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**NOVEL LOW VISCOUS, GREEN AND AMPHIPHILIC N-
OXIDES/PHENYLACETIC ACID BASED
DEEP EUTECTIC SOLVENTS**

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ABSTRACT

Four novel Deep Eutectic Solvents (DESs) were prepared by mixing phenylacetic acid (which is a natural molecule present in honey) with amine N-oxides, which are molecules easily biodegradable in nature. Three of these N-oxides are amphiphilic. The novel DESs have very low freezing points (from -34°C to 20°C) and they have very low viscosity, much lower than the most common and used DES in literature so far (choline chloride/urea mixture). The conductivity values resulted low and the ionicity analysis showed these DESs to be “super ionic”. Their polarity resulted high enough and it can be compared with other commonly used solvents or ionic liquids.

ACCEPTED MANUSCRIPT

KEYWORDS

Deep Eutectic Solvents (DESs), N-oxide, surfactants, low viscous liquids, green solvents.

1. INTRODUCTION

The design of innovative organic solvents plays a key-role in the green chemistry framework[1–3]. The novel liquids have advantageous green properties compared with typical organic solvents: low vapour pressure, low flammability, recycling capabilities (whenever used as reaction media) and so on. From this point of view Ionic Liquids (ILs) have played an important role for many years, thanks to their unique properties[4–6] ILs have been used in many topics such as extraction media, solubilizing agents and so on, but the most studied property of these liquids is represented by their use as reaction media for a wide number of chemical reactions[7–9]. Unfortunately, ILs showed high toxic properties, and this represents a disadvantage in terms of their “greenness”[10,11]. The *onium* salts present in the liquids has effects on the cell membranes of living cells, therefore, they determine the toxicity of these liquids[12,13].

Deep Eutectic Solvents (DESs) represent a step ahead in the design of novel green organic solvents[14–17]. These liquids are formed by simply mixing two (or more) high melting point compounds; the interactions occurring between these molecules lead to a significant decrease of the melting points of the mixtures, often to room temperature (RTDESs, Room Temperature Deep Eutectic Solvents)[18]. The properties of the DESs are similar to the ones of ILs. They have in fact low melting points (spanning from room temperature or lower to 60–80°C), low vapour pressure, low flammability, high recycle capability whenever used as reaction media and so on, but they have significant green advantages compared to ILs. The first green advantage of these mixtures is that their syntheses do not require any solvents or any other reactants except for the ones composing them: they can be easily obtained in fact by simply mixing and gently heating two or more solid compounds. The second green advantage of the DESs is represented by their non-toxicity and their biodegradability as demonstrated in many recent papers and reviews[19–21].

DESs are classified in literature as type I, II, III and IV depending on the kind of molecules involved in the liquid mixtures formation[17]. Considering the most used and studied mixtures in literature (choline chloride / urea and similar mixtures), this kind of classification can be simplified interpreting the DESs as mixtures of a hydrogen bond donor molecule (HBD) and a hydrogen bond acceptor molecule (HBA)[22,23]. However, changes in the molecules composing the DESs can provoke significant changes in their properties, and this leads to the realization and the studies of novel DESs mixtures, specifically designed for specific roles[24–30].

DESSs were studied in literature as reaction media for a wide number of reactions[16,31,32], and they can act as “innocent DESSs” (if their role is unspecified or not clearly understood in the reaction) or “active DESSs” (if the liquid mixture has a role in the reaction i.e. acid catalyst)[33]. There are also several applications of these novel liquids reported in literature such as: extraction media, solubilization of nanoparticles, separation media, use for carbon dioxide capture, use for drug delivery in biomedical applications, and so on[17,34–37].

Starting from our experience on the synthesis and on the characterization of specific molecules for specific roles and of novel ionic liquids[38–40], recently we prepared novel aromatic, aliphatic and amphiphilic DESSs[18,41]. In this work, we show the preparation and the characterization of novel N-oxide-based zwitterionic DESSs. These mixtures are formed by differently structured N-oxides as HBA molecules (also amphiphilic ones) and phenylacetic acid (PhAA) as HBD compound. There are many green advantages on the choice of these molecules: N-oxide compounds (particularly N-oxide surfactants) are environmentally friendly as they can be easily degraded in nature both via aerobic and anaerobic conditions[42,43]; PhAA is a compound largely present in honey and plants[44–46]. Therefore, these DESSs could possess relevant green properties.

2. EXPERIMENTAL

2.1 REAGENTS AND DESSs REALIZATION

Benzoic acid, salicylic acid, 2-chlorobenzoic acid, 3-chlorobenzoic acid, glycolic acid, 2-furoic acid, phenylacetic acid were purchased from Sigma-Aldrich and were used without further purifications.

- Synthesis of N-oxides (AO-12, AO-18, MO, MO-12): N-oxides can be synthesized with different procedures[47,48]. In this work, we used a simple and cheap procedure based on the use of hydrogen peroxide: the corresponding amine was put at 65-70°C in EtOH with 1.5 equivalents of H₂O₂. After 6h MnO₂ was added to destroy H₂O₂ excess, the liquid was filtered and the solvent was removed under vacuum. The resulting semi-solids were recrystallized twice in acetone/Et₂O mixtures.

N,N-dimethyldodecyl-N-amine oxide (AO-12): m.p. = 89-91°C; ¹H-NMR (400 MHz, CDCl₃) δ = 3.33-3.29 (m, 2H) 3.27 (s, 6H), 1.91-1.77 (m, 2H), 1.33-1.24 (m, 18H), 0.87 (t, 3H, J=8 Hz); ¹³C-NMR (101 MHz, CDCl₃) δ = 71.50, 58.10, 32.03, 29.73, 29.72, 29.62, 29.54, 29.45, 29.44, 26.71, 23.95, 22.81, 14.25; [M+H]⁺ = 230.2484 (calc.: 230.2484).

N,N-dimethylottadecyl-N-amine oxide (AO-18): m.p. = 91-97°C; ¹H-NMR (400 MHz, CDCl₃) δ = 3.32-3.28 (m, 2H) 3.27 (s, 6H), 1.90-1.76 (m, 2H), 1.32-1.24 (m, 30H), 0.86 (t, 3H, J=8 Hz); ¹³C-NMR (101 MHz, CDCl₃) δ = 71.49, 58.06, 32.06, 29.83, 29.80, 29.79, 29.74, 29.64, 29.55, 29.45, 26.71, 23.95, 22.82, 14.25; [M+H]⁺ = 286.3122 (calc.: 286.3104).

N-dodecylmorpholine-N-oxide (MO-12): m.p. = 71-78°C; ¹H-NMR (400 MHz, CDCl₃) δ = 4.47-4.41 (m, 2H), 3.81-3.78 (m, 2H), 3.36-3.29 (m, 7H), 1.98-1.86 (m, 2H), 1.35-1.26 (m, 20H), 0.89 (t, 3H, J=8 Hz). ¹³C-NMR (101 MHz, CDCl₃) δ = 72.02, 63.66, 61.69, 32.02, 29.72, 29.63, 29.47, 26.79, 22.80, 21.99, 14.23; [M+H]⁺ = 272.2554 (calc.: 272.2589).

N-methylmorpholine-N-oxide (MO): m.p. = 180-184°C; ¹H-NMR (400 MHz, CDCl₃) δ = 4.41-4.36 (m, 2H), 3.72-3.75 (m, 2H), 3.32-3.37 (m, 2H), 3.22 (s, 3H), 3.11-3.08 (m, 2H). ¹³C-NMR (101 MHz, CDCl₃) δ = 66.13, 61.73, 61.25; [M+H]⁺ = 118.0841 (calc.: 118.0868).

- DESs were prepared by mixing the solid compounds at the proper HBD/HBA molar ratio and heating the mixtures at 90°C when necessary, up to obtain a liquid phase.

- The water content of the novel mixtures is about 5% w/w as resulted via Karl-Fischer titration.

2.2 MELTING POINT DETERMINATION OF DESs

In a 10 mL round-bottomed flask, equipped with a thermometer, were introduced weighed amounts of N-oxides and phenylacetic acid. The binary systems were gently heated and mixed until became homogenous liquids, and then were gradually cooled first to room temperature then immersed in an acetone/liquid nitrogen mixture.

2.3 DENSITY MEASUREMENTS

The density values at eutectic ratio at different temperatures were obtained by measuring the weight of the sample in a 2.00 mL volumetric flask. The flasks were held in a thermostated bath for 1 hour then brought to volume by eliminating the amount of liquid with a Pasteur pipette. The flask was then thermostated at room temperature for 1 hour and then weighed on analytical balance.

2.4 VISCOSITY MEASUREMENTS

The viscosity of the eutectic mixtures was measured using a Fungilab Expert L viscometer, fitted with a thermostatic jacket and a temperature probe. The viscometer jacket was connected to an external thermostated bath. The viscosity measurements were obtained using a spindle attachment.

2.5 CONDUCTIVITY MEASUREMENTS

Conductivity measures were performed with an Analytical Control - Model 120 Microprocessor conductivity meter with a platinum cell (Cell constant $K = 1.05 \text{ cm}^{-1}$). The mixtures were thermostated with a glass-jacked beaker connected to a thermostatic bath. The readings were taken after 20–25 minutes for each temperature selected.

2.6 POLARITY MEASUREMENTS

The absorbance spectra of Nile Red (Sigma-Aldrich) in the DESs were registered in a Shimadzu UV-2401 PC spectrophotometer with a wavelength resolution of $\lambda \pm 0.2$. The dye solutions (10 mL for each sample) in the DESs were prepared putting 10 μL of a CHCl_3 solution of Nile Red ($2 \cdot 10^{-3} \text{ M}$) in a 10 mL flask; the chloroform was carefully evaporated using a nitrogen flux and the DESs were added to the dried dye. Three samples were acquired for each reading point, and the standard deviation between the absorbance of the three samples was considered as the precision of the measures.

2.7 KARL-FISCHER TITRATION MEASURES

The water content of all the DESs was evaluated via Karl-Fischer titration with Metrohm 684 KF Coulometer.

2.8 NMR AND MASS SPECTROMETRY MEASURES

^1H -NMR and ^{13}C -NMR spectra were recorded on a Bruker Avance III 400 MHz.

ESI MS measurements were performed on a Quadrupole Time-of-Flight mass spectrometer instrument (Xevo[®] G2 QToF; Waters Corporation, Milford, USA), equipped with a high-performance Z Spray[™] source and operating with MassLynx[™] Software package (Version 4.1, Waters Corporation). The instrument was calibrated using a 5 mM sodium formate solution in 90:10 2-propanol:water, in the m/z range 50-1200. The spectra were recorded in positive polarity, sensitivity mode. Source parameters: Source Temperature: 150°C; desolvation temperature: 250 °C; capillary voltage: 3.0 kV cone Voltage: 15V; Extraction Cone: 2.0V.

3. RESULTS AND DISCUSSION

N,N-dimethyldodecyl-N-amine oxide (AO-12) was chosen as HBA molecule for a preliminary screening with different solid carboxylic acids as HBD molecules. The freezing points of different mixtures with different carboxylic acids at different molar ratios were examined. In Table 1 the acids tested for this screening with their melting points, the optimal molar ratios acid/AO-12 (in terms of the lower melting points observed) and the freezing points of the DESs mixtures are reported.

Table 1: Acids tested as HBD, melting points (m.p.) of the acids, acid/AO-12 molar ratio, freezing points of the DESs mixtures.

Acid	Acid m.p. (°C)	Acid/AO-12 molar ratio	DES freezing point (°C) ^a
Benzoic	121-125	1.5	55
Salicylic	158-161	1.5	50
2-Chlorobenzoic	138-140	1.5	45
3-Chlorobenzoic	153-157	1.5	5
Glycolic	75-80	2	30
2-Furoic	128-132	2	15
Phenylacetic	76-78	1	-34

^aAO-12 m.p. = 89-91°C

From this screening on the acids as HBD, phenylacetic acid / N,N-dimethyldodecyl-N-amine oxide (PhAA/AO-12) mixture showed the lowest melting point in the set. Therefore, PhAA was chosen as HBD compound, considering also the natural source of the molecule and the greenness of the resulting DESs.

As well as with AO-12, PhAA was then mixed with other three differently structured N-oxides to form novel zwitterionic amphiphilic N-oxide based DESs: N,N-dimethyloctadecyl-N-amine oxide (AO-18); N-dodecylmorpholine-N-oxide (MO-12); N-methylmorpholine-N-oxide (MO). These HBA molecules were chosen for several reasons: AO-12 and AO-18 represent amphiphilic compounds and therefore they can form DESs with peculiar amphiphilic properties. MO and MO-12 were chosen in order to evaluate the effect of the chain length of these molecules on the DESs, because N-methylmorpholine-N-oxide is very poorly hygroscopic compared to the correspondent short-chain N-oxides of AO-12 and AO-18. The low water content is important because it can act a significant structural role in the DESs

mixtures. The synthetic procedure used to obtain these molecules is very easy and cheap: it is made treating the correspondent amine with H_2O_2 . Moreover, also other techniques can be efficaciously used for their preparation (i.e. O_2 catalytic oxidation)[47,48]. The molar ratio of N-oxide / PhAA was maintained as 1/1. In Figure 1 the structures of the molecules composing the DESs are reported.

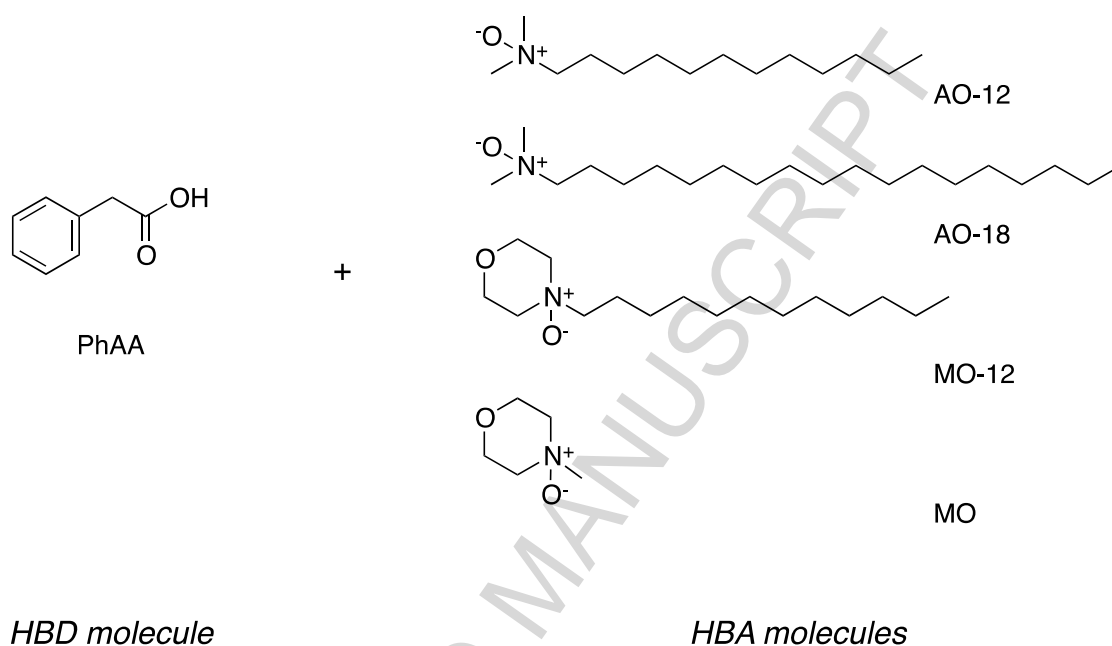


Figure 1: Structures of the molecules composing the novel DESs. PhAA: Phenylacetic acid; AO-18: N,N-dimethyloctadecyl-N-amine oxide; AO-12: N,N-dimethyldodecyl-N-amine oxide; MO-12: N-dodecylmorpholine-N-oxide; MO: N-methylmorpholine-N-oxide.

In Table 2 are reported the melting points of the N-oxides, the freezing points of the obtained DESs and the ΔT of melting between the ones of N-oxides and of the DESs.

Table 2: Melting points (m.p.) of the N-oxides, freezing points of the obtained DESs and Δt of melting between the ones of N-oxides and of the DESs. Molar ratio N-oxides/PhAA = 1/1.

DES	N-oxide m.p. (°C)	DES freezing point (°C)	Δt (°C)
AO-12/PhAA	89-91	-34	123
AO-18/PhAA	91-97	20	70
MO-12/PhAA	71-78	-21	92
MO/PhAA	180-184	-27	207

^a PhAA m.p. = 76-78°C

All the mixtures are liquid at room temperature. The freezing point of AO-18/PhAA resulted the highest of the set (20°C), just below room temperature. The other ones have very low freezing points, spanning from -21°C to -34°C. AO-18/PhAA mixture showed a liquid-solid transition, while the others showed transitions to semi-solid phases decreasing the temperature.

These novel four systems were analyzed and characterized via measurements of density, viscosity, conductivity, ionicity (by Walden Plot) and polarity (by Nile Red dye).

3.1 DENSITY

The density values of these mixtures were measured in the range of temperatures between 20°C and 70°C. The values at 25°C and 65°C are reported in Table 3, all the measures are reported in Supplementary data. The values of AO-18/PhAA and MO-12/PhAA DESs are slightly under 1 g/mL, while the values of AO-12/PhAA and MO/PhAA DESs are slightly over 1 g/mL. These density values were used to measure the viscosity (in cST) and molar conductivity values.

Table 3: Density values (ρ) at 25°C and 65°C of all the DESs mixtures.

DES	ρ (g/mL) at 25°C	ρ (g/mL) at 65°C
AO-12/PhAA	1.156	1.106
AO-18/PhAA	0.977	0.947
MO/PhAA	1.156	1.106
MO-12/PhAA	0.995	0.955

3.2 VISCOSITY

The viscosity (η) of these mixtures is exponentially dependant on the temperature, following the Arrhenius equation.

$$\ln \eta = \ln \eta_0 + \frac{E_\eta}{RT}$$

The viscosities of the novel N-oxide DESs mixtures were measured in a temperature range between 20°C to 65°C; the profiles of $\ln \eta$ (in cST) vs. $1/T$ (in K^{-1}) are reported in Figure 2; all the data are reported in Supplementary data.

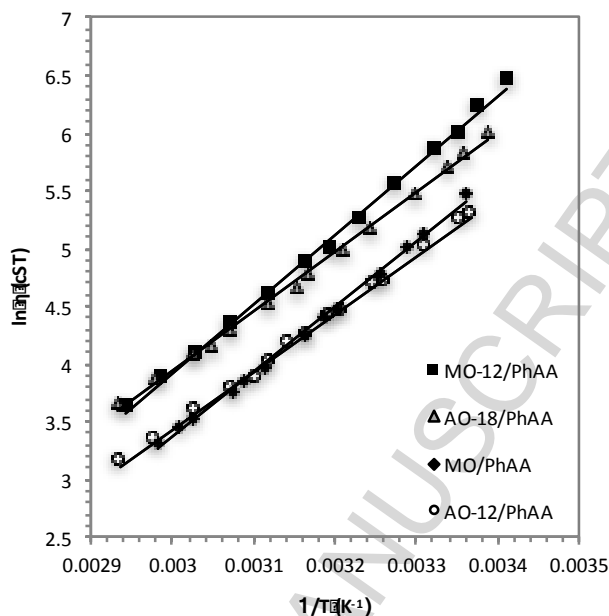


Figure 2: Viscosity profiles of N-oxide DESs in the temperature range between 20°C and 65°C. Black squares = MO-12/PhAA; grey triangles = AO-18/PhAA; black diamonds = MO/PhAA; empty circles = AO-12/PhAA.

All the DESs showed low viscosity in all the temperature range analyzed and Newtonian behaviours. In Table 4 the values at 25° and 40°C and the activation energies of viscosity E_η (calculated via Arrhenius equation) are reported. In the same table values of two other zwitterionic DESs and of the most studied DESs in literature are reported: a) Gly/TMG, glycolic acid/trimethylglycine; b) SB3-12/CSA, 3-(dodecyldimethylammonio)propane-1-sulfonate/[(1S)-(+)-10-camphorsulfonic acid (that is also amphiphilic) c) ChCl/U, choline chloride/urea mixture[14,15,18,41,49].

Table 4: Activation energies of viscosity (E_η) and viscosity values (η at 25° and 40°C) measured for all the novel DESs compared with those of and of ChCl/U DES and of other zwitterionic DESs (Gly/TMG; SB3-12/CSA).

DES	E_η (kJ/mol)	η (cST) at 25°C	η (cST) at 40°C
AO-12/PhAA	-41.6	175.07	83.20
AO-18/PhAA	-43.1	314.32	144.73
MO-12/PhAA	-49.8	412.36	167.15
MO/PhAA	-46.9	214.34	86.66
ChCl/U ¹⁴	-59.6	600.00	140.92
Gly/TMG ⁴¹	-42.6		745.72
SB3-12/CSA ¹⁸	-38.2		3617.05 ^a

^a T=80°C

The activation energies (that are determined by the packing capabilities of the molecules in the liquid structures) are almost the same for all the novel DESs, and the values are similar to the ones of the other DESs reported in literature. On the contrary, the values of viscosity, especially the ones at room temperature, are much lower than those observed with the other DESs systems (from 175 cST to 412 cST compared to 600 cST). At higher temperatures, ChCl/U decreases its viscosity until a value similar to that of amine oxide-based systems. The analyzed amphiphilic sulfobetaine-based DESs (SB3-12/CSA) showed much higher values than the other systems (3617.05 cST, determined at 80°C). This suggested that the interactions occurring in these novel systems are much different from the ones observed in sulfobetaine-based DESs, even if the chain length is the same. Such low viscosity values support these DESs as promising novel organic liquids for different applications, even at room temperature.

3.3 CONDUCTIVITY

Conductivity is a technique that can give structural information about a liquid system. The conductivity values are dependent on the amount of free charges in a system and on their mobility, therefore on their dimensions. Small molecules (therefore with high mobility) with high charge density lead in fact to higher conductivity values compared with the ones observed with molecules having lower charge density, larger dimensions and therefore lower mobility. The mobility of the charged molecules is a key factor when charged molecules can

interact with larger dimension molecules such as DNA, microbial cells or TiO_2 suspensions; this is because a decrease of the conductivity is observed as a consequence of interaction with lower mobility systems[50–53]. In an organic liquid such as a DES, the conductivity values are determined by the amount of free charges in the system, therefore they are usually low. In Figure 3 are reported the plots of the conductivity values ($\ln \sigma$, S) of the DESs measured at different temperatures ($1/T$, K^{-1}).

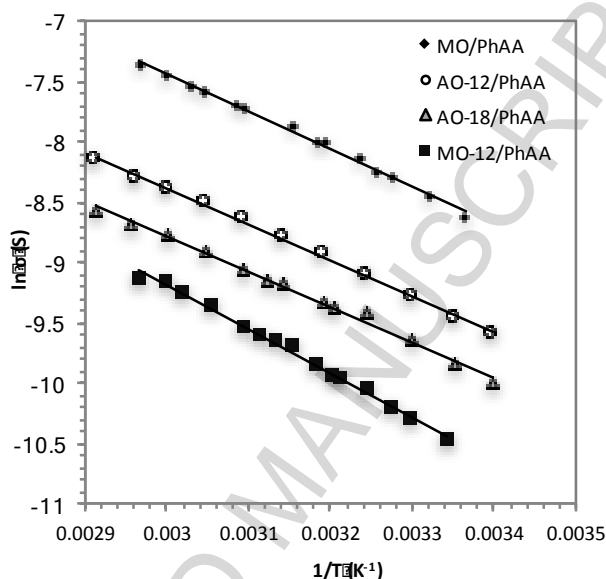


Figure 3: plot of conductivity ($\ln \sigma$, S) vs $1/T$ (K^{-1}) of the N-oxide based DESs. Black diamonds = MO/PhAA; empty circles = AO-12/PhAA; grey triangles = AO-18/PhAA; black squares = MO-12/PhAA.

In Table 5 the values of the activation energies (E_A) calculated by these plots (even the conductivity has an Arrhenius behavior) and the conductivity values (in mS/cm) observed at 25° and 60°C of the novel DESs are collected. All the data are reported in Supplementary data.

Table 5: Conductivity activation values (E_A) and conductivity values (σ) at 25° and 60°C of the novel DESs.

DES	E_A	σ (mS/cm)	σ (mS/cm)
	(kJ/mol)	at 25°C	at 60°C
MO/PhAA	25.03	0.180	0.586
MO-12/PhAA	30.26	0.029	0.104

AO-12/PhAA	24.81	0.078	0.228
AO-18/PhAA	24.05	0.053	0.154

The values of activation energies (E_A) observed are slightly under those reported for other DESs mixtures in literature (ChCl/Oxalic acid = 34.6 kJ/mol; Gly/TMG = 31.1 kJ/mol; SB3-12/CSA = 33.0 kJ/mol), except for MO-12/PhAA DES that is more similar to them[14,18,41]. The values of activation energies are related to the energies required for the formation or expansions of the vacancies in the liquid structures[54]. These values suggested an easier formation of vacancies in the liquid structures compared to the other DESs systems analyzed. The conductivity values observed are low: in literature, the values reported for protic ionic liquids (which are similar to HBD/HBA DESs but they are formed by a complete hydrogen transfer) are much higher and they vary from 150 mS/cm at 25 °C up to 470 mS/cm at 100 °C[55]. So, these novel N-oxide-based DESs cannot be considered as charged species mixtures such as protic ionic liquids; this is because of their low conductivity values observed. MO/PhAA DES showed conductivity values higher than the other ones in the set; this is because of the higher mobility of morpholinium (for its smaller dimensions) compared with the other amphiphilic HBA molecules.

3.4 IONICITY

The Walden plot is a simple semi-quantitative method to establish the ionicity extent of a novel organic liquid and it is based on the Walden law that correlates the molar conductivity (Λ) with the viscosity (η)[56,57]:

$$\Lambda \cdot \eta = \text{Constant}$$

This method has been largely used for ILs and DESs in the recent years to establish the relationships between their conductivity and viscosity and to define the extent of ion association of a liquid compared to an ideal electrolyte solution. In fact, in the Walden plot the diagonal indicates the molar conductivity vs. the logarithm of inverse viscosity of an aqueous solution of 0.01 M KCl; the liquids with values on the lower side of the plot under this diagonal are called “poor ionic” liquids due to the high ion association of their components; on the

upper side of the diagonal “super ionic” liquids are found, indicating a charge separation in their structures.

In Figure 4 the Walden plots of the novel DESs AO-12/PhAA, AO-18/PhAA, MO/PhAA, MO-12/PhAA are reported. In the same plot the values of other similar organic liquids are reported as comparison: a typical ionic liquid ([BMIM][BF₄], 1-butyl-3-methylimidazolium tetrafluoroborate, $t=25^{\circ}\text{C}$), a choline chloride-based deep eutectic solvent (ChCl/Eg, choline chloride/ethylene glycol, $t=20^{\circ}\text{C}$), a zwitterionic betaine-based DES (Gly/TMG, glycolic acid/trimethylglycine, $t=45^{\circ}\text{C}$), a zwitterionic sulfobetaine-based DES (SB3-12/CSA, 3-(dodecyldimethylammonio)propane-1-sulfonate/(1S)-(+)-10-camphorsulfonic acid, $t=75^{\circ}\text{C}$)[18,41,56,57].

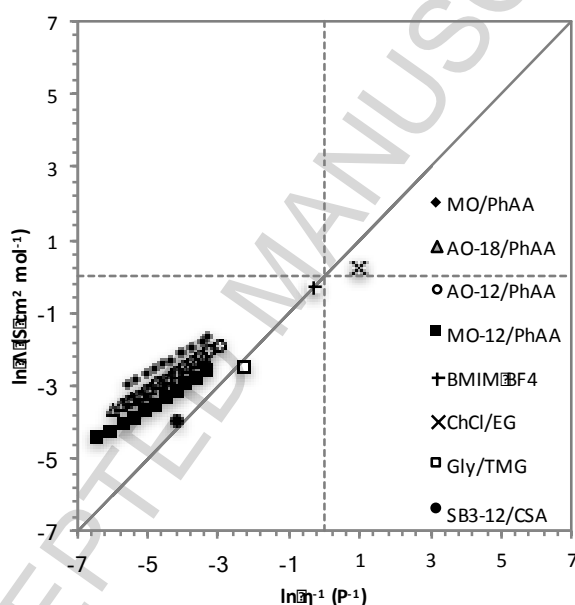


Figure 4: Walden plots of the novel N-oxide DESs (in the temperature range 25°C - 70°C) and of other similar organic liquids. Black diamonds = MO/PhAA; grey triangles = AO-18/PhAA; empty circles = AO-12/PhAA; black squares = MO-12/PhAA; + = [BMIM] [BF₄] ($t=25^{\circ}\text{C}$)[54], X ChCl/Eg ($t=20^{\circ}\text{C}$)[53]; empty square = Gly/TMG ($t=45^{\circ}\text{C}$)[41]; circle = SB3-12/CSA ($t=75^{\circ}\text{C}$)[18].

All novel N-oxide based DESs showed “super ionic” nature and all of them showed linear profiles, therefore Walden behavior. However, the low values of both molar conductivity and viscosity observed lead to the position in the negative portion of the plot. This position is interesting and uncommon considering the other similar DESs and organic liquids. The other

zwitterionic DESs are closer (or slightly under) the diagonal, therefore they can be considered “poor ionic” liquids; this indicates a higher charge separation in the novel DESs. PILs (Protic Ionic Liquids, with a complete proton transfer from the HBD to the HBA molecules) and ILs (with discrete ionic species) are on the contrary on the right portion on the Walden plot and this suggests a different structure of the liquids.

3.5 POLARITY

UV-VIS measures with solvatochromic dyes were performed in literature using a wide number of probes and on a wide number of solvents or ILs or DESs to evaluate the polarity of these media[15,58–60]; in these works Reichardt’s dye represents one of the most used molecule thanks to its properties[61,62]. Our systems are based on HBD – HBA interactions, therefore Reichardt’s probe is not applicable due to its sensitivity to proton-donor species. Nile Red dye was therefore used for its solvatochromic sensitivity even in presence of HBD species[63].

This dye manifests a positive solvatochromism, thus the maximum of the wavelength adsorption changes depending on the polarity of the media: higher polar media lead to longer wavelengths of absorption. Nile Red has a large bathochromic shift: a change of over 100 nm in λ_{\max} can be observed passing from water to pentane. For these reasons this dye is widely used in determining empirical scales of polarity of different media[64].

In Table 6 are reported the values of λ_{\max} (in nm) observed for AO-12/PhAA, MO-12/PhAA and MO/PhAA DESs and in another zwitterionic DES (glycolic acid/trimethylglycine mixture, GA/TMG) at 25°C. Unfortunately, AO-18/PhAA DES was not studied with this dye because the temperature studied (25°C) was close to its freezing point (20°C), therefore the dye was not properly solubilized and gave unreproducible results. In the same table are reported the values observed in literature in a choline-based DES (choline chloride/D-(+)-xylose mixture, ChCl/Xyl), and in a typical ionic liquid ([BMIM][PF₆], 1-butyl-3-methyl imidazolium hexafluorophosphate)[65,66].

Table 6: Maximums of wavelength adsorption of Nile Red dye in the analyzed liquids.

	λ_{\max} , nm
AO-12/PhAA	546.7
MO-12/PhAA	549.7
MO/PhAA	561.3

GA/TMG	564.2
ChCl/Xyl	563.0
[BMIM] [PF ₆]	547.5

In Figure 5 the maximum of wavelength absorption of a wide series of typical organic liquids (as well as water and the ones reported in Table 6) are reported as comparison; all the values are reported in Supplementary data.

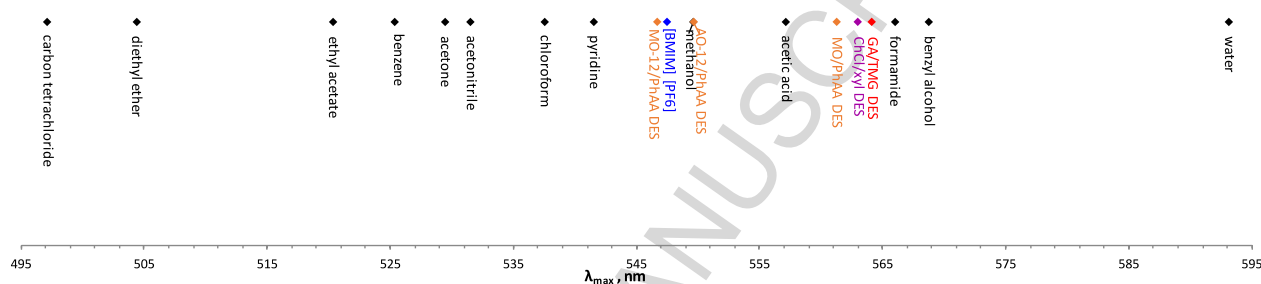


Figure 5: Maximum of wavelength absorption of Nile Red dye in a series of common organic solvents, in water, in an ionic liquid ([BMIM] [PF₆]), in a typical DES (ChCl/Xyl), in a zwitterionic DES (GA/TMG), in three of our novel Amine-oxide DESs (MO-12/PhAA, AO-12/PhAA, MO/PhAA mixtures).

As it can be observed, the polarity of these mixtures resulted high enough, with values among typical organic solvents. The amphiphilic mixtures (AO-12/PhAA and MO-12/PhAA) showed polarities that are similar to the ones of methanol (with values almost overlapped with AO-12/PhAA DES) and of the ionic liquid [BMIM][PF₆]; the non-amphiphilic DES MO/PhAA showed a higher polarity, also higher than the one of acetic acid. The three novel DESs analyzed showed a polarity that is lower than the one observed for the other zwitterionic DES GA/TMG and also of the one of ChCl/Xyl mixture.

4. CONCLUSIONS

Four novel amine N-oxide-based DESs were prepared and characterized; three of them are formed by amphiphilic molecules. These liquids are prepared with eco-compatible components: N-oxides (which are biodegradable) and phenylacetic acid (which is a molecule present in honey). The novel mixtures showed very low freezing points, spanning from -34°C to 20°C . Their densities are slightly over (AO-12/PhAA and MO/PhAA) or slightly under (AO-18/PhAA and MO-12/PhAA) the density of water. It is relevant to notice that their viscosities are very low, much lower than the ones of other zwitterionic DESs and of the most common and used DES described in literature so far (ChCl/U). These values are very low even at 25°C , promoting these liquids for their use at room temperature. Their conductivity values are very low, much lower than the ones reported in literature for protic ionic liquids; this indicates that the proton is not completely transferred from HBD to HBA molecule in these novel liquids. Their position in the Walden plot is peculiar: they are located in the negative portion both of molar conductivity and viscosity, but they are “super ionic” for their charge separation. The polarity of these mixtures resulted high enough, and it can be compared with the one of typical organic solvents or ionic liquids, with AO-12/PhAA almost overlapping methanol value and MO-12/PhAA much similar to the one of [BMIM][PF6] ionic liquid. MO/PhAA mixture showed the highest value in the set, but its polarity resulted lower than the one of other zwitterionic DESs (GA/TMG) or commonly used DES (ChCl/Xyl). These characteristics promote a use of these novel liquids in the same manners of other DESs in literature but with advantageous properties compared to them. Measures of solubilization capabilities of various polymers in these DESs are currently in progress.

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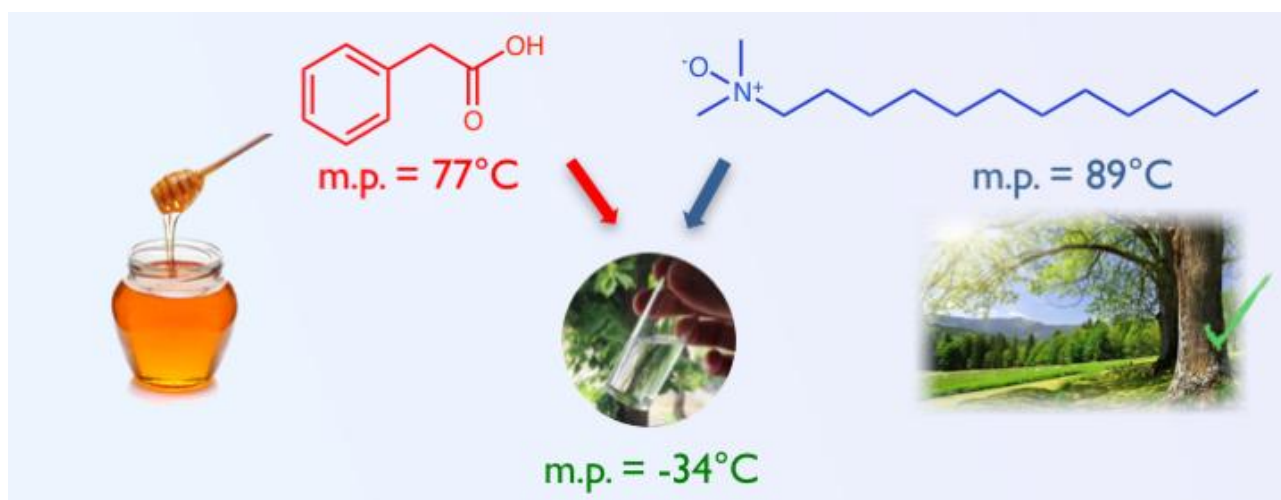
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ACCEPTED MANUSCRIPT



Graphical abstract

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HIGHLIGHTS

- The preparation and the characterizations of four novel DESs are reported
- The DESs are formed mixing green molecules (Phenylacetic acid and N-oxides)
- The novel DESs have very low freezing points, spanning from -36°C to 20°C
- The novel DESs have very low viscosity, lower than other common DESs in literature
- The novel DESs have low conductivity, high enough polarity and are “super ionic” (via Walden Plot)

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