCA.2012.05.031.
- [107] C.H.J.T. Dietz, J.T. Creemers, M.A. Meuleman, C. Held, G. Sadowski, M. Van Sint Annaland, F.
 Gallucci, M.C. Kroon, Determination of the Total Vapor Pressure of Hydrophobic Deep
 Eutectic Solvents: Experiments and Perturbed-Chain Statistical Associating Fluid Theory
 Modeling, ACS Sustain. Chem. Eng. 7 (2019) 4047–4057.
 https://doi.org/10.1021/acssuschemeng.8b05449.
- 1285[108]A. Roda, A.A. Matias, A. Paiva, A.R.C. Duarte, Polymer science and engineering using deep1286eutectic solvents, Polymers (Basel). 11 (2019) 1–22. https://doi.org/10.3390/polym11050912.
- 1287 [109] Z. Yang, K.R. Gluesenkamp, A. Frazzica, Equilibrium vapor pressure properties for absorbent
 1288 and adsorbent materials, Int. J. Refrig. 124 (2021) 134–166.
 1289 https://doi.org/10.1016/J.IJREFRIG.2020.12.013.
- [110] K. Xin, I. Roghair, F. Gallucci, M. van Sint Annaland, Total vapor pressure of hydrophobic deep
 eutectic solvents: Experiments and modelling, J. Mol. Liq. 325 (2021) 115227.
 https://doi.org/10.1016/J.MOLLIQ.2020.115227.
- .293[111]Z. Yang, Toxicity and biodegradability of deep eutectic solvents and natural deep eutectic.294solvents, Deep Eutectic Solvents Synth. Prop. Appl. (2019) 43–60..295https://doi.org/10.1002/9783527818488.ch3.
- .296[112]L. Lomba, M.P. Ribate, E. Sangüesa, J. Concha, M.P. Garralaga, D. Errazquin, C.B. Garc, B..297Giner, applied sciences Deep Eutectic Solvents : Are They Safe ?, Appl. Sci. MDPI. (2021).

- 1298 [113] H.G. Morrison, C.C. Sun, S. Neervannan, Characterization of thermal behavior of deep eutectic
 1299 solvents and their potential as drug solubilization vehicles, Int. J. Pharm. 378 (2009) 136–139.
 1300 https://doi.org/10.1016/j.ijpharm.2009.05.039.
- 1301 [114] M. Hayyan, M.A. Hashim, A. Hayyan, M.A. Al-Saadi, I.M. AlNashef, M.E.S. Mirghani, O.K.
 1302 Saheed, Are deep eutectic solvents benign or toxic?, Chemosphere. 90 (2013) 2193–2195.
 1303 https://doi.org/10.1016/J.CHEMOSPHERE.2012.11.004.
- [115] S. Mao, K. Li, Y. Hou, Y. Liu, S. Ji, H. Qin, F. Lu, Synergistic effects of components in deep
 eutectic solvents relieve toxicity and improve the performance of steroid biotransformation
 catalyzed by Arthrobacter simplex, J. Chem. Technol. Biotechnol. 93 (2018) 2729–2736.
 https://doi.org/10.1002/jctb.5629.
- 1308 [116] I. Juneidi, M. Hayyan, O. Mohd Ali, Toxicity profile of choline chloride-based deep eutectic
 1309 solvents for fungi and Cyprinus carpio fish, Environ. Sci. Pollut. Res. 23 (2016) 7648–7659.
 1310 https://doi.org/10.1007/s11356-015-6003-4.
- 1311 [117] I.P.E. Macário, S.P.M. Ventura, J.L. Pereira, A.M.M. Gonçalves, J.A.P. Coutinho, F.J.M.
 1312 Gonçalves, The antagonist and synergist potential of cholinium-based deep eutectic solvents,
 1313 Ecotoxicol. Environ. Saf. 165 (2018) 597–602. https://doi.org/10.1016/J.ECOENV.2018.09.027.
- 1314 [118] K. Radošević, M. Cvjetko Bubalo, V. Gaurina Srček, D. Grgas, T. Landeka Dragičević, R.I.
 1315 Redovniković, Evaluation of toxicity and biodegradability of choline chloride based deep
 1316 eutectic solvents, Ecotoxicol. Environ. Saf. 112 (2015) 46–53.
 1317 https://doi.org/10.1016/J.ECOENV.2014.09.034.
- I.P.E. Macário, F. Jesus, J.L. Pereira, S.P.M. Ventura, A.M.M. Gonçalves, J.A.P. Coutinho, F.J.M.
 Gonçalves, Unraveling the ecotoxicity of deep eutectic solvents using the mixture toxicity
 theory, Chemosphere. 212 (2018) 890–897.
 https://doi.org/10.1016/J.CHEMOSPHERE.2018.08.153.
- [120] R. Ahmadi, B. Hemmateenejad, A. Safavi, Z. Shojaeifard, M. Mohabbati, O. Firuzi, Assessment
 of cytotoxicity of choline chloride-based natural deep eutectic solvents against human HEK293 cells: A QSAR analysis, Chemosphere. 209 (2018) 831–838.
 https://doi.org/10.1016/J.CHEMOSPHERE.2018.06.103.
- 1326 [121] OECD GUIDELINE FOR TESTING OF CHEMICALS, (n.d.).
- [122] Q. Wen, J.X. Chen, Y.L. Tang, J. Wang, Z. Yang, Assessing the toxicity and biodegradability of
 deep eutectic solvents, Chemosphere. 132 (2015) 63–69.
 https://doi.org/10.1016/J.CHEMOSPHERE.2015.02.061.
- [123] D. Lapeña, D. Errazquin, L. Lomba, C. Lafuente, B. Giner, Ecotoxicity and biodegradability of
 pure and aqueous mixtures of deep eutectic solvents: glyceline, ethaline, and reline, Environ.
 Sci. Pollut. Res. 28 (2021) 8812–8821. https://doi.org/10.1007/s11356-020-11144-w.
- 1333[124]D. Coleman, N. Gathergood, Biodegradation studies of ionic liquids, Chem. Soc. Rev. 39 (2010).334.334.339/10.1039/b817717c.
- .335 [125] Z. Yang, Toxicity and Biodegradability of Deep Eutectic Solvents and Natural Deep Eutectic
 .336 Solvents, Deep Eutectic Solvents. (2019) 43–60. https://doi.org/10.1002/9783527818488.ch3.
- [126] B.Y. Zhao, P. Xu, F.X. Yang, H. Wu, M.H. Zong, W.Y. Lou, Biocompatible Deep Eutectic Solvents
 Based on Choline Chloride: Characterization and Application to the Extraction of Rutin from
 Sophora japonica, ACS Sustain. Chem. Eng. 3 (2015) 2746–2755.

- 1340 https://doi.org/10.1021/acssuschemeng.5b00619.
- 1341 [127] I. Juneidi, M. Hayyan, M.A. Hashim, Evaluation of toxicity and biodegradability for cholinium1342 based deep eutectic solvents, RSC Adv. 5 (2015) 83636–83647.
 1343 https://doi.org/10.1039/c5ra12425e.
- 1344 [128] G.W. Meindersma, A.B. de Haan, Conceptual process design for aromatic/aliphatic separation
 1345 with ionic liquids, Chem. Eng. Res. Des. 86 (2008) 745–752.
 1346 https://doi.org/10.1016/J.CHERD.2008.02.016.
- 1347 [129] V.R. Ferro, E. Ruiz, J. De Riva, J. Palomar, Introducing process simulation in ionic liquids
 1348 design/selection for separation processes based on operational and economic criteria through
 1349 the example of their regeneration, Sep. Purif. Technol. 97 (2012) 195–204.
 1350 https://doi.org/10.1016/J.SEPPUR.2012.02.026.
- [130] P. García-Gutiérrez, J. Jacquemin, C. McCrellis, I. Dimitriou, S.F.R. Taylor, C. Hardacre, R.W.K.
 Allen, Techno-Economic Feasibility of Selective CO2 Capture Processes from Biogas Streams
 Using Ionic Liquids as Physical Absorbents, Energy and Fuels. 30 (2016) 5052–5064.
 https://doi.org/10.1021/acs.energyfuels.6b00364.
- 1355 [131] E. Słupek, P. Makoś, J. Gębicki, Theoretical and Economic Evaluation of Low-Cost Deep
 1356 Eutectic Solvents for Effective Biogas Upgrading to Bio-Methane, Energies. 13 (2020) 3379.
 1357 https://doi.org/10.3390/en13133379.
- 1358 [132] E. Słupek, P. Makoś, J. Gębicki, Deodorization of model biogas by means of novel non-ionic
 1359 deep eutectic solvent, Arch. Environ. Prot. 46 (2020) 41–46.
 1360 https://doi.org/10.24425/aep.2020.132524.
- 1361 [133] C. Ma, Y. Xie, X. Ji, C. Liu, X. Lu, Modeling, simulation and evaluation of biogas upgrading using
 aqueous choline chloride/urea, Appl. Energy. 229 (2018) 1269–1283.
 https://doi.org/10.1016/J.APENERGY.2017.03.059.
- [134] M. Candia-Lomelí, I. Covarrubias-Garcia, A. Aizpuru, S. Arriaga, Preparation and
 physicochemical characterization of deep eutectic solvents and ionic liquids for the potential
 absorption and biodegradation of styrene vapors, J. Hazard. Mater. 441 (2023) 129835.
 https://doi.org/10.1016/J.JHAZMAT.2022.129835.
- 1368[135]D. Kundu, P.S. Rao, T. Banerjee, First-Principles Prediction of Kamlet-Taft Solvatochromic1369Parameters of Deep Eutectic Solvent Using the COSMO-RS Model, Ind. Eng. Chem. Res. 591370(2020) 11329–11339. https://doi.org/10.1021/acs.iecr.0c00574.
- [136] C. Florindo, A.J.S. McIntosh, T. Welton, L.C. Branco, I.M. Marrucho, A closer look into deep eutectic solvents: Exploring intermolecular interactions using solvatochromic probes, Phys.
 1373 Chem. Chem. Phys. 20 (2017) 206–213. https://doi.org/10.1039/c7cp06471c.
- 1374 [137] C.C. Chen, Y.H. Huang, S.M. Hung, C. Chen, C.W. Lin, H.H. Yang, Hydrophobic deep eutectic
 1375 solvents as attractive media for low-concentration hydrophobic VOC capture, Chem. Eng. J.
 1376 424 (2021) 130420. https://doi.org/10.1016/j.cej.2021.130420.
- .377[138]L. Lomba, F. Tucciarone, B. Giner, M. Artal, C. Lafuente, Thermophysical characterization of
choline chloride: Resorcinol and its mixtures with water, Fluid Phase Equilib. 557 (2022).379113435. https://doi.org/10.1016/J.FLUID.2022.113435.
- .380[139]A. Haz, P. Strizincova, V. Majova, A. Skulcova, M. Jablonsky, Thermal stability of selected deep.381eutectic solvents, Int. J. Recent Sci. Res. 7 (2016) 14441–14444.

- [140] N. Rodriguez Rodriguez, A. Van Den Bruinhorst, L.J.B.M. Kollau, M.C. Kroon, K. Binnemans,
 Degradation of Deep-Eutectic Solvents Based on Choline Chloride and Carboxylic Acids, ACS
 Sustain. Chem. Eng. 7 (2019) 11521–11528.
- 1385 https://doi.org/10.1021/acssuschemeng.9b01378.
- [141] Q. Liu, X. Zhao, D. Yu, H. Yu, Y. Zhang, Z. Xue, T. Mu, Novel deep eutectic solvents with
 different functional groups towards highly efficient dissolution of lignin, Green Chem. 21
 (2019) 5291–5297. https://doi.org/10.1039/c9gc02306b.
- 1389 [142] P. Makoś, G. Boczkaj, Deep eutectic solvents based highly efficient extractive desulfurization
 1390 of fuels Eco-friendly approach, J. Mol. Liq. 296 (2019) 111916–111927.
 1391 https://doi.org/10.1016/j.molliq.2019.111916.
- 1392 [143] R.K. Ibrahim, M. Hayyan, M.A.A. Al-saadi, A. Hayyan, Diethylene glycol based deep eutectic
 1393 solvents and their physical properties, Stud. Univ. Babeş-Bolyai. (2017) 433–450.
 1394 https://doi.org/10.24193/subbchem.2017.4.37.
- [144] F. Gabriele, M. Chiarini, R. Germani, M. Tiecco, N. Spreti, Effect of water addition on choline
 chloride/glycol deep eutectic solvents: Characterization of their structural and
 physicochemical properties, J. Mol. Liq. 291 (2019) 111301.
 https://doi.org/10.1016/j.molliq.2019.111301.
- [145] G. Xu, M. Shi, P. Zhang, Z. Tu, X. Hu, X. Zhang, Y. Wu, Tuning the composition of deep eutectic
 solvents consisting of tetrabutylammonium chloride and n-decanoic acid for adjustable
 separation of ethylene and ethane, Sep. Purif. Technol. 298 (2022) 121680.
 https://doi.org/10.1016/J.SEPPUR.2022.121680.
- 1403 [146] M. Mu, X. Zhang, G. Yu, R. Xu, N. Liu, N. Wang, B. Chen, C. Dai, Effective absorption of
 1404 dichloromethane using deep eutectic solvents, J. Hazard. Mater. 439 (2022) 129666.
 1405 https://doi.org/10.1016/J.JHAZMAT.2022.129666.

[147] L. Moura, T. Moufawad, M. Ferreira, H. Bricout, S. Tilloy, E. Monflier, M.F. Costa Gomes, D.
Landy, S. Fourmentin, Deep eutectic solvents as green absorbents of volatile organic
pollutants, Environ. Chem. Lett. 15 (2017) 747–753. https://doi.org/10.1007/s10311-0170654-y.

- 1410 [148] T. Moufawad, M. Costa Gomes, S. Fourmentin, Deep eutectic solvents as absorbents for VOC
 1411 and VOC mixtures in static and dynamic processes, Chem. Eng. J. 448 (2022) 137619.
 1412 https://doi.org/10.1016/j.cej.2022.137619.
- 1413 [149] E. Słupek, P. Makoś-Chełstowska, J. Gębicki, Removal of siloxanes from model biogas by
 1414 means of deep eutectic solvents in absorption process, Materials (Basel). 14 (2021) 1–20.
 1415 https://doi.org/10.3390/ma14020241.

1416[150]Y. Song, S. Chen, F. Luo, L. Sun, Absorption of Toluene Using Deep Eutectic Solvents: Quantum1417Chemical Calculations and Experimental Investigation, Ind. Eng. Chem. Res. 59 (2020) 22605–141822618. https://doi.org/10.1021/acs.iecr.0c04986.

.419[151]P. Makoś-Chełstowska, E. Słupek, A. Małachowska, Superhydrophobic sponges based on.420green deep eutectic solvents for spill oil removal from water, J. Hazard. Mater. 425 (2022)..421https://doi.org/10.1016/j.jhazmat.2021.127972.

[152] P. Makoś-Chełstowska, E. Słupek, A. Kramarz, J. Gębicki, New carvone-based deep eutectic solvents for siloxanes capture from biogas, Int. J. Mol. Sci. 22 (2021) 9551–9574.

.422

- 1424 https://doi.org/10.3390/ijms22179551.
- [153] C.C. Chen, Y.H. Huang, J.Y. Fang, Hydrophobic deep eutectic solvents as green absorbents for
 hydrophilic VOC elimination, J. Hazard. Mater. 424 (2022) 127366.
 https://doi.org/10.1016/j.jhazmat.2021.127366.
- 1428 [154] F. Bergua, M. Castro, J. Muñoz-Embid, C. Lafuente, M. Artal, Hydrophobic eutectic solvents:
 1429 Thermophysical study and application in removal of pharmaceutical products from water,
 1430 Chem. Eng. J. 411 (2021) 128472. https://doi.org/10.1016/J.CEJ.2021.128472.
- 1431 [155] P. Villarim, E. Genty, J. Zemmouri, S. Fourmentin, Deep eutectic solvents and conventional solvents as VOC absorbents for biogas upgrading: A comparative study, Chem. Eng. J. 446
 1433 (2022) 136875. https://doi.org/10.1016/J.CEJ.2022.136875.
- 1434 [156] D.J.G.P. Van Osch, C.H.J.T. Dietz, J. Van Spronsen, M.C. Kroon, F. Gallucci, M. Van Sint
 1435 Annaland, R. Tuinier, A Search for Natural Hydrophobic Deep Eutectic Solvents Based on
 1436 Natural Components, ACS Sustain. Chem. Eng. 7 (2019) 2933–2942.
 1437 https://doi.org/10.1021/acssuschemeng.8b03520.
- 1438 [157] P.J. Castro, A.E. Redondo, J.E. Sosa, M.E. Zakrzewska, A.V.M. Nunes, J.M.M. Araújo, A.B.
 1439 Pereiro, Absorption of Fluorinated Greenhouse Gases in Deep Eutectic Solvents, Ind. Eng.
 1440 Chem. Res. 59 (2020) 13246–13259. https://doi.org/10.1021/acs.iecr.0c01893.
- 1441[158]What is BTEX and why is it important?, (n.d.). https://www.aeroqual.com/blog/what-is-btex1442(accessed March 29, 2022).
- I.G.C. Bretón, R.M.C. Bretón, S.M. Morales, J.D.W. Kahl, C. Guarnaccia, R. del Carmen Lara
 Severino, M.R. Marrón, E.R. Lara, M. de la Luz Espinosa Fuentes, M.P.U. Chi, G.L. Sánchez,
 Health risk assessment of the levels of BTEX in ambient air of one urban site located in leon,
 guanajuato, mexico during two climatic seasons, Atmosphere (Basel). 11 (2020).
 https://doi.org/10.3390/atmos11020165.
- 1448[160]K.A.U. Johansson, Characterisation of contaminants in biogas before and after upgrading to1449vehicle gas, Rapp. SGC 246. (2012).
- 1450 [161] F. Abbasi, H. Pasalari, J.M. Delgado-Saborit, A. Rafiee, A. Abbasi, M. Hoseini, Characterization
 1451 and risk assessment of BTEX in ambient air of a Middle Eastern City, Process Saf. Environ. Prot.
 1452 139 (2020) 98–105. https://doi.org/10.1016/J.PSEP.2020.03.019.
- [162] Y. Li, C.P. Alaimo, M. Kim, N.Y. Kado, J. Peppers, J. Xue, C. Wan, P.G. Green, R. Zhang, B.M.
 Jenkins, C.F.A. Vogel, S. Wuertz, T.M. Young, M.J. Kleeman, Composition and Toxicity of
 Biogas Produced from Different Feedstocks in California, Environ. Sci. Technol. (2019).
 https://doi.org/10.1021/acs.est.9b03003.
- 1457 [163] X. Qiao, X. Sun, H. Yang, H. An, F. Li, W. Xue, Y. Wang, Solubilities of Benzene, Toluene, and
 1458 Ethylbenzene in Deep Eutectic Solvents, J. Chem. Eng. Data. 66 (2021) 2460–2469.
 1459 https://doi.org/10.1021/acs.jced.1c00091.
- .460 [164] A.N. Baghani, A. Sorooshian, M. Heydari, R. Sheikhi, S. Golbaz, Q. Ashournejad, M. Kermani, F.
 .461 Golkhorshidi, A. Barkhordari, A.J. Jafari, M. Delikhoon, A. Shahsavani, A case study of BTEX
 .462 characteristics and health effects by major point sources of pollution during winter in Iran,
 .463 Environ. Pollut. 247 (2019) 607–617. https://doi.org/10.1016/J.ENVPOL.2019.01.070.
- .464[165]M.J. Milazzo, J.M. Gohlke, D.L. Gallagher, A.A. Scott, B.F. Zaitchik, L.C. Marr, Potential for city.465parks to reduce exposure to BTEX in air, Environ. Sci. Process. Impacts. 21 (2019) 40–50.

- 1466 https://doi.org/10.1039/c8em00252e.
- 1467 [166] C. Peng, J.W. Lee, H.T. Sichani, J.C. Ng, Toxic effects of individual and combined effects of
 1468 BTEX on Euglena gracilis, J. Hazard. Mater. 284 (2015) 10–18.
 1469 https://doi.org/10.1016/J.JHAZMAT.2014.10.024.
- 1470 [167] C.C. Chang, T.Y. Chen, C.Y. Lin, C.S. Yuan, S.C. Liu, Effects of reactive hydrocarbons on ozone
 1471 formation in southern Taiwan, Atmos. Environ. 39 (2005) 2867–2878.
 1472 https://doi.org/10.1016/J.ATMOSENV.2004.12.042.
- 1473 [168] S. Rasi, J. Läntelä, J. Rintala, Trace compounds affecting biogas energy utilisation A review,
 1474 Energy Convers. Manag. 52 (2011) 3369–3375.
 1475 https://doi.org/10.1016/j.enconman.2011.07.005.
- 1476 [169] E. Ryckebosch, M. Drouillon, H. Vervaeren, Techniques for transformation of biogas to
 1477 biomethane, Biomass and Bioenergy. 35 (2011) 1633–1645.
 1478 https://doi.org/10.1016/j.biombioe.2011.02.033.
- 1479 [170] G. Quijano, A. Couvert, A. Amrane, G. Darracq, C. Couriol, P. Le Cloirec, L. Paquin, D. Carrié,
 1480 Absorption and biodegradation of hydrophobic volatile organic compounds in ionic liquids,
 1481 Water. Air. Soil Pollut. 224 (2013). https://doi.org/10.1007/s11270-013-1528-y.
- 1482 [171] M.J. Salar-García, V.M. Ortiz-Martínez, F.J. Hernández-Fernández, A.P. de los Ríos, J. Quesada1483 Medina, Ionic liquid technology to recover volatile organic compounds (VOCs), J. Hazard.
 1484 Mater. 321 (2017) 484–499. https://doi.org/10.1016/J.JHAZMAT.2016.09.040.
- 1485[172]R.C. Castells, Determination of gas–liquid partition coefficients by gas chromatography, J.1486Chromatogr. A. 1037 (2004) 223–231. https://doi.org/10.1016/J.CHROMA.2003.12.019.
- 1487[173]L. Rohrschneider, Solvent Characterization by Gas-Liquid Partition Coefficients of Selected1488Solutes, Anal. Chem. 45 (1973) 1241–1247. https://doi.org/10.1021/ac60329a023.
- 1489 [174] M.J. Patel, S.C. Popat, M.A. Deshusses, Determination and correlation of the partition
 1490 coefficients of 48 volatile organic and environmentally relevant compounds between air and
 1491 silicone oil, Chem. Eng. J. 310 (2017) 72–78. https://doi.org/10.1016/J.CEJ.2016.10.086.
- [175] M.T. Cesário, W.A. Beverloo, J. Tramper, H.H. Beeftink, Enhancement of gas-liquid mass
 transfer rate of apolar pollutants in the biological waste gas treatment by a dispersed organic
 solvent, Enzyme Microb. Technol. 21 (1997) 578–588. https://doi.org/10.1016/S01410229(97)00069-0.
- 1496 [176] T. Moufawad, L. Moura, M. Ferreira, bastien Tilloy, E. Monflier, M. Costa Gomes, D. Landy, S.
 1497 Fourmentin, First Evidence of Cyclodextrin Inclusion Complexes in a Deep Eutectic Solvent, 11
 1498 (2022) 16. https://doi.org/10.1021/acssuschemeng.9b00044.
- 1499[177]S. Panda, S. Fourmentin, Cyclodextrin-based supramolecular low melting mixtures: efficient1500absorbents for volatile organic compounds abatement, Environ. Sci. Pollut. Res. 29 (2022)1.501264–270. https://doi.org/10.1007/s11356-021-16279-y.
- .502 [178] M. Kfoury, D. Landy, S. Fourmentin, Contribution of headspace to the analysis of cyclodextrin
 .503 inclusion complexes, J. Incl. Phenom. Macrocycl. Chem. 93 (2019) 19–32.
 .504 https://doi.org/10.1007/s10847-018-0818-9.
 - [179] M.E. Di Pietro, G. Colombo Dugoni, M. Ferro, A. Mannu, F. Castiglione, M. Costa Gomes, S. Fourmentin, A. Mele, Do Cyclodextrins Encapsulate Volatiles in Deep Eutectic Systems?, ACS

- 1507Sustain. Chem. Eng. 7 (2019) 17397–17405.1508https://doi.org/10.1021/acssuschemeng.9b04526.
- [180] W. Wang, Y. Zhang, W. Liu, Bioinspired fabrication of high strength hydrogels from noncovalent interactions, Prog. Polym. Sci. 71 (2017) 1–25.
 https://doi.org/10.1016/J.PROGPOLYMSCI.2017.04.001.
- [181] T. Brouwer, S.R.A. Kersten, G. Bargeman, B. Schuur, trends in solvent impact on infinite
 dilution activity coefficients of solutes reviewed and visualized using an algorithm to support
 selection of solvents for greener fluid separations, Sep. Purif. Technol. 272 (2021) 118727.
 https://doi.org/10.1016/J.SEPPUR.2021.118727.
- 1516 [182] A.-S. Rodriguez Castillo, P.-F. Biard, S. Guihéneuf, L. Paquin, A. Amrane, A. Couvert,
 1517 Assessment of VOC absorption in hydrophobic ionic liquids: Measurement of partition and
 1518 diffusion coefficients and simulation of a packed column, Chem. Eng. J. 360 (2019) 1416–
 1519 1426. https://doi.org/https://doi.org/10.1016/j.cej.2018.10.146.
- 1520 [183] W. Wang, X. Ma, S. Grimes, H. Cai, M. Zhang, Study on the absorbability, regeneration
 1521 characteristics and thermal stability of ionic liquids for VOCs removal, Chem. Eng. J. 328
 1522 (2017) 353–359. https://doi.org/10.1016/J.CEJ.2017.06.178.
- IS23 [184] J. Bruneel, C. Walgraeve, K. Van Huffel, H. Van Langenhove, Determination of the gas-to-liquid
 partitioning coefficients using a new dynamic absorption method (DynAb method), Chem.
 Eng. J. 283 (2016) 544–552. https://doi.org/10.1016/J.CEJ.2015.07.053.
- 1526 [185] T. Moufawad, M. Costa Gomes, S. Fourmentin, Deep eutectic solvents as absorbents for VOC
 1527 and VOC mixtures in static and dynamic processes, Chem. Eng. J. 448 (2022) 137619.
 1528 https://doi.org/10.1016/j.cej.2022.137619.
- 1529 [186] E. Supek, P. Makoś, J. Gębicki, A. Rogala, Purification of model biogas from toluene using deep eutectic solvents, E3S Web Conf. 116 (2019).
 1531 https://doi.org/10.1051/e3sconf/201911600078.
- 1532 [187] E. Słupek, P. Makos, D. Dobrzyniewski, B. Szulczynski, J. Gebicki, Process control of biogas
 1533 purification using electronic nose, Chem. Eng. Trans. 82 (2020).
 1534 https://doi.org/10.3303/CET2082072.
- 1535 [188] G. Li, C. Gui, R. Zhu, Z. Lei, Deep eutectic solvents for efficient capture of cyclohexane in
 1536 volatile organic compounds: Thermodynamic and molecular mechanism, AIChE J. 68 (2022) 1–
 1537 12. https://doi.org/10.1002/aic.17535.
- [189] R. Chromá, M. Vilková, I. Shepa, P. Makoś-Chełstowska, V. Andruch, Investigation of
 tetrabutylammonium bromide-glycerol-based deep eutectic solvents and their mixtures with
 water by spectroscopic techniques, J. Mol. Liq. 330 (2021) 115617.
 https://doi.org/10.1016/j.molliq.2021.115617.
- 1542 [190] P. Makoś-Chełstowska, R. Chromá, V. Andruch, Closer look into the structures of
 1543 tetrabutylammonium bromide–glycerol-based deep eutectic solvents and their mixtures with
 1544 water, J. Mol. Liq. 338 (2021) 116676. https://doi.org/10.1016/J.MOLLIQ.2021.116676.
- .545 [191] E. Słupek, P. Makoś, Absorptive Desulfurization of Model Biogas Stream Using Choline
 .546 Chloride-Based Deep Eutectic Solvents, Sustainability. 12 (2020) 1619–1635.
 .547 https://doi.org/10.3390/su12041619.
- .548 [192] A.I. Adnan, M.Y. Ong, S. Nomanbhay, K.W. Chew, P.L. Show, Technologies for biogas

- 1549 upgrading to biomethane: A review, Bioengineering. 6 (2019) 1–23.
- 1550 https://doi.org/10.3390/bioengineering6040092.
- [193] I. Angelidaki, L. Xie, G. Luo, Y. Zhang, H. Oechsner, A. Lemmer, R. Munoz, P.G. Kougias, Biogas
 Upgrading: Current and Emerging Technologies, Biofuels Altern. Feed. Convers. Process. Prod.
 Liq. Gaseous Biofuels. (2019) 817–843. https://doi.org/10.1016/B978-0-12-816856-1.00033-6.
- 1554 [194] S. Varjani, R. Joshi, V.K. Srivastava, H.H. Ngo, W. Guo, Treatment of wastewater from
 1555 petroleum industry: current practices and perspectives, Environ. Sci. Pollut. Res. 27 (2020)
 1556 27172–27180. https://doi.org/10.1007/s11356-019-04725-x.
- [195] G. Boczkaj, P. Makoś, A. Fernandes, A. Przyjazny, New procedure for the control of the
 treatment of industrial effluents to remove volatile organosulfur compounds, J. Sep. Sci. 39
 (2016). https://doi.org/10.1002/jssc.201600608.
- 1560 [196] C.L. Lee, P. Brimblecombe, Anthropogenic contributions to global carbonyl sulfide, carbon
 1561 disulfide and organosulfides fluxes, Earth-Science Rev. 160 (2016) 1–18.
 1562 https://doi.org/10.1016/J.EARSCIREV.2016.06.005.
- 1563[197]A. De Angelis, Natural gas removal of hydrogen sulphide and mercaptans, Appl. Catal. B1564Environ. 113–114 (2012) 37–42. https://doi.org/10.1016/J.APCATB.2011.11.026.
- 1565 [198] S. Lee, Q. Xu, M. Booth, T.G. Townsend, P. Chadik, G. Bitton, Reduced sulfur compounds in gas
 1566 from construction and demolition debris landfills, Waste Manag. 26 (2006) 526–533.
 1567 https://doi.org/10.1016/J.WASMAN.2005.10.010.
- 1568[199]P.L. Kasper, A. Feilberg, Regenerative one-stage catalytic absorption process with cupric ions1569for removal of reduced sulfur compounds in polluted air, Environ. Technol. (United Kingdom).1570(2022) 1–11. https://doi.org/10.1080/09593330.2022.2077132.
- 1571 [200] F.A.T. Andersson, A. Karlsson, B.H. Svensson, J. Ejlertsson, Occurrence and abatement of
 1572 volatile sulfur compounds during biogas production, J. Air Waste Manag. Assoc. 54 (2004)
 1573 855–861. https://doi.org/10.1080/10473289.2004.10470953.
- 1574[201]B.P. Lomans, C. Van Der Drift, a Pol, H.J.M.O. Den Camp, Cellular and Molecular Life Sciences1575Microbial cycling of volatile organic sulfur compounds, Cell. Mol. Life Sci. 59 (2002) 575–588.
- 1576 [202] E. Smet, P. Lens, H. Van Langenhove, Treatment of waste gases contaminated with odorous
 1577 sulfur compounds, Crit. Rev. Environ. Sci. Technol. 28 (1998) 89–117.
 1578 https://doi.org/10.1080/10643389891254179.
- 1579 [203] C.H. Hsu, H. Chu, C.M. Cho, Absorption and reaction kinetics of amines and ammonia
 1580 solutions with carbon dioxide in flue gas, J. Air Waste Manag. Assoc. 53 (2003) 246–252.
 1581 https://doi.org/10.1080/10473289.2003.10466139.
- 1582[204]K. Zhang, S. Ren, X. Yang, Y. Hou, W. Wu, Y. Bao, Efficient absorption of low-concentration1583SO2 in simulated flue gas by functional deep eutectic solvents based on imidazole and its1584derivatives, Chem. Eng. J. 327 (2017) 128–134. https://doi.org/10.1016/j.cej.2017.06.081.
- [205] J. Lemus, J. Bedia, C. Moya, N. Alonso-Morales, M.A. Gilarranz, J. Palomar, J.J. Rodriguez,
 Ammonia capture from the gas phase by encapsulated ionic liquids (ENILs), RSC Adv. 6 (2016)
 61650–61660. https://doi.org/10.1039/c6ra11685j.
 - [206] N. Wang, L. Tan, L. Xie, Y. Wang, T. Ellis, Investigation of volatile methyl siloxanes in biogas and the ambient environment in a landfill, J. Environ. Sci. 91 (2020) 54–61.

- 1590 https://doi.org/10.1016/J.JES.2020.01.005.
- [207] C. Pascual, S. Cantera, R. Lebrero, Volatile Siloxanes Emissions: Impact and Sustainable
 Abatement Perspectives, Trends Biotechnol. 39 (2021) 1245–1248.
 https://doi.org/10.1016/J.TIBTECH.2021.05.003.
- 1594 [208] T.M. Tran, A.Q. Hoang, S.T. Le, T.B. Minh, K. Kannan, A review of contamination status,
 1595 emission sources, and human exposure to volatile methyl siloxanes (VMSs) in indoor
 1596 environments, Sci. Total Environ. 691 (2019) 584–594.
 1597 https://doi.org/10.1016/J.SCITOTENV.2019.07.168.
- 1598 [209] E. Gallego, J.F. Perales, F.J. Roca, X. Guardino, E. Gadea, Volatile methyl siloxanes (VMS)
 1599 concentrations in outdoor air of several Catalan urban areas, Atmos. Environ. 155 (2017) 108–
 1600 118. https://doi.org/10.1016/J.ATMOSENV.2017.02.013.
- 1601 [210] E.A. McBean, Siloxanes in biogases from landfills and wastewater digesters, Can. J. Civ. Eng. 35
 1602 (2008) 431–436. https://doi.org/10.1139/L07-144.
- 1603 [211] G. Piechota, Removal of siloxanes from biogas upgraded to biomethane by Cryogenic
 1604 Temperature Condensation System, J. Clean. Prod. 308 (2021) 127404.
 1605 https://doi.org/10.1016/J.JCLEPRO.2021.127404.
- 1606[212]I.H. Bell, E. Mickoleit, C.-M. Hsieh, S.-T. Lin, J. Vrabec, C. Breitkopf, A. Jä, A Benchmark Open-1607Source Implementation of COSMO-SAC, (2020). https://doi.org/10.1021/acs.jctc.9b01016.
- 1608[213]R. Atkinson, Atmospheric chemistry of VOCs and NOx, Atmos. Environ. 34 (2000) 2063–2101.1609https://doi.org/10.1016/S1352-2310(99)00460-4.
- 1610 [214] R. Beale, P.S. Liss, J.L. Dixon, P.D. Nightingale, Quantification of oxygenated volatile organic
 1611 compounds in seawater by membrane inlet-proton transfer reaction/mass spectrometry,
 1612 Anal. Chim. Acta. 706 (2011) 128–134. https://doi.org/10.1016/J.ACA.2011.08.023.
- [215] S.J. Borghoff, T.S. Poet, S. Green, J. Davis, B. Hughes, T. Mensing, S.S. Sarang, A.M. Lynch, G.C.
 Hard, Methyl isobutyl ketone exposure-related increases in specific measures of α2u-globulin
 (α2u) nephropathy in male rats along with in vitro evidence of reversible protein binding,
 Toxicology. 333 (2015) 1–13. https://doi.org/10.1016/J.TOX.2015.02.003.
- 1617 [216] M. Gupta, P. Chaudhary, A. Singh, A. Verma, D. Yadav, B.C. Yadav, Development of MoO3-CdO
 1618 nanoparticles based sensing device for the detection of harmful acetone levels in our skin and
 1619 body via nail paint remover, Sensors Actuators B Chem. 368 (2022) 132102.
 1620 https://doi.org/10.1016/J.SNB.2022.132102.
- 1621[217]J. Auvinen, L. Wirtanen, The influence of photocatalytic interior paints on indoor air quality,1622Atmos. Environ. 42 (2008) 4101–4112. https://doi.org/10.1016/J.ATMOSENV.2008.01.031.
- 1623[218]W. Li, H.T. Lu, M.S. Doblin, A. Bacic, G.W. Stevens, K.A. Mumford, A solvent loss study for the
application of solvent extraction processes in the pharmaceutical industry, Chem. Eng. Sci.1.625250 (2022) 117400. https://doi.org/10.1016/J.CES.2021.117400.
- .626 [219] G. Boczkaj, P. Makoś, A. Przyjazny, Application of dynamic headspace and gas
 .627 chromatography coupled to mass spectrometry (DHS-GC-MS) for the determination of
 .628 oxygenated volatile organic compounds in refinery effluents, Anal. Methods. 8 (2016).
 .629 https://doi.org/10.1039/c5ay03043a.
 - [220] S. Indra, R. Subramanian, S. Daschakraborty, Absorption of Volatile Organic Compounds

- 1631Toluene and Acetaldehyde in Choline Chloride-Based Deep Eutectic Solvents, J. Phys. Chem. B.1632126 (2022) 3705–3716. https://doi.org/10.1021/acs.jpcb.2c00076.
- 1633 [221] S. Indra, R. Subramanian, S. Daschakraborty, Interaction of volatile organic compounds
 1634 acetone and toluene with room temperature ionic liquid at the bulk and the liquid-vacuum
 1635 interface, J. Mol. Liq. 331 (2021) 115608. https://doi.org/10.1016/J.MOLLIQ.2021.115608.
- 1636[222]D.W.H. Rankin, CRC handbook of chemistry and physics, 89th edition, edited by David R. Lide,1637Crystallogr. Rev. 15 (2009) 223–224. https://doi.org/10.1080/08893110902764125.
- 1638 [223] F.A. Almomani, R.R. Bhosale, M.A.M.M. Khraisheh, A. Kumar, C. Kennes, Mineralization of
 1639 dichloromethane using solar-oxidation and activated TiO2: Pilot scale study, Sol. Energy. 172
 1640 (2018) 116–127. https://doi.org/10.1016/J.SOLENER.2018.07.042.
- 1641 [224] L. Bailón, M. Nikolausz, M. Kästner, M.C. Veiga, C. Kennes, Removal of dichloromethane from
 1642 waste gases in one- and two-liquid-phase stirred tank bioreactors and biotrickling filters,
 1643 Water Res. 43 (2009) 11–20. https://doi.org/10.1016/J.WATRES.2008.09.031.
- 1644 [225] F. Almomani, E.R. Rene, M.C. Veiga, R.R. Bhosale, C. Kennes, Treatment of waste gas
 1645 contaminated with dichloromethane using photocatalytic oxidation, biodegradation and their
 1646 combinations, J. Hazard. Mater. 405 (2021) 123735.
 1647 https://doi.org/10.1016/J.JHAZMAT.2020.123735.
- 1648 [226] P. Makoś-Chełstowska, E. Słupek, J. Gębicki, Deep eutectic solvent-based green absorbents for 1649 the effective removal of volatile organochlorine compounds from biogas, Green Chem. 23
 1650 (2021) 4814–4827. https://doi.org/10.1039/d1gc01735g.
- 1651 [227] A.R. Ribeiro, O.C. Nunes, M.F.R. Pereira, A.M.T. Silva, An overview on the advanced oxidation
 processes applied for the treatment of water pollutants defined in the recently launched
 Directive 2013/39/EU, Environ. Int. 75 (2015) 33–51.
 https://doi.org/10.1016/J.ENVINT.2014.10.027.
- 1655[228]A. Buekens, H. Huang, Comparative evaluation of techniques for controlling the formation and1656emission of chlorinated dioxins/furans in municipal waste incineration, J. Hazard. Mater. 621657(1998) 1–33. https://doi.org/https://doi.org/10.1016/S0304-3894(98)00153-8.
- 1658 [229] A.S. Rodriguez Castillo, P.F. Biard, S. Guihéneuf, L. Paquin, A. Amrane, A. Couvert, Assessment
 1659 of VOC absorption in hydrophobic ionic liquids: Measurement of partition and diffusion
 1660 coefficients and simulation of a packed column, Chem. Eng. J. 360 (2019) 1416–1426.
 1661 https://doi.org/10.1016/j.cej.2018.10.146.
- [230] Z. Wu, S. Shi, G. Zhan, F. Chang, Y. Bai, X. Zhang, J. C. S. Wu, S. Zeng, Ionic liquid screening for
 dichloromethane absorption by multi-scale simulations, Sep. Purif. Technol. 275 (2021)
 119187. https://doi.org/10.1016/J.SEPPUR.2021.119187.
- [231] W. Wu, T. Li, H. Gao, D. Shang, W. Tu, B. Wang, X. Zhang, Efficient absorption of
 dichloromethane using imidazolium based ionic liquids, Guocheng Gongcheng Xuebao/The
 Chinese J. Process Eng. 19 (2019) 173–180. https://doi.org/10.12034/j.issn.1009606X.218162.
- .669 [232] Y. Zhou, L. Zhou, X. Zhang, Y. Chen, Preparation of zeolitic imidazolate framework-8 /graphene
 .670 oxide composites with enhanced VOCs adsorption capacity, Microporous Mesoporous Mater.
 .671 225 (2016) 488–493. https://doi.org/10.1016/j.micromeso.2016.01.047.
- .672 [233] J.E. Sosa, R.P.P.L. Ribeiro, P.J. Castro, J.P.B. Mota, A.B. Pereiro, J.M.M. Araújo, Sorption of

- 1673fluorinated greenhouse gases in silica-supported fluorinated ionic liquids, J. Environ. Chem.1674Eng. 10 (2022) 108580. https://doi.org/10.1016/J.JECE.2022.108580.
- 1675 [234] S. Asensio-Delgado, F. Pardo, G. Zarca, A. Urtiaga, Vapor-Liquid Equilibria and Diffusion
 1676 Coefficients of Difluoromethane, 1,1,1,2-Tetrafluoroethane, and 2,3,3,3-Tetrafluoropropene
 1677 in Low-Viscosity Ionic Liquids, J. Chem. Eng. Data. 65 (2020) 4242–4251.
 1678 https://doi.org/10.1021/acs.jced.0c00224.
- 1679 [235] E.A. Heath, Amendment to the Montreal Protocol on Substances that Deplete the Ozone
 1680 Layer (Kigali Amendment), Int. Leg. Mater. 56 (2017) 193–205.
 1681 https://doi.org/10.1017/ilm.2016.2.
- [236] F.A. Hatab, O.A.Z. Ibrahim, S.E.E. Warrag, A.S. Darwish, T. Lemaoui, M.M. Alam, T. Alsufyani,
 V. Jevtovic, B. Jeon, F. Banat, S.W. Hasan, I.M. Alnashef, Y. Benguerba, Solvent Regeneration
 Methods for Combined Dearomatization, Desulfurization, and Denitrogenation of Fuels
 Using Deep Eutectic Solvents, ACS Omega. (2022).
 https://doi.org/10.1021/acsomega.2c05776.
- 1687 [237] J. González-Rivera, C. Pelosi, E. Pulidori, C. Duce, M.R. Tiné, G. Ciancaleoni, L. Bernazzani,
 1688 Guidelines for a correct evaluation of Deep Eutectic Solvents thermal stability, Curr. Res.
 1689 Green Sustain. Chem. 5 (2022) 1–5. https://doi.org/10.1016/j.crgsc.2022.100333.
- 1690 [238] B. Wang, J. Cheng, D. Wang, X. Li, Q. Meng, Z. Zhang, J. An, X. Liu, M. Li, Study on the
 1691 Desulfurization and Regeneration Performance of Functional Deep Eutectic Solvents, ACS
 1692 Omega. 5 (2020) 15353–15361. https://doi.org/10.1021/acsomega.0c01467.
- 1693 [239] S. E. E. Warrag, A. S. Darwish, F. O. S. Abuhatab, I. A. Adeyemi, M. C. Kroon, I. M. AlNashef,
 1694 Combined Extractive Dearomatization, Desulfurization, and Denitrogenation of Oil Fuels Using
 1695 Deep Eutectic Solvents: A Parametric Study, Ind. & amp; Eng. Chem. Res. 59 (2020) 11723–
 1696 11733. https://doi.org/10.1021/acs.iecr.0c01360.
- 1697 [240] Y. Dai, N. Zhang, C. Xing, Q. Cui, Q. Sun, The adsorption, regeneration and engineering
 applications of biochar for removal organic pollutants: A review, Chemosphere. 223 (2019)
 1699 12–27. https://doi.org/10.1016/j.chemosphere.2019.01.161.
- 1700 [241] S. Kulkarni, J. Kaware, Regeneration and Recovery in Adsorption- a Review, Int. J. Innov. Sci.
 1701 Eng. Technol. 1 (2014) 61–64.
- 1702 [242] C. Shu, T. Sun, Extractive desulfurisation of gasoline with tetrabutyl ammonium chloride1703 based deep eutectic solvents, Sep. Sci. Technol. 51 (2016) 1336–1343.
 1704 https://doi.org/10.1080/01496395.2016.1155602.
- 1705 [243] M.C. Ali, Q. Yang, A.A. Fine, W. Jin, Z. Zhang, H. Xing, Q. Ren, Efficient removal of both basic
 1706 and non-basic nitrogen compounds from fuels by deep eutectic solvents, Green Chem. 18
 1707 (2015) 157–164. https://doi.org/10.1039/c5gc01823d.

.710