Is it possible to correlate various physicochemical properties of Natural Deep eutectic systems in order to predict their behaviours as solvents?

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ABSTRACT

The classification of Natural Deep Eutectic Systems (NADES) as promising alternative solvents for the 21st century has been reported. Although this is mainly due to their very interesting characteristics that have attracted the attention of the scientific community, there is, however, a lack of information regarding many physicochemical properties of these compounds. Therefore, the main objective of this work was to characterize and relate the properties, both of hydrophilic and hydrophilic NADES, regarding their water content, density, viscosity, refractive index, dielectric constant, dipole moment, surface tension, as well solvatochromic parameters. Comparatively to the set of organic solvents also explored, it was observed that for these parameters studied, the values of hydrophilic systems are mostly higher than those of organic solvents, which in turn tend to be higher than those of hydrophobic systems. Moreover, the analysis of solvatochromic parameters (polarity and Kamlet-Taft parameters) provided new evidence for the usefulness of NADES as potential substitute solvents for sustainable development. Finally, regarding the general list of compounds, it was proved with statistical parameters (Pearson correlation coefficient and p-value) that most of the studied properties are strong and significantly correlated with each other.

1. Introduction

Deep Eutectic Systems (or DES) are a new class of solvents formed by mixing two or more compounds which could be solids or liquids. A DES is a non-ideal mixture which is formed by acid/base pairs (Hydrogen Bond Donor, HBD and Hydrogen Bond Acceptor, HBA) which at a specific molar ratio establish stable intermolecular forces, by hydrogen bonding interactions, that lead, consequently, to a decrease in the melting point of the formulated mixture [1]. Currently, these mixtures have been drawing the interest of many researchers because of their remarkable features, such as: low vapor pressure, a broad range of polarity and viscosity, non-flammability, low cost, straightforward, easy and green preparation method [2]. Generally, if natural-based compounds are used for the preparation of a eutectic system, then these are classified as Natural Deep Eutectic Systems (or NADES) [34]. In fact, in DES field, NADES have been one of the most explored subclasses by the scientific community, certainly due to their biodegradability and low toxicity, water-compatibility, environment friendly, among other features that distinguish them as a promising new generation of green solvents [5-7]. Moreover, another advantage of DES is that they can be

designed specifically for a given application, which explains their ascending evolution in fields such as biocatalysis, extraction, biomedical applications, cosmetic, etc., [8-12]. However, it is also true that the amount of information regarding most of DES's physicochemical properties is still very limited, mainly for the most recent combinations, which are not choline chloride-based. In the reviews written by several authors, for example, by El Achkar et al. [13], Ijardar et al. [14], and most recently by Omar and Sadeghi [15], two observations became noticeable: first, is that the characterization of DES has been mostly done by a set of physicochemical properties such as melting point, density, viscosity, conductivity, surface tension, polarity, refractive index, pH, hydrophobicity/hydrophilicity, water effect, etc.; second, is that choline chloride-based DES (e.g., choline chloride with urea, glycerol, or ethylene glycol) are undeniably the most well-described systems in the literature. This makes it increasingly difficult to explore the application of new systems (e.g., betaine- or menthol-based DES) due to the lack of their physicochemical characterization. Moreover, since in the vast majority of the studies reported in the literature, the interest of the research is to use or explore the ability of eutectic mixtures as a media for extraction or chromatography processes, but mainly in the

Table 1
Information on the chemicals used in this work.

Chemical name	Abb.	CAS no.	Purity (mass %)	Brand	Supplier
4-Nitroaniline	**4NA**	100–01-6	99.0	Sigma-Aldrich	Laborspirit
Acetic acid (glacial)	**AcetA**	64–19-7	$\geq$ 99.0	Sigma-Aldrich	Laborspirit
Betaine	**Bet**	107–43-7	$\geq$ 99.0	Sigma-Aldrich	Laborspirit
Borneol	**Bor**	464–45-9	97.0	Sigma-Aldrich	Laborspirit
Choline Chloride	**Chcl**	67–48-1	98.0	Alfa Aesar	Laborspirit
Cyclohexane	**CHx**	110–82-7	99.5	Riedel-de Haën	N/A
D-(+)-Sucrose	**Suc**	57–50-1	99.5	Sigma-Aldrich	Normax
D-(-)-Fructose	**Glc**	57–48-7	$\geq$ 99.5	Sigma-Aldrich	Laborspirit
D-(+)-Glucose anhydrous	**Fru**	50–99-7	$\geq$ 97.5	Merck	Laborspirit
Decanoic acid	**DecA**	334–48-5	$\geq$ 98.0	Sigma-Aldrich	Laborspirit
DL-Menthol	**Men**	89–78-1	$\geq$ 95.0	Sigma-Aldrich	Laborspirit
Dimethyl Sulfoxide	**DMSO**	67–68-5	N/A	Corning	Enzifarma
D-Sorbitol	**Sorb**	50–70-4	98.0	Sigma-Aldrich	Laborspirit
Ethanol	**EtOH**	64–17-5	99.8	Fisher chemical	Enzimatic
Ethylene glycol	**EG**	107–21-1	$\geq$ 99.5	Carlo Erba	Laborspirit
Glycerol	**Gly**	56–81-5	99.5	Scharlau	Laborspirit
Hexane	**Hx**	110–54-3	96	Carlo Erba	Laborspirit
Ibuprofen	**Ibu**	15687–27-1	99.0	Alfa Aesar	Laborspirit
Lactic acid	**LactA**	50–21-5	$\geq$ 85.0	Sigma-Aldrich	Laborspirit
Lauric acid	**LauA**	143–07-07	$\geq$ 98.0	Sigma-Aldrich	Laborspirit
Levulinic acid	**LevA**	123–76-2	$\geq$ 97.5	Sigma-Aldrich	Laborspirit
L-Proline	**Pro**	147–85-3	99.0	Alfa Aesar	Laborspirit
Methanol	**MeOH**	67–56-1	99.0	Sigma-Aldrich	Laborspirit
Myristic acid	**MyrA**	544–63-8	98.0	Sigma-Aldrich	Laborspirit
N, N-Dimethyl-4-nitroaniline	**DMNA**	100–23-2	98.0	Alfa Aesar	Laborspirit
Nile red	**NR**	7385–67-3	$\geq$ 98.0	Sigma-Aldrich	Laborspirit
Propan-1-ol	**1-prOH**	71–23-8	99.5	Carlo Erba	Laborspirit
Propan-2-ol	**2-prOH**	67–63-0	99.5	Sigma-Aldrich	Laborspirit
Thymol	**Thy**	89–83-8	$\geq$ 98.5	TCI	Laborspirit
Trehalose	**Tre**	6138–23-4	$\geq$ 99.0	Hayashibara	Hayashibara
Urea	**Ure**	57–13-6	98.0	N/A	Normax

N/A = Not Available.

replacement some organic solvents (e.g., DMSO) [16,17], knowledge of such parameters for a wide range of different combinations can be very advantageous for future work.

On the other hand, as reviewed by Kovács *et al.* [18], currently, there are many simple computational (empirical) models, mainly based on machine learning or group-contribution methods, which allow the predict and quantify some physical properties of NADES, such as melting point, density, viscosity, surface tension and refractive index [19-21]. Besides, using these computational approaches, several equations that establish correlations between two or more physicochemical properties have been increasingly developed. These allow quantifying a desired parameter, which can be at first more laborious and difficult to measure, from a simple correlation with related properties. Furthermore, given the high possibility of NADEŚs combination, it is very important to discover which properties are correlated and how strong is its relationship.

In this perspective, according to the mentioned lack of comprehensive investigation for physicochemical properties of NADES, this work has as its main goal not only characterizing physicochemical properties of a set of NADES (including 18 hydrophilic and 21 hydrophobic systems), such as water content, viscosity, density, surface tension, refractive index, and dielectric constant but also using a set of models reported in the literature to estimate other properties such as solvatochromic parameters and dipole moment which are the less studied parameters in the open literature;

2. Materials and methods

2.1. Materials

A short description of the chemicals used in this work is listed in Table 1. Here, information on the compound́s specification, namely, CAS number, as well their mass-based purity and supplier can be found. In addition, it is also shown the abbreviated (Abb.) name of used

compounds, which will be used more often as work progresses to refer to a specific compound.

2.2. NADES preparation

In general, the NADES in this study were prepared following the "Heating and Stirring" method described by *L. Meneses et al.* [22]: Mixing the NADES components, previously weighted in an analytic balance KERN ABS 220–4 N (with the uncertainty of 0.0001 g) and letting them to stir with temperature around 65 °C, until forming a typically viscous and translucid liquid. Some extra precautions were considered in the preparation of NADES with the following bio-base:

- Choline chloride and Urea: The method of *Y. Dai et al.* [4], was used in the preparation of Choline chloride-based NADES: Due to their hygroscopic characteristic, choline chloride and urea used to prepare systems such as Chcl:EG (1:2), Chcl:Gly (1:2), and Chcl:Ure (1:2) was stored and dried at least 24 h, in an oven vacuum, at 60 °C, to avoid moisture adhesion and consequently a possible water interference. Pre-drying procedure was not carried out for other investigated compounds in this study.

- Amino acids: For eutectic mixtures of proline-based such as (e.g., Bet: Suc:Pro:W (5:2:2:21), Glc:Pro:Gly:W (3:5:3:20), and Pro:Gly:Sorb:W (1:1:1:13)), the temperature must be adjusted to $\leq$ 40 °C, because of the degradation process. Furthermore, these systems also showed some photosensitivity as they degrade (becoming darker and darker over time) when exposed to light.

After preparation of NADES, the amounts of water content (W%) in mass percentage were measured by an 831 Karl Fischer coulometer with a generator electrode (Metrohm) and a moisture analyzer DAB (Kern). All the measurements were performed at room temperature (293.15 K) and the results are listed in Table 2. The presented values correspond to an average of at least three measures and their respective standard

Table 2

List of NADES investigated in this work with the references (Ref.) where they were retrieved.

NADES	ID*	Mw (g/mol)	Water content (mass%)	Classification
Bet:Glc:W (5:2:10)	B1	66.24	18.6 ± 0.84	hydrophilic
Bet:Gly:Suc:W (2:3:1:5)	B2	85.72	8.58 ± 1.32	hydrophilic
Bet:Sorb:W (3:1:10)	B3	50.98	12.96 ± 1.11	hydrophilic
Bet:Suc:Pro:W (5:2:2:21)	B4	62.63	11.97 ± 0.46	hydrophilic
Chcl:EG (1:2)	C1	87.92	0.19 ± 0.04	hydrophilic
Chcl:Gly (1:2)	C2	107.94	1.18 ± 0.3	hydrophilic
Chcl:Ure (1:2)	C3	86.58	2.15 ± 0.02	hydrophilic
Fru:Glc:Suc:W (1:1:1:10)	F1	67.90	18.09 ± 3.65	hydrophilic
Glc:Pro:Gly:W (3:5:3:20)	G1	56.54	21.53 ± 2.74	hydrophilic
Gly:Fru (4:1)	G2	109.71	0.17 ± 0.09	hydrophilic
Gly:Fru:Sorb:W (1:1:1:3)	G3	84.74	11.27 ± 0.53	hydrophilic
Gly:Glc (4:1)	G4	109.71	0.14 ± 0.08	hydrophilic
Gly:Glc:Sorb:W (1:1:1:3)	G5	84.74	9.4 ± 0.31	hydrophilic
Gly:Suc:Sorb:W (2:1:2:10)	G6	71.40	13.01 ± 0.55	hydrophilic
Gly:Tre:Sorb:W (2:1:2:10)	G7	71.40	19.25 ± 2.08	hydrophilic
Pro:Gly:Sorb:W (1:1:1:13)	P1	38.97	36.31 ± 1.2	hydrophilic
Tre:Fru:W (1:2:13)	T1	58.55	25.84 ± 1.11	hydrophilic
Tre:Glc:W (1:2:13)	T2	58.55	27.64 ± 0.25	hydrophilic
Men:AcetA (1:1)	M1	108.16	0.27 ± 0.04	hydrophobic
Men:Bor (7:2)	M2	155.82	0.16 ± 0.03	hydrophobic
Men:DecA (1:1)	M3	164.26	0.85 ± 0.04	hydrophobic
Men:DecA (2:1)	M4	161.60	0.20 ± 0.02	hydrophobic
Men:DecA (4:1)	M5	159.47	0.43 ± 0.03	hydrophobic
Men:DecA (7:2)	M6	159.82	0.14 ± 0.01	hydrophobic
Men:LauA (2.7:1)	M7	168.17	0.29 ± 0.0	hydrophobic
Men:LauA (2:1)	M8	170.95	0.07 ± 0.01	hydrophobic
Men:LauA (4.5:1)	M9	164.27	0.18 ± 0.01	hydrophobic
Men:LauA (4:1)	M10	165.08	0.17 ± 0.02	hydrophobic
Men:LauA (5.3:1)	M11	163.26	0.15 ± 0.01	hydrophobic
Men:LauA (8:1)	M12	161.16	0.06 ± 0.01	hydrophobic
Men:LauA:DecA (2:1:1)	M13	171.28	0.14 ± 0.02	hydrophobic
Men:LauA:DecA (4:1:1)	M14	166.27	0.09 ± 0.01	hydrophobic
Men:LevA (1:1)	M15	136.19	0.48 ± 0.03	hydrophobic
Men:MyrA (4:1)	M16	170.69	0.34 ± 0.07	hydrophobic
Men:MyrA (8:1)	M17	164.28	0.26 ± 0.02	hydrophobic
Men:Thy (1:1)	M18	153.24	0.16 ± 0.01	hydrophobic
Men:Thy (2:1)	M19	154.25	0.13 ± 0.02	hydrophobic
Men:Thy (4:1)	M20	155.06	0.13 ± 0.01	hydrophobic
Men:Thy (8:1)	M21	155.59	0.55 ± 0.02	hydrophobic

Mw – Molecular weight.

deviation.

For a clear analysis, the systems were subdivided into two categories, hydrophobic and hydrophilic. The choice criterion was based on the hydrophilic/hydrophobic nature of its constituents and the presence of water as a component of the system. Thus, Table 2 reports details of NADES constituents with their respective molar ratios, their ID, molecular weights, the water contents measured from Karl-Fischer and their classification as hydrophilic or hydrophobic systems.

2.3. NADES characterization

To characterize and fundament the applicability of NADES as a solvent, the following set of properties were measured:

2.3.1. Viscosity and density

The dynamic viscosity and density of NADES were measured using an automated rotation Stabinger Viscometer-Densimeter, model SVM 3001 from Anton Paar over temperature range of 293.15 – 333.15 K, with steps of 10 K and at atmospheric pressure (100 ± 5 kPa). Furthermore, to avoid a possible degradation of proline-based eutectic systems, their viscosities and densities were measured in the temperature range of 293.15 to 313.15 K, with steps of 5 K. The apparatus was calibrated with the water, air and the company's standard oil set. The uncertainties of controlling temperature and measuring densities and relative viscosities by the apparatus were 0.02 K, 0.0001 g/cm³ and 0.35% for the relative viscosity, respectively.

2.3.2. Refractive index

The Refractive index measurements were performed at room temperature (293.15 ± 0.01 K) and atmospheric pressure (100 ± 5 kPa), using a monochromatic Abbe-2WAJ Refractometer with an uncertainty of 0.0002. The methodology consists in dropping a few drops of the sample in the refractometer and with the help the two handwheels, move them in order to place the horizontal line, seen through the eyepiece, in the centre of the circle. During all the measurements the equipment should be pointed in the direction of the light.

2.3.3. Dielectric constant

The measurement of dielectric constants (or relative permittivity) was obtained at room temperature (290.15 K ± 0.5 K for NADES and at 298.15 ± 0.5 K, for organic solvents) and atmospheric pressure (100 ± 5 kPa), performing the protocol established by R. Craveiro *et al.*[31]: With an Alpha-N impedance Analyzer from Novocontrol, GmBh at a frequency range from 10^{-1} Hz to 1 MHz, using the Dielectric Relaxation Spectroscopy (DRS) method. For this technique, few drops of the sample were placed between 2 stainless steel electrodes of Au (10 mm diameter) in a BDS 1200 parallel plate capacitor and using two silicon spacers (50 μm) to prevent contact between the electrodes.

2.3.4. Surface tension

NADES Surface tension was obtained using the pendant drop-method, following the procedure described by Decaro junior *et al.* [32]. To form the pendant droplets, it a needle (with an exterior diameter of 0.52 mm) was used, connected to a Hamilton® graduated syringe (up to 5 μL of volume). The analysis was then carried out, at the temperature of 296.15 ± 0.5 K and atmospheric pressure (100 ± 5 kPa), using an OCA20 tensiometer, from Dataphysics, armed with a CCD high-speed and high-definition camera to capture droplet formation. The SCA20 software was used to automate the apparatus and handle the images that were captured on a computer. At least three pendant droplets were created for each spraying NADES and were analysed by the software using the Young-Laplace equation. The uncertainty of surface tension measurement was 0.02 m.Nm $^{-1}$.

2.3.5. Solvatochromic method

Before starting the spectroscopic analysis, stock solutions of each dye (NR, DM4A, and 4NA) were prepared by dissolving 1 mg of the probe in 1 mL of ethanol and stored in ambered glass vials [33]. Following, the determination of both, polarity and Kamlet-Taft parameters (KTPs), was carried out following the methodology explained by Amos K. Dwamena *et al.* [34]: The samples were prepared in cuvettes of plastic (length: 1.5 cm, from Laborspirit), through a diluting of 1:200 (5 μL of the dye solutions in 1000 μL of NADES) and analysed, at room temperature, using a Thermo Scientific™ GENESYS™ 50 Vis/UV–Vis Spectrophotometer. The samples stained with NR were read in a wavelength range of 400–650 nm, while those marked with DM4A and 4NA in a range of 300–450 nm, and the calculations of polarity and KTPs were made using the wavelength of the maximum absorption applied, in turn, in equations showed in section 2.3.6.2.

2.4. Theory

2.4.1. Dipole moment

It is almost impossible to present the dielectric constant and not discuss of the dipole moment as these two properties are entirely related. Similarly to the dielectric constants, the reported NADES dipole moment data in the literature are very limited. Despite this, there are many equations that allow the prediction of the dipole moment through simple correlations with other related properties. Two of these models were evaluated in this work. First, the Onsager's equation [35] (μ_O, **eqn. (1)**, which establishes a relation between the dipole moment and the refractive index (n_D) and dielectric constant ($\dot{\varepsilon}$). This method is very useful and was used by Huyskens [36], investigating the dipole moment of complexes formed by hydrogen bonds in the liquid phase.

$$\mu_O = \sqrt{\left(\frac{9k_BT \times 10^{39}}{4\pi N_A}\right)\frac{(\varepsilon\hat{A} - n_D^2)(2\varepsilon\hat{A} - n_D^2)}{\varepsilon\hat{A}(n_D^2 + 2)^2} \times \frac{1}{F_B}} \qquad (1)$$

Where, k_B is the Boltzmann constant (1.38×10^{-23} $m^2.kg.s^{-2}.K^{-1}$); T, the absolute temperature (in Kelvins); N_A, the Avogadro's number (6.02×10^{23} mol^{-1}) and F_B, the formal concentration (in $mol.dm^{-3}$, being $F_B = 1/V_m$).

Second, the Salem's equation [37] (μ_S, **eqn. (2)**, that correlates the dipole moment of a compound with its dielectric constant and molar volume (V_m).

$$\mu_S = \sqrt{\frac{\varepsilon\hat{A} \times V_m}{184} - 1} \qquad (2)$$

2.4.2. Solvatochromic parameters

One of the main applications of DES or NADES, which has largely been explore is their ability to act as solvents. Polarity is among the various parameters that may help in this path. In both, DES or ionic liquids (ILs) fields, polarity is commonly determined using a colorimetric essay, or also called solvatochromic method [24,33].

2.4.2.1. Polarity (E_{NR} scale).

Nile red (NR) has been one of the most often used probes to evaluate the polarity, following the equation (**eqn. (3)** [31]:

$$E_{NR} = hc\nu_{max}N_A = \frac{28591.5}{\lambda_{max}} \qquad (3)$$

where E_{NR} is the molar transition energy or electrophilicity (Nile red dye scale, in Kcal/mol); h, c, ν, N_A and λ_{max} are Planck's constant (6.63×10^{-34} $m^2.kg/s$), speed of light in vacuum (3.00×10^8 m/s), wavenumber, Avogadro's number (6.02×10^{23} mol^{-1}) and maximum wavelength (in nm). As hydrophilic systems tend to absorb ultraviolet light at longer wavelengths (typically $\lambda_{max} \geq 570$ nm) and hydrophobic ones, in turn, at shorter wavelengths, according to **eqn. (3)**, it is possible to expect the E_{NR} of hydrophobic systems to be greater than that of hydrophilic systems.

2.4.2.2. Kamlet-Taft parameters.

The probes n,n-dimethyl-4-nitroaniline (DM4A) and 4-nitroaniline (4NA), like NR, show positive solvatochromism [38]. These two, in combination with E_{NR}, are frequently used to calculate Kamlet-Taft parameters (KTP) of DES and it is an essential tool to be applied in this instigation, since it allows describe the solvent's activities, evaluating their properties such as dipolarity/polarizability (π^*), hydrogen-bond donor ability or acidity (α) and hydrogen-bond acceptor ability or basicity (β) [24]. As there is a large discrepancy between the values reported in the literature, here, the analysis will be made using two approaches (original equations [39] versus simplified ones [34]).

2.4.2.2.1. Dipolarity/polarizability scale (π^*).

The π^* parameter provides, in simultaneous, an estimation of the solvent's dipolarity and polarizability, by measuring, simultaneously, the non-specific intermolecular interaction (dispersive/ van der Waals interactions, dipole–dipole e dipole-induced) involved in solute–solvent and the ability of the solvent to stabilize a nearby charge or dipole through nonspecific dielectric interactions [39,40]. The π^* scale, when normalized, using the DM4A probe wavenumber obtained from pair hexane ($\pi^* = 0.0$) and DMSO ($\pi^* = 1.0$), is calculated through the **eqn. (4)** [39]:

$$\pi^*(1) = \frac{\upsilon_{solvent} - \upsilon_{hexane}}{\upsilon_{DMSO} - \upsilon_{hexane}} \qquad (4)$$

where, υ (in KiloKaiser (kK)), is the wavenumber ($\upsilon = 10^7/ \lambda_{max}$ (nm)). The **eqn. (4)** can be simplified to give the **eqn. (5)** [34,39]:

$$\pi^*(2) = 0.314(27.52 - \varpi_{DM4A}) \qquad (5)$$

Being ϖ, also the wavelength, in cm^{-1} ($\varpi = 1/ (\lambda_{max}$ (nm) $\times 10^{-4})$).

2.4.2.2.2. Hydrogen-bond donor ability scale (α).

The Kamlet-Taft α parameter is related to the acidity, or the capacity of a solvent to donate charges. Its estimation is usually made using the correlation shown in **eqn. (6)** [39], which corresponds to a modification of the original equation that uses the Reichardt's dye scale (E_T (30)), as this is not suitable for this study, due to the acid character of the hydrophobic NADES.

$$\alpha(1) = 0.0649*(E_{NR}) - 0.72\pi^* - 2.03 \qquad (6)$$

However, recently Dwamena *et al.*, [34] proposed a new equation that allow to evaluate the α parameter of eutectic mixtures (**eqn. (7)**.

$$\alpha(2) = \frac{19.967 - 1.024\pi^* - \varpi_{NR}}{1.6078} \qquad (7)$$

2.4.2.2.3. Hydrogen-bond acceptor ability scale (β).

The basicity of a HBA solvent or its capacity to function as an electron-pair donor, through a specific dye-solvent, can be measured through the β parameter. It is usually done using the **eqn. (8)** [39]. The β parameter of the desired solvent can be estimated if the maximum absorption number waves of the indicator's pair, such as DM4A/4NA, in the referenced solvents DMSO and hexane are known.

$$\beta(1) = \frac{0.76(\Delta\upsilon_{solvent} - \Delta\upsilon_{hexane})}{\Delta\upsilon_{DMSO} - \Delta\upsilon_{hexane}} \qquad (8)$$

where $\Delta\nu = \nu$ (n,n-dimethyl-4-nitroaniline) $- \nu$ (4-nitroaniline). Commonly, **eqn. (8)** is simplified and written as **eqn. (9)** [34,39]:

$$\beta(2) = \frac{1.035\varpi_{DM4A} + 2.64 - \varpi_{4NA}}{2.80} \qquad (9)$$

2.4.3. Group-contribution methods

One of the most well-known characteristic of DES is its ability as being "designer solvents" that can be adapted to attend different applications, varying, for example, just the molar ratio of a system with the same components [8,13,16,41]. Although this is indeed a very interesting feature, it is at the same time very challenging, given the number of laboratory tests and time-consuming that would have to be carried out until a solvent with the desired characteristics is found. Therefore, computational approaches such as models based on group-contribution methods (GC) have been increasingly employed in investigations involving the physicochemical or thermodynamic characterization of DES [18,42–45]. These models allow the prediction properties of a given solvent using solely the functional groups present in its molecular structure. For example, R. Haghbakhsh *et al.* [21], used five GC to calculate properties of DES such as refractive index, density, speed of sound, heat capacity, and surface tension. The results obtained from that study show a very low absolute average relative deviation percent (AARD%) in relation to the experimental values. Therefore, this approach can be very useful to enrich this investigation, as it will allow to predict and evaluate some of the properties of the listed NADES that may not be found in literature. Hence, density, refractive index and
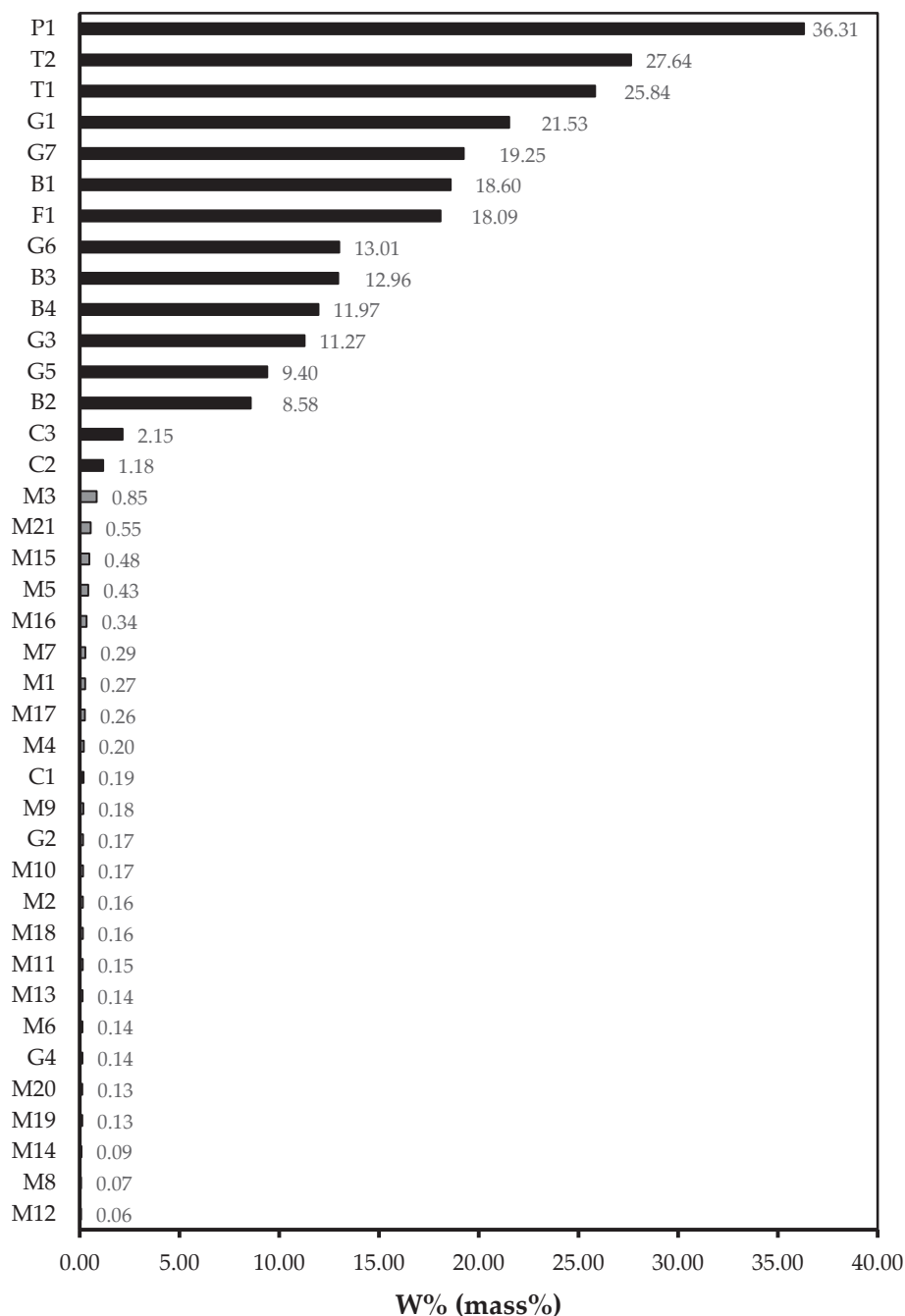
Fig. 1. Water contents (mass%) of the investigated NADES at room temperature (293.15 K).

surface tension were also predicted using the group-contribution method. Although heat capacity and speed of sound are also undoubtedly important characterization parameters, their study does not make part of this investigation and therefore, further information is not discussed. Thus, all the procedures used for the calculation of density, refractive index and surface tension can be found in the literature [21].

2.4.4. Statistical analysis

The analysis of the intercorrelation between the studied parameters for both general list of NADES or solely hydrophilic and hydrophobic systems, was carried out using the software GraphPad prism 8 and evaluated according to the statistical parameters, Pearson correlation parameter and p-value. The Pearson correlation coefficient (r between -1 and 1) is a statistic parameter that measures the intensity and direction of a linear correlation between two variables. Variables that vary

proportionally have a coefficient, $r > 0.5$, which indicates a strong positive correlation between them. On the other hand, if one of the variables increases with the decrease of the other, it means that $r < -0.5$, that is, a strong negative correlation. Nevertheless, if the r is close to 0 it means that there is no significant correlation [44]. The P value, in turn, indicates how significant or reliable the result obtained is, that is, whether the null hypothesis test, which assumes that there is no type of relationship between the variables of interest, should be accepted or not [45].

3. Results and discussion

3.1. Water content (W%)

Eutectic mixtures are strongly ruled by hydrogen bond interactions,

Table 3
Comparison between the water contents the hydrophilic systems obtained in this work and the values reported in the literature.

NADES	This work			Water content (in mass %) reported in Literature
	W %(Weighted) [a]	W %(Measured) [b]	ΔW%*	
B1	16.00	18.6 ± 0.84	+2.60	–
B2	9.57	8.58 ± 1.32	−0.99	10.3 ± 0.4 [23]
B3	25.33	12.96 ± 1.11	−12.37	–
B4	20.18	11.97 ± 0.46	−8.21	20.2 ± 0.5 [23]; 19.3 ± 1.2 [55]
C1	–	0.19 ± 0.04	–	0.2 [53]; < 240 (in ppm) [56]; 403.17 (in ppm) [43]
C2	–	1.18 ± 0.3	–	< 290 (in ppm) [56]; 655 (in ppm) [43]
C3	–	2.15 ± 0.02	–	0.1 [53]; < 200 (in ppm) [56]
F1	21.99	18.09 ± 3.65	−3.90	24.5 ± 0.5 [23]
G1	20.54	21.53 ± 2.74	+0.99	21.5 ± 1.3 [23]
G2	–	0.17 ± 0.09	–	–
G3	10.62	11.27 ± 0.53	+0.65	29.5 ± 0.5 [23]
G4	–	0.14 ± 0.08	–	3.70 ± 0.2 [23]
G5	10.62	9.4 ± 0.31	−1.22	11.9 ± 0.6 [23]
G6	16.81	13.01 ± 0.55	−3.80	16.3 ± 0.5 [23]
G7	12.94	19.25 ± 2.08	+6.31	20.4 ± 0.8 [23]
P1	8.95	36.31 ± 1.2	+27.36	13.0 ± 0.5 [23]
T1	24.99	25.84 ± 1.11	+0.85	32.6 ± 0.9 [23]
T2	24.98	27.64 ± 0.25	+2.66	26.9 ± 0.3 [23]

Observation: W% = ppm × 10^{-4}.

" - " = Not available.

*ΔW% = (W%(Measured) - W%(Weighted)).

[a] W%(Weighted): Obtained by converting molar ratio of water in DES into mass fraction.

[b] W%(Measured): Obtained from Karl-Fischer method.

which implies that their physicochemical properties can be easily modified in the presence of highly polar solvents such as water. This is due to the fact that water molecules can act either as HBD or HBA, therefore they can disrupt the HBA/HBD hydrogen bonding network of NADES [4,46]. As stated by T. El Achkar *et al.* [47], the eutectic mixtures can be prepared with both their constituents in hydrated or anhydrous forms, although the molar ratio of the formed systems may different. In fact, some studies have shown that the nature of the constituents plays a very important role in dictating the speed and extent of the effect that the amount of water present in eutectic mixtures will have on their physicochemical properties. For example, for highly hygroscopic systems such as Chcl-based DES (e.g., Reline (Chcl:Ure)), it has proven, through the studies of molecular dynamic simulations, that a continuous increase of the water content leads to a monotonic increasing in the hydration of all of the components present in the mixture [48,49]. This will lead several structural modifications, which affect, consequently, their physicochemical properties [50]. On the other hand, there are systems, normally ternary and quaternary, where a certain amount of water is intentionally added to the mixture, to make part of the it as one of the components that will facilitate and strengthen the intermolecular bonds between the other constituents [4,51]. Contrarily to Chcl-based DES, studies have demonstrated that for some systems such as Bet:Gly: W or Tre:Glc:W, up until 50% of water content (v/v) the bonds the systems structure are retained [4,23,48,52,53]. Still, what is common in both cases is that a continuous increase of water content will lead to a seamless transition from DES to an aqueous solution of DES, i.e., "DES in water". Hence, before initializing any assay that targets the evaluation of the applicability of a given system, it is extremely important the knowledge of its water content (*W%*).

The systems under research were organized in the graph shown in Fig. 1, by descending order of W%, and considering the results, it was possible to observe that, as expected, the majority of the hydrophilic systems had a higher amount of water than the hydrophobic ones, being

P1 and **M12** found, respectively as the extremes in this scale. Furthermore, by examining the substitutioń effect on the HBD compound, it is possible to observe that the W%C3 > W%C2 > W%C1. This same effect was also reported by Al-Murshedi *et al.* [54], who argued that, compared to Chcl:EG (**C1**) or Chcl:Gly (**C2**), the two components of the system Chcl:Ure (**C3**) have a greater preference for interacting with water than with each other. In addition, the effect of replacing glucose with fructose was also evaluated in analogous systems, in this case, **G2/G4**, **G3/G5**, and **T1/T2**. What was concluded is that despite the variation of the W% is not linear, the difference observed between their values is not very significant.

Regarding the hydrophobic mixtures (**M1** – **M21**), the results show that the water content does not have a direct relationship with the HBD fraction, and it varies from system to system. Another interesting observation was that even though myristic acid (MyrA, C14H28O2) is clearly the more lipophilic compound presented, when mixed with menthol the formulated NADES seems to contain more water than other mixtures such as Men:LauA, Men:DecA, and even Gly:Glc (4:1); revelling once more the unpredictable behaviour of NADES.

Taking into account the hydrophilic NADES (**B1 – B4**, **F1**, **G1 – G7**, **P1** and **T1 – T2**) that contain water as one of the mixture's components (ternary and quaternary ones), as it can be observed in Table 3, for each system, the differences (in mass%) between the amounts of water weighted for the preparation (W%(Weighted)) and measured after NADES formation (W%(Measured)), shown to be very little for the majority of NADES, except **B3**, **B4**, **G7** and **P1**.

Regarding the negative values of ΔW%, the assumption proposed here is that they arise due to the limitation of the Karl-Fischer equipment in measuring more accurately samples with high water contents, such as some of those studied systems in this work (e.g., B1, B3 or B4). Therefore, when performing this kind of measurement, it is important to be awareness on the possible deviation that Karl Fisher titration presents, and that in some cases can be very large. Therefore, maybe in some these cases it would be better to use other techniques to measure more accurately the water contents.

In addition, comparing the results obtained in this work (W %(Measured)) with those reported in the literature, it is possible to observe that most of them are in the same range of values, being the systems **B4**, **F1**, **G3** and **P1** those found with the highest differences (|W(this work) − W(literature)| ≥ 5 units). This observation is very important since such differences may help to better understand possible variations that may influence the results of the other physicochemical parameters investigated in this work, as it will be discussed further. Additionally, these observations also demonstrate the relevance in determining and report the water content of a DES as significant differences might be observed.

3.2. Viscosity and density

The experimental values of dynamic viscosities (η) and densities (ρ) at different temperatures (T) are presented in Table 4. As can be seen, for the majority of the systems described, it was not possible to locate further data provided in the literature for both viscosity and density. Yet, it can be observed that the values obtained in this work are consistent with those published in the literature by comparing them to the little data collected, for instance, of systems like M1, M4, M8, or M18. Additionally, regarding to the values of average relative deviation percentage (ARD%) between the experimental and predicted values of densities, it can be conclude that used model (R. Haghbakhsh *et al.* [21]) works very well, especially for hydrophilic systems (ARD% < 9%). In hydrophobic case, the ARD% are all above 17%.

Viscosity along with density, are two of the most important parameters that characterize eutectic mixtures, as they provide a good basis for understanding their interactions at the molecular level, in the liquid phase, which may even explain the solubility behaviour of each system. For a better analysis of the dynamic viscosity (η) and density (ρ), the NADES were separated into two groups according to their nature, as

Table 4

Experimental (Exp.) data of dynamic viscosity (η) and density (ρ) of NADES at different temperatures (T), comparing with values found in the literature (Lit.) and predicted (Pred.) [21] using empirical models. The molar volume (V_m) of each system was calculated at different temperatures. All the measurements were performed at atmospheric pressure (100 kPa).

NADES	[a] T (K)	[b] η (mPa.s)		[c] ρ (g/cm³)			Lit.	V_m[*]
		Exp.	Lit.	Exp.	Pred. [i]	ARD% [d]		(cm³/mol)
B1	293.15	1032.05	N/A	1.2268	1.2331	0.51	N/A	54.0
	298.15	679.90	N/A	1.2239	1.2307	0.56	N/A	54.1
	303.15	459.68	N/A	1.2211	1.2284	0.60	N/A	54.2
	308.15	319.89	N/A	1.2184	1.2261	0.63	N/A	54.4
	313.15	228.37	N/A	1.2156	1.2238	0.67	N/A	54.5
B2	293.15	6486.25	N/A	1.2979	1.2389	4.54	N/A	66.0
	298.15	3936.65	N/A	1.2947	1.2366	4.49	N/A	66.2
	303.15	2457.90	N/A	1.2915	1.2343	4.43	N/A	66.4
	308.15	1578.45	N/A	1.2885	1.2320	4.39	N/A	66.5
	313.15	1044.30	N/A	1.2855	1.2296	4.35	N/A	66.7
B3	293.15	123.27	N/A	1.1881	1.2837	8.05	N/A	42.9
	298.15	90.87	N/A	1.1848	1.2814	8.15	N/A	43.0
	303.15	68.21	N/A	1.1820	1.2791	8.21	N/A	43.1
	308.15	52.24	N/A	1.1790	1.2767	8.29	N/A	43.2
	313.15	40.76	N/A	1.1761	1.2744	8.36	N/A	43.3
	318.15	32.34	N/A	1.1731	1.2721	8.44	N/A	43.5
	323.15	26.06	N/A	1.1700	1.2698	8.53	N/A	43.6
	328.15	21.31	N/A	1.1671	1.2675	8.60	N/A	43.7
	333.15	17.65	N/A	1.164	1.2651	8.69	N/A	43.8
	338.15	14.79	N/A	1.1610	1.2628	8.77	N/A	43.9
	343.15	12.53	N/A	1.1578	1.2605	8.87	N/A	44.0
B4[e]	293.15	N/A	508.54	N/A	1.2015	4.79	1.2620	49.6
	303.15	N/A	386.64	N/A	1.1992	4.75	1.2590	49.7
	313.15	N/A	197.50	N/A	1.1945	4.70	1.2534	50.0
	323.15	N/A	109.87	N/A	1.1899	4.63	1.2477	50.2
	333.15	N/A	66.19	N/A	1.1853	4.56	1.2419	50.4
	343.15	N/A	49.89	N/A	1.1806	4.70	1.2389	50.6
C1[f]	308.15	N/A	30.90	N/A	1.1040	0.62	1.1109	79.1
	313. 15	N/A	25.80	N/A	1.1017	0.58	1.1081	79.3
	318. 15	N/A	21.90	N/A	1.0993	0.54	1.1053	79.5
	323. 15	N/A	18.80	N/A	1.0970	0.50	1.1025	79.7
	328. 15	N/A	16.20	N/A	1.0947	0.46	1.0997	79.9
	333. 15	N/A	14.20	N/A	1.0924	0.41	1.0969	80.2
	338. 15	N/A	12.50	N/A	1.0901	0.37	1.0941	80.4
	343. 15	N/A	11.00	N/A	1.0877	0.33	1.0913	80.6
	353. 15	N/A	8.79	N/A	1.0831	0.25	1.0858	81.0
	363. 15	N/A	7.11	N/A	1.0785	0.17	1.0803	81.4
C2[f]	293.15	N/A	520.00	N/A	1.1884	0.49	1.1942	90.4
	303.15	N/A	264.00	N/A	1.1837	0.42	1.1887	90.8
	313.15	N/A	146.00	N/A	1.1791	0.34	1.1831	91.2
	323.15	N/A	88.80	N/A	1.1745	0.27	1.1776	91.7
	333.15	N/A	58.60	N/A	1.1698	0.19	1.1721	92.1
	343.15	N/A	39.60	N/A	1.1652	0.12	1.1666	92.5
	353.15	N/A	28.40	N/A	1.1605	0.05	1.1611	93.0
	3.63.15	N/A	20.90	N/A	1.1559	0.03	1.1556	93.4
C3[h]	293.15	N/A	1371.97	N/A	1.1456	4.54	1.2001	72.1
	303.15	N/A	527.28	N/A	1.1410	4.48	1.1945	72.5
	313.15	N/A	238.08	N/A	1.1363	4.41	1.1887	72.8
	323.15	N/A	119.80	N/A	1.1317	4.34	1.1831	73.2
	333.15	N/A	68.65	N/A	1.1271	4.27	1.1773	73.5
	343.15	N/A	41.96	N/A	1.1224	4.13	1.1708	73.9
	353.15	N/A	28.11	N/A	1.1178	3.93	1.1635	74.4
	363.15	N/A	19.95	N/A	1.1131	3.66	1.1554	74.9
F1	293.15	3842.00	N/A	1.3962	1.3062	6.45	N/A	48.6
	298.15	2395.55	N/A	1.3940	1.3039	6.47	N/A	48.7
	303.15	1347.67	N/A	1.3898	1.3015	6.35	N/A	48.9
	308.15	887.59	N/A	1.3877	1.2992	6.38	N/A	48.9
	313.15	546.47	N/A	1.3835	1.2969	6.26	N/A	49.1
G1	293.15	478.77	N/A	1.2900	1.2471	3.33	N/A	43.8
	298.15	322.55	N/A	1.2869	1.2448	3.27	N/A	43.9
	303.15	223.05	N/A	1.2841	1.2425	3.24	N/A	44.0
	308.15	158.54	N/A	1.281	1.2401	3.19	N/A	44.1
	313.15	115.69	N/A	1.2781	1.2378	3.15	N/A	44.2
G2	293.15	15709.50	N/A	1.3402	1.3022	2.83	N/A	81.9
	303.15	5431.60	N/A	1.3336	1.2976	2.70	N/A	82.3
	313.15	2061.55	N/A	1.3267	1.2930	2.54	N/A	82.7
	323.15	863.38	N/A	1.3200	1.2883	2.40	N/A	83.1
	333.15	395.31	N/A	1.3127	1.2837	2.21	N/A	83.6
G3	293.15	13013.00	N/A	1.3833	1.3230	4.36	N/A	61.3
	303.15	4078.60	N/A	1.3765	1.3184	4.22	N/A	61.6
	313.15	1446.05	N/A	1.3695	1.3138	4.07	N/A	61.9

Table 4 (*continued*)

NADES	[a] T (K)	[b] η (mPa.s)		[c] ρ (g/cm³)			Lit.	V_m*
		Exp.	Lit.	Exp.	Pred. [i]	ARD% [d]		(cm³/mol)
	323.15	584.56	N/A	1.3625	1.3091	3.92	N/A	62.2
	333.15	268.14	N/A	1.3552	1.3045	3.74	N/A	62.5
G4	293.15	17974.00	N/A	1.3375	1.3024	2.62	N/A	82.0
	303.15	6230.25	N/A	1.3310	1.2978	2.49	N/A	82.4
	313.15	2395.95	N/A	1.3246	1.2932	2.37	N/A	82.8
	323.15	1022.65	N/A	1.3182	1.2885	2.25	N/A	83.2
	333.15	481.74	N/A	1.3119	1.2839	2.14	N/A	83.6
G5	293.15	14695.5	N/A	1.3790	1.3232	4.05	N/A	61.5
	303.15	4554.05	N/A	1.3725	1.3186	3.93	N/A	61.7
	313.15	1648.85	N/A	1.3660	1.3139	3.81	N/A	62.0
	323.15	684.9	N/A	1.3599	1.3093	3.72	N/A	62.3
	333.15	318.84	N/A	1.3537	1.3046	3.62	N/A	62.6
G6	293.15	3522.80	N/A	1.3617	1.3050	4.16	N/A	52.4
	303.15	1251.65	N/A	1.3550	1.3004	4.03	N/A	52.7
	313.15	515.10	N/A	1.3487	1.2958	3.93	N/A	52.9
	323.15	239.84	N/A	1.3422	1.2911	3.81	N/A	53.2
	333.15	123.70	N/A	1.3355	1.2865	3.67	N/A	53.5
G7	293.15	1469.60	N/A	1.3407	1.3056	2.62	N/A	53.3
	303.15	590.19	N/A	1.3347	1.3009	2.53	N/A	53.5
	313.15	268.01	N/A	1.3287	1.2963	2.44	N/A	53.7
	323.15	135.74	N/A	1.3225	1.2917	2.33	N/A	54.0
	333.15	75.22	N/A	1.3161	1.2870	2.21	N/A	54.3
P1	293.15	25.74	N/A	1.2134	1.2346	1.75	N/A	32.1
	298.15	20.17	N/A	1.2105	1.2323	1.80	N/A	32.2
	303.15	16.06	N/A	1.2074	1.2300	1.87	N/A	32.3
	308.15	12.99	N/A	1.2046	1.2277	1.91	N/A	32.4
	313.15	10.67	N/A	1.2017	1.2253	1.97	N/A	32.4
T1	293.15	553.06	N/A	1.3576	1.3785	1.54	N/A	43.1
	298.15	238.57	N/A	1.3517	1.3738	1.64	N/A	43.3
	303.15	115.09	N/A	1.3451	1.3692	1.79	N/A	43.5
	308.15	61.83	N/A	1.3381	1.3646	1.98	N/A	43.8
	313.15	36.33	N/A	1.3312	1.3599	2.16	N/A	44.0
T2	293.15	669.86	N/A	1.3557	1.3774	1.60	N/A	43.2
	303.15	289.39	N/A	1.3502	1.3727	1.67	N/A	43.4
	313.15	141.01	N/A	1.3447	1.3681	1.74	N/A	43.5
	323.15	76.29	N/A	1.3389	1.3635	1.83	N/A	43.7
	333.15	44.83	N/A	1.3329	1.3588	1.95	N/A	43.9
M1	293.15	11.44	N/A	0.9347	1.1056	18.29	0.935 [25]	115.7
	303.15	7.07	N/A	0.9264	1.1010	18.85	0.927 [25]	116.8
	313.15	4.69	N/A	0.9181	1.0964	19.42	0.919 [25]	117.8
	323.15	3.30	N/A	0.9099	1.0917	19.98	0.911 [25]	118.9
	333.15	2.43	N/A	0.9015	1.0871	20.58	0.902 [25]	120.0
M2	293.15	150.69	N/A	0.9131	1.0953	19.95	N/A	170.6
	303.15	56.22	N/A	0.9058	1.0906	20.41	N/A	172.0
	313.15	25.22	N/A	0.8985	1.0860	20.87	N/A	173.4
	323.15	12.94	N/A	0.891	1.0813	21.36	N/A	174.9
	333.15	7.44	N/A	0.8833	1.0999	24.52	N/A	176.4
M3	293.15	20.23	20.49 [27]	0.9000	1.0968	21.86	0.9000 [27]	182.5
	303.15	12.79	12.75 [27]	0.8926	1.0921	22.35	0.8927 [27]	184.0
	313.15	8.55	8.503 [27]	0.8852	1.0875	22.85	0.89853 [27]	185.6
	323.15	6.01	5.972 [27]	0.8779	1.0829	23.35	0.8779 [27]	187.1
	333.15	4.41	4.389 [27]	0.8704	1.0782	23.88	0.8704 [27]	188.7
M4	293.15	28.08	N/A	0.8993	1.0959	21.86	N/A	179.7
	303.15	16.19	N/A	0.8913	1.0913	22.43	N/A	181.3
	313.15	10.07	N/A	0.8825	1.0866	23.13	N/A	183.1
	323.15	6.69	N/A	0.8719	1.0820	24.09	N/A	185.3
	333.15	4.69	N/A	0.8594	1.0773	25.36	N/A	188.0
M5	293.15	39.34	N/A	0.8991	1.0951	21.80	N/A	177.4
	303.15	20.48	N/A	0.8917	1.0904	22.29	N/A	178.8
	313.15	11.79	N/A	0.8845	1.0858	22.76	N/A	180.3
	323.15	7.38	N/A	0.8771	1.0812	23.26	N/A	181.8
	333.15	4.93	N/A	0.8696	1.0765	23.79		183.4
M6	293.15	36.46	N/A	0.8993	1.0952	21.79	N/A	177.7
	303.15	19.43	N/A	0.8919	1.0906	22.28	N/A	179.2
	313.15	11.39	N/A	0.8846	1.0859	22.76	N/A	180.7
	323.15	7.23	N/A	0.8773	1.0813	23.25	N/A	182.2
	333.15	4.89	N/A	0.8698	1.0767	23.78	N/A	183.7
M7	293.15	35.20	N/A	0.8970	1.0937	21.92	N/A	187.5
	303.15	19.51	N/A	0.8898	1.0890	22.39	N/A	189.0
	313.15	11.74	N/A	0.8825	1.0844	22.88	N/A	190.6
	323.15	7.59	N/A	0.8752	1.0797	23.37	N/A	192.2
	333.15	5.21	N/A	0.8678	1.0751	23.89	N/A	193.8
M8	293.15	32.03	N/A	0.8960	1.0934	22.03	0.897 [25]	190.8
	303.15	18.47	N/A	0.8890	1.0888	22.47	0.890 [25]	192.3
	313.15	11.42	N/A	0.8810	1.0841	23.06	0.883 [25]	194.0

Table 4 (*continued*)

NADES	[a] T (K)	[b] η (mPa.s)		[c] ρ (g/cm³)			Lit.	V_m [*]
		Exp.	Lit.	Exp.	Pred. [i]	ARD% [d]		(cm³/mol)
	323.15	7.54	N/A	0.8740	1.0795	23.51	0.876 [25]	195.6
	333.15	5.25	N/A	0.8670	1.0749	23.97	0.868 [25]	197.2
M9	293.15	44.00	N/A	0.8974	1.0938	21.89	N/A	183.1
	303.15	22.63	N/A	0.8902	1.0892	22.36	N/A	184.5
	313.15	12.88	N/A	0.8829	1.0846	22.84	N/A	186.1
	323.15	7.97	N/A	0.8756	1.0799	23.34	N/A	187.6
	333.15	5.29	N/A	0.8682	1.0753	23.85	N/A	189.2
M10	293.15	42.50	N/A	0.8973	1.0938	21.90	N/A	184.0
	303.15	22.22	N/A	0.8901	1.0892	22.37	N/A	185.5
	313.15	12.87	N/A	0.8828	1.0845	22.85	N/A	187.0
	323.15	8.03	N/A	0.8755	1.0799	23.35	N/A	188.6
	333.15	5.36	N/A	0.8681	1.0753	23.86	N/A	190.2
M11	293.15	46.47	N/A	0.8975	1.0939	21.88	N/A	181.9
	303.15	23.48	N/A	0.8903	1.0892	22.34	N/A	183.4
	313.15	13.19	N/A	0.8830	1.0846	22.83	N/A	184.9
	323.15	8.09	N/A	0.8757	1.0799	23.32	N/A	186.4
	333.15	5.32	N/A	0.8682	1.0753	23.85	N/A	188.0
M12	293.15	55.27	N/A	0.8971	1.0939	21.93	N/A	179.6
	303.15	26.42	N/A	0.8897	1.0892	22.43	N/A	181.1
	313.15	14.23	N/A	0.8824	1.0846	22.91	N/A	182.6
	323.15	8.45	N/A	0.8750	1.0799	23.42	N/A	184.2
	333.15	5.41	N/A	0.8676	1.0753	23.94	N/A	185.8
M13	293.15	23.24	N/A	0.8976	1.0946	21.95	N/A	190.8
	303.15	14.53	N/A	0.8902	1.0900	22.44	N/A	192.4
	313.15	9.66	N/A	0.8831	1.0853	22.90	N/A	194.0
	323.15	6.71	N/A	0.8758	1.0807	23.40	N/A	195.6
	333.15	4.88	N/A	0.8684	1.0761	23.91	N/A	197.2
M14	293.15	30.11	N/A	0.8981	1.0947	21.89	N/A	185.1
	303.15	17.36	N/A	0.8907	1.0900	22.38	N/A	186.7
	313.15	10.83	N/A	0.8836	1.0854	22.84	N/A	188.2
	323.15	7.15	N/A	0.8763	1.0808	23.33	N/A	189.7
	333.15	5.00	N/A	0.8689	1.0761	23.85	N/A	191.4
M15	293.15	39.87	N/A	0.9831	1.1507	17.05	N/A	138.5
	303.15	21.48	N/A	0.9752	1.1461	17.52	N/A	139.7
	313.15	12.82	N/A	0.9673	1.1414	18.00	N/A	140.8
	323.15	8.28	N/A	0.9595	1.1368	18.48	N/A	141.9
	333.15	5.70	N/A	0.9516	1.1321	18.97	N/A	143.1
M16	293.15	46.32	N/A	0.8957	1.0926	21.98	N/A	190.6
	303.15	24.25	N/A	0.8885	1.0880	22.45	0.8884 [27]	192.1
	313.15	13.96	N/A	0.8814	1.0833	22.91	0.8812 [27]	193.7
	323.15	8.71	N/A	0.8741	1.0787	23.41	0.8739 [27]	195.3
	333.15	5.82	N/A	0.8668	1.0741	23.91	0.8665 [27]	196.9
M17	293.15	57.58	N/A	0.8962	1.0933	22.00	N/A	183.3
	303.15	27.7	N/A	0.8884	1.0887	22.54	N/A	184.9
	313.15	14.99	N/A	0.8799	1.0840	23.20	N/A	186.7
	323.15	8.94	N/A	0.8713	1.0794	23.88	N/A	188.5
	333.15	5.72	N/A	0.8623	1.0748	24.64	N/A	190.5
M18	293.15	53.95	54.98 [30]	0.9364	1.1279	20.45	0.936 [30]	163.6
	303.15	24.47	24.52 [30]	0.9289	1.1233	20.93	0.930 [30]	165.0
	313.15	12.94	12.94 [30]	0.9214	1.1186	21.41	0.921 [30]	166.3
	323.15	7.67	7.68 [30]	0.9138	1.1140	21.91	0.915 [30]	167.7
	333.15	4.95	4.95 [30]	0.9061	1.1094	22.43	0.909 [30]	169.1
M19	293.15	68.94	64.93 [30]	0.9236	1.1166	20.90	0.924 [30]	167.0
	303.15	29.77	28.45 [30]	0.9162	1.1120	21.37	0.918 [30]	168.4
	313.15	15.16	14.54 [30]	0.9088	1.1073	21.84	0.909 [30]	169.7
	323.15	8.64	8.4 [30]	0.9013	1.1027	22.34	0.902 [30]	171.1
	333.15	5.42	5.29 [30]	0.8937	1.0980	22.86	0.897 [30]	172.6
M20	293.15	79.69	84.45 [30]	0.9137	1.1075	21.21	0.914 [30]	169.7
	303.15	33.34	33.73 [30]	0.9063	1.1028	21.68	0.908 [30]	171.1
	313.15	16.47	16.54 [30]	0.8990	1.0982	22.16	0.899 [30]	172.5
	323.15	9.15	9.17 [30]	0.8915	1.0935	22.66	0.892 [30]	173.9
	333.15	5.60	5.61 [30]	0.8839	1.0889	23.19	0.887 [30]	175.4
M21	293.15	86.31	N/A	0.9064	1.1013	21.51	N/A	171.7
	303.15	35.31	N/A	0.8991	1.0967	21.98	N/A	173.1
	313.15	17.08	N/A	0.8918	1.0921	22.46	N/A	174.5
	323.15	9.36	N/A	0.8844	1.0874	22.96	N/A	175.9
	333.15	5.66	N/A	0.8769	1.0828	23.48	N/A	177.4

Uncertainties (u): [a] u(T) = 0.02 K; [b] u(η) = 0.35%; [c] u(ρ) = 0.0001 g.cm⁻³.

N/A – Not available.

[i] Predicted by Haghbakhsh et al. Group contribution model[21].

[*] Molar volume (V_m) = Mw/ρ.

[d] Absolute Relative Deviation percent (ARD%) = $100[(X^{Pred} - X^{Exp})/ X^{Exp}]$.

[e, f, g, and h] Data of viscosities and densities retrieved from references [55], [57], [41] and [58] respectively. Both ARD% and V_m were calculated using these data of density. These data will be used in the further discussion of this work.
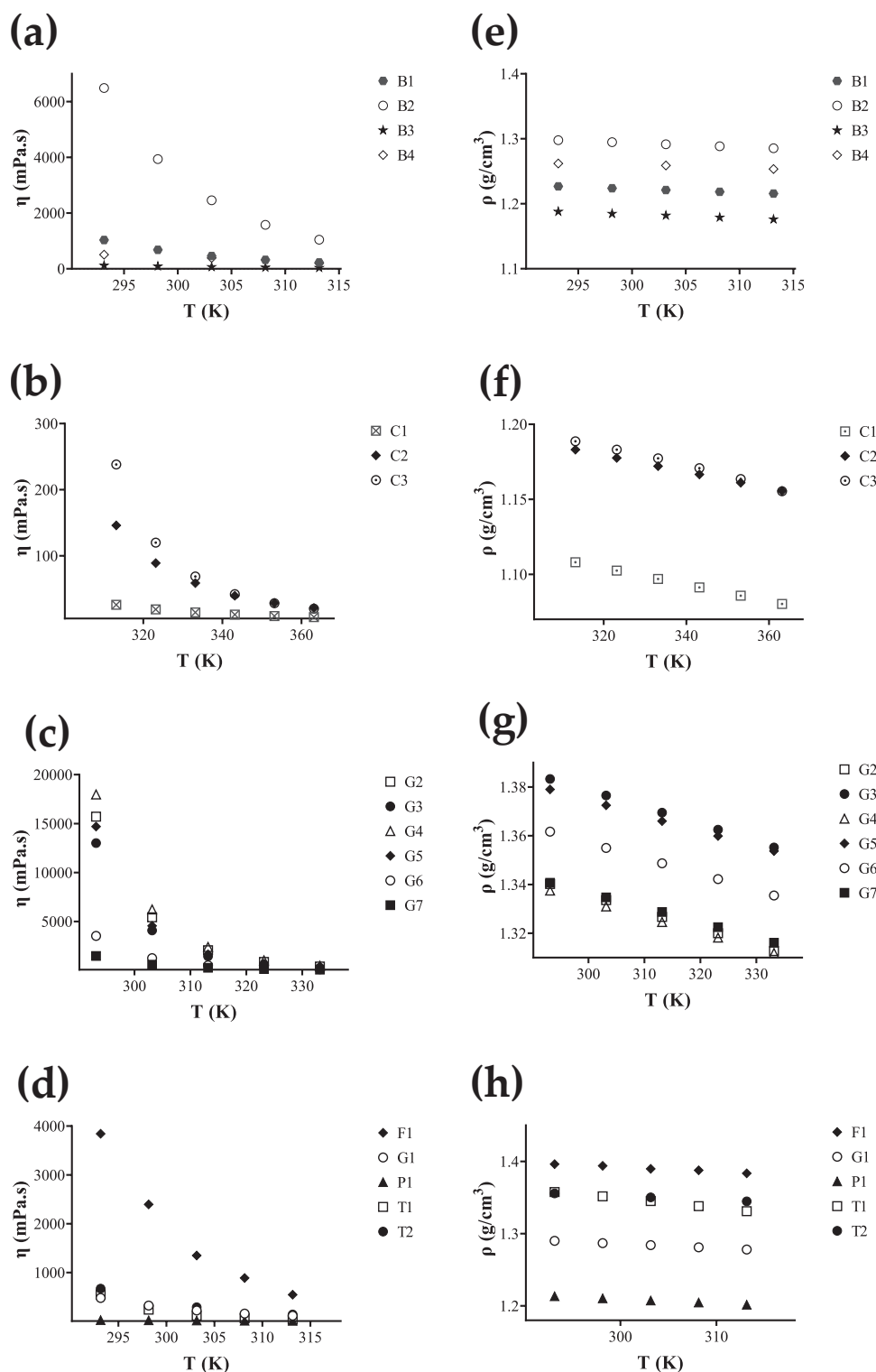
Fig. 2. Variation of the dynamic viscosity of hydrophilic NADES (from (a) to (d)) and their respective density (from (e) to (h)) at different temperatures. From ID, B1 to T2, following the same numbering order, are represented the systems: B1 (Bet:Glc:W (5:2:10)), B2 (Bet:Gly:Suc:W (2:3:1:5)), B3 (Bet:sorb:W (3:1:10)), B4 (Bet:Suc:Pro:W (5:2:2:21)), C1 (Chcl:EG (1:2) [57]), C2 (Chcl:Gly (1:2) [41]), C3 (Chcl:Ure (1:2) [58]), F1 (Fru:Glc:Suc:W (1:1:1:10)), G1 (Glc:Pro:Gly:W(3:5:3:20)), G2 (Gly:Fru (4:1)), G3 (Gly:Fru:Sorb:W (1:1:1:3)), G4 (Gly:Glc (4:1)), G5 (Gly:Glc:Sorb:W (1:1:1:3)), G6 (Gly:Suc:Sorb:W (2:1:2:10)), G7 (Gly:Tre:Sorb:W (2:1:2:10)), P1 (Pro:Gly:Sorb:W (1:1:1:13)), T1 (Tre:Fru:W (1:2:13)) and T2 (Tre:Glc:W (1:2:13)).

previously mentioned: hydrophilic systems (Fig. 2) and hydrophobic systems (Fig. 3). At the viscosity level, both types of systems are much more viscous than water. Furthermore, except for **P1** and **C1** mixtures, all the other hydrophilic systems are significantly more viscous than hydrophobic ones. The cause is normally associated with the extensive network of hydrogen bonds created between the components of hydrophilic NADES, such as sugars, which results in a decrease in the mobility of free species within the NADES [59]. In addition, the existence of an inherently very viscous component such as glycerol in a mixture with negligible water content, perfectly justifies the position of **G4** and **G2** as the most viscous systems being used in this study. At the same time, the high water content of **P1** may explain its low viscosity.

Regarding density, contrary to the hydrophilic systems, all the hydrophobic ones exhibit a density lower than water. Furthermore, the results also show that both the nature and the molar fraction of HBD have a significant effect on viscosity or density. For example, unlike the viscosity of the Men:Thy system (from **M18** to **M21**), which increases with decreasing of the HBD (thymol) fraction, its density increases

(a)

(e)

(b)

(f)

(c)

(g)

(d)

(h)
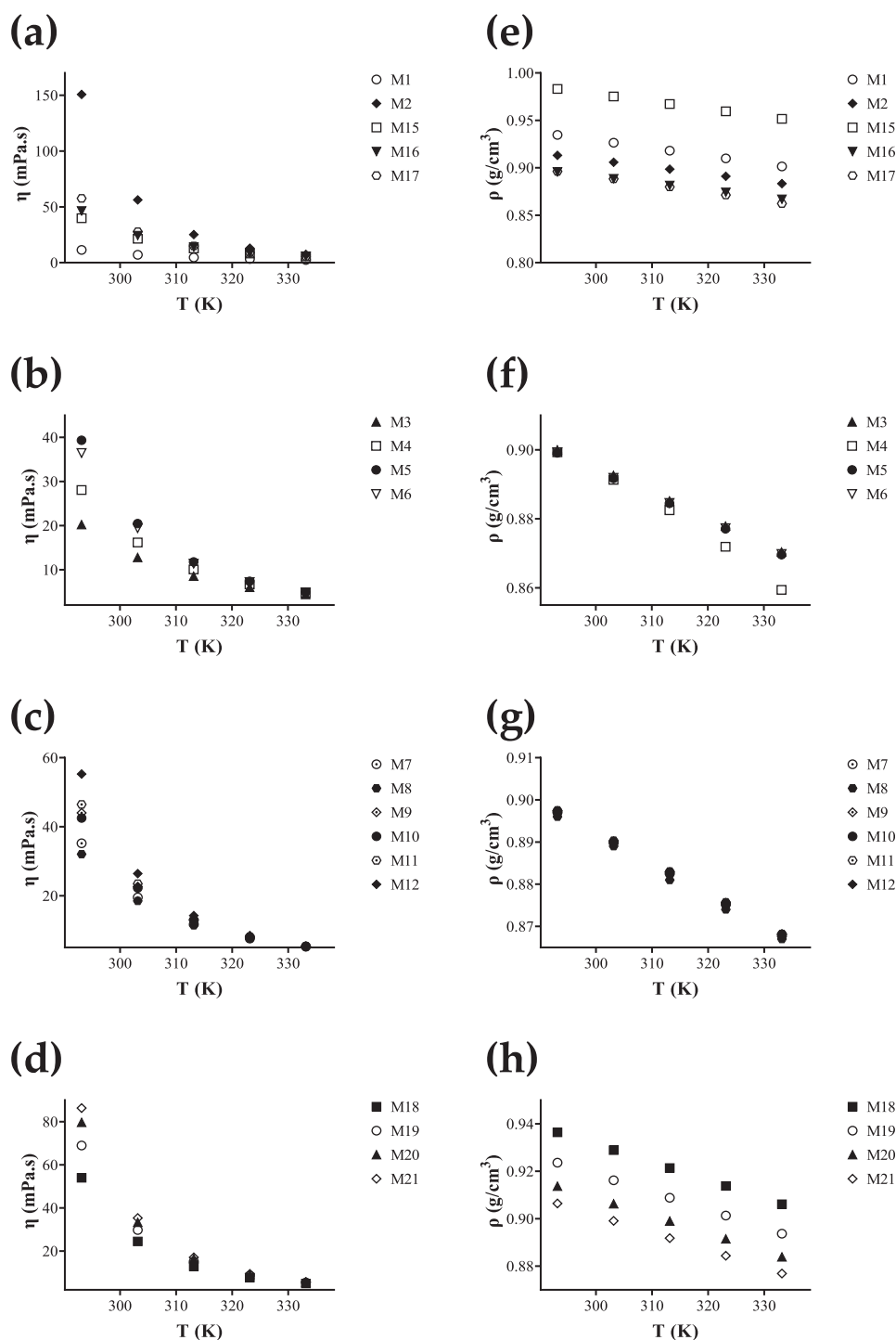
Fig. 3. Variation of the dynamic viscosity of hydrophobic NADES ((a) to (d)) and their respective density ((e) to (h)) at different temperatures. From ID M1 to M21, following the same numbering order, are represented the systems M1 (Men:AcetA (1:1)), M2 (Men:Bor (7:2)), M3 (Men:DecA (1:1)), M4 (Men:DecA (2:1)), M5 (Men:DecA (4:1)), M6 (Men:DecA (7:2)), M7 (Men:LauA (2.7:1)), M8 (Men:LauA (2:1)), M9 (Men:LauA (4.5:1)), M10 (Men:LauA (4:1)), M11 (Men:LauA (5.3:1)), M12 (Men:LauA (8:1)), M13 (Men:LauA:DecA (2:1:1)), M14 (Men:LauA:DecA (4:1:1)), M15 (Men:LevA (1:1)), M16 (Men: MyrA (4:1)), M17 (Men:MyrA (8:1)), M18 (Men: Thy (1:1)), M19 (Men:Thy (2:1)), M20 (Men:Thy (4:1)) and M21 (Men:Thy (8:1)).

linearly with the HBD fraction. This is due to the fact that, differently from the one of menthol, the ring of thymol is an aromatic one, which means that structurally thymol is more rigid than menthol, therefore it allows a more efficient packing [29]. On the other hand, in the case of the Men:LauA system (from **M7** to **M12**), both viscosity and density increase with the decreasing of HBD fraction. Being the density of a compound entirely related to its atomic weight, and which consequently dictates its shape, packing, and possible interactions [59]. This means that a hydrophobic system such as Men:Thy has a better packaging and molecular arrangement, the higher the percentage of thymol, whereas an HBD like lauric, decanoic or myristic acid has the opposite effect.

3.3. Refractive index

The refractive index (n_D) is considered one of key physical properties of eutectic mixtures since it allows an optical characterization of these compounds [2]. The measured values of refractive indices are presented in Table 5. Regarding yet to the experimental results organized and shown in Fig. 4, the first observation is that the refractive indexes of all the investigated systems are much higher than water ($n_D = 1.333$ [60]).

On the other hand, as it can be confirmed, the refractive indices of hydrophilic systems are tendentially higher than hydrophobic ones, except for terpenes-terpenes formulations (e.g., **M18** (Men:Thy (1:1)), which exhibit refractive index similar or higher to some hydrophilic

Table 5

Experimental (Exp.) and predicted (Pred.) values of refractive index (n_D, at 293.15 K) and surface tension (γ_{LV}, at 296.15 K), compared to those reported in the literature (Lit.). All the measurements were performed at atmospheric pressure (100 kPa).

NADES	n_D^a This work Exp.	Pred. [c]	ARD% [d]	Lit.	γ_{LV} (mN/m) [b] This work Exp.	Pred. [c]	ARD% [d]	Lit.
B1	1.4762	1.5571	5.48	N/A	41.04 ± 3.95	112.3	173.51	N/A
B2	1.4865	1.5265	2.69	N/A	54.87 ± 1.01	71.9	31.05	N/A
B3	1.4598	1.6133	10.51	N/A	N/A	N/A	N/A	N/A
B4	1.4824	1.5936	7.50	N/A	48.18 ± 3.79	N/A	N/A	N/A
C1	1.4764	1.4696	0.46	1.4682*[66]; 1.4507* [67]	N/A	47.6	N/A	49.40 [68]; 48.0* [69]
C2	1.4677	1.4844	1.14	1.4867* [66]; 1.4718* [67]	N/A	55.7	N/A	57.80 [70]; 56.0* [69]
C3	1.4779	1.4941	1.10	1.5117*[71]; 1.4583* [67]	N/A	55.5	N/A	52.02 [72]; 52.0* [69]
F1	1.4849	1.6079	8.28	N/A	48.44 ± 0.3	115.9	139.23	N/A
G1	1.4799	1.5743	6.38	N/A	45.24 ± 1.34	110.7	144.60	N/A
G2	1.4911	1.5276	2.45	N/A	N/A	56.3	N/A	N/A
G3	1.4924	1.5067	0.96	N/A	N/A	72.5	N/A	N/A
G4	1.4913	1.5275	2.42	N/A	N/A	56.5	N/A	N/A
G5	1.4923	1.5084	1.08	N/A	N/A	73.1	N/A	N/A
G6	1.4849	1.5561	4.80	N/A	46.15 ± 2.1	85.8	85.99	N/A
G7	1.4776	1.5585	5.47	N/A	49.34 ± 2.41	86.5	75.31	N/A
P1	1.4413	1.6381	13.66	N/A	34.75 ± 1.65	N/A	N/A	N/A
T1	1.4735	1.6766	13.78	N/A	N/A	N/A	N/A	N/A
T2	1.4742	1.6799	13.96	N/A	47.41 ± 1.21	N/A	N/A	N/A
M1	1.4407	1.4803	2.75	N/A	30.37 ± 0.35	43.4	42.86	N/A
M2	1.4667	1.4687	0.14	N/A	32.78 ± 0.47	29.9	8.85	N/A
M3	1.4497	1.4701	1.41	1.44615 [28]	31.77 ± 1.45	28.1	11.67	28.79 [28]
M4	1.4533	1.4696	1.12	1.45079 [28]	31.30 ± 1.48	28.5	8.84	28.47 [28]
M5	1.4569	1.4692	0.84	N/A	30.82 ± 0.51	28.9	6.15	N/A
M6	1.4561	1.4692	0.90	N/A	32.02 ± 0.55	28.9	9.87	N/A
M7	1.4564	1.4702	0.95	N/A	N/A	28.3	N/A	N/A
M8	1.4550	1.4707	1.08	N/A	33.09 ± 0.22	28.1	15.18	N/A
M9	1.4585	1.4696	0.76	N/A	32.75 ± 0.63	28.7	12.49	N/A
M10	1.4593	1.4697	0.71	N/A	31.83 ± 0.86	28.6	10.21	N/A
M11	1.4583	1.4695	0.76	N/A	33.12 ± 0.03	28.8	13.16	N/A
M12	1.4591	1.4692	0.69	N/A	32.30 ± 0.17	29.0	10.28	N/A
M13	1.4513	1.4711	1.36	N/A	33.49 ± 0.04	27.7	17.14	N/A
M14	1.4547	1.4701	1.06	N/A	33.51 ± 1.08	28.3	15.63	N/A
M15	1.4538	1.4777	1.65	N/A	31.54 ± 0.87	37.1	17.50	N/A
M16	1.4608	1.4704	0.66	N/A	31.98 ± 0.68	28.4	11.13	N/A
M17	1.4604	1.4695	0.62	N/A	32.62 ± 0.23	28.8	11.56	N/A
M18	1.4923	1.4725	1.33	N/A	33.21 ± 0.33	32.8	1.24	29.72[30]
M19	1.4818	1.4711	0.72	N/A	32.30 ± 0.18	31.6	2.10	29.01[30]
M20	1.4740	1.4701	0.27	N/A	31.57 ± 0.46	30.8	2.59	28.82[30]
M21	1.4682	1.4695	0.09	N/A	31.38 ± 0.77	30.2	3.75	N/A

Uncertainties (u): [a] u (n_D) = 0.0002; [b] u (γ_{LV}) = 0.02 m. Nm^{-1}.

*Data at 298.15 K.

[c] Predicted by Haghbakhsh et al. Group contribution model [21].

[d] Absolute Relative Deviation percent (ARD%) = $100[(X^{Pred} - X^{Exp})/ X^{Exp}]$.
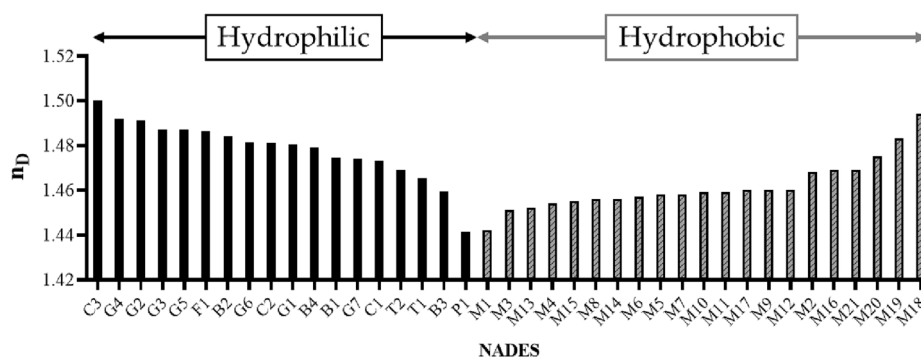
Fig. 4. Refractive index (n_D) of the investigated hydrophilic (black bars, at left side) and hydrophilic (grey bars, at right side) eutectic systems, at the temperature of 296.15 K.

ones. This happens due to good packing provide by thymol (HBD) as well as to the interaction of light with the delocalized electrons in the aromatic ring of thymol, since refractive index increases linearly with the number of electrons (electronic polarizability) in a substance. Such assumption may also explain the slightly higher results of n_D obtained for hydrophilic NADES comparatively to the hydrophobic ones, as hydrophilic formulations are fundamentally much more complex and in most of the cases are constituted by more than three components.

(a)

(b)
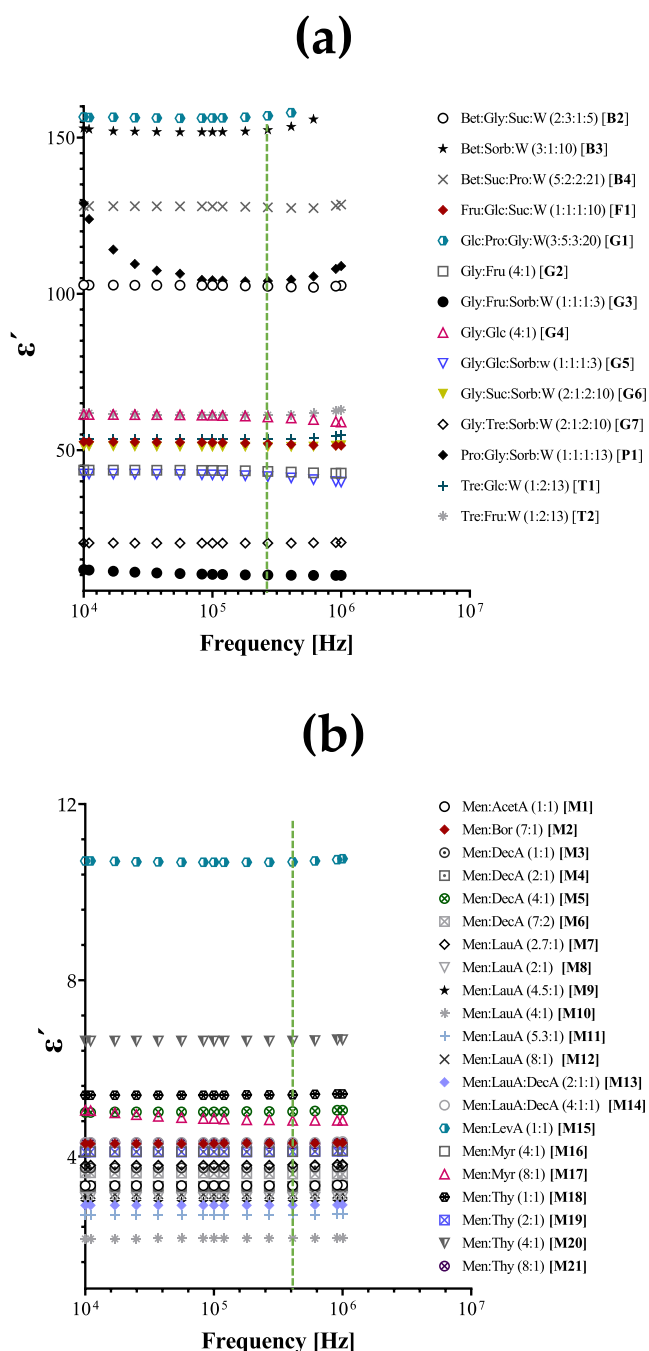
Fig. 5. Dielectric constant of the hydrophilic [a] and hydrophobic systems [b] in a frequency range of 10^4-10^6 Hz (see Tables S. 2 to S. 5, in the Supplementary section, for more details). The vertical green dashed line indicates the frequency point where studied $\acute{\varepsilon}$ were acquired.

3.4. Dielectric constant

Concerning NADES field, few studies of its dielectric properties are available in the literature [61-63], therefore, the results presented here may indeed contribute significantly to the future work in the area. In order to know the frequency or reference point where the NADES dielectric constant should be obtained, a list of organic solvents was used, as their values are already reported in the literature (**Table S1**, in **the Supplementary section**). Here, it was observed that at a frequency of 4.1×10^5 Hz, most of the results obtained here are similar to those in the literature (**Table S2**, in **the Supplementary section**). Hence, this same frequency was then used to evaluate the dielectric Constant of

eutectic systems which are presented in the Fig. 5.

By analysing the results presented in Fig. 5, it is possible to observe that the spectral behaviour of the system P1 differs from all the other NADES. According to the study of Ethaline systems dielectric constant, performed by Daniel Reuter *el al.*[64], a similar behaviour, such that observed in P1, is a typical signature for the relaxational process and it is related mainly to the reorientational motion of the various dipolar components present in this system. In fact, if taking into account the high water content of system P1, as well all the remains polar compounds present in this mixture, such behaviour is somehow expected. Furthermore, as explained by these authors, the significant increments in $\acute{\varepsilon}$, which tend to reach exceptionally high values, seen at lower frequencies, are attributed to external, non-intrinsic factors related to the electrodes (often known as 'blocking electrodes'). These types of systems are identified as materials that conduct ions and occur when the mobile ions accumulate at the electrodes during low frequencies, forming narrow, inefficiently conductive space-charge areas, behaving like enormous capacitors. Moreover, as it was expected, the dielectric constants of all the hydrophilic systems are higher than the hydrophobic, and most of them even higher than water. In practice, solvents with high dielectric constants allow the dissolution of more salts [65]. This means that in the presence of an external field, systems such as those based on betaine, glycerol, fructose, or glucose are more easily polarized than those based on menthol. In addition, dielectric constants is often used as a relative solvent polarity scale, indicating that the more polar the solvent is the higher its dielectric constants and therefore it will dissolve more salts [65]. Thus, according to this assumption, **G1** (Glc: Pro:Gly:W (3:5:3:20)) and **M10** (Men:LauA (4:1)) are, respectively, the more and the less polar systems found in this list.

3.5. Dipole moment

Evaluating the performance of these models in the previously listed organic solvents, the results (in **the Supplementary section**, **Table S6**) show a large discrepancy between the theoretical dipole moments and the predicted ones by Onsager and Salems methods (**eqn. (1)** [36] and **eqn. (2)** [37], respectively). Despite this, by correlating the literature values with the predicted ones (**Fig. S1** and **Table S7**, **the Supplementary section**), there is clear evidence that values tend to increase accordingly, however, more data would be needed to confirm this, and possibly develop a more direct relationship between the two methods. These observations are, nonetheless, still very important, as it allows to use the results of organic solvents as reference values, helping to better understand the extension and behaviour of NADES relatively to these solvents. For instance, by examining the results of NADES dipole moments estimated with the two approaches and illustrated in Fig. 6, it is possible to conclude that in most of the cases the difference between them is quite negligible. The highest gaps are only observed in the dipole moments of the hydrophobic systems (from **M10** to **M15**).

Furthermore, it is possible to observe that the dipole moments of hydrophilic organic solvents (e.g., water, methanol, ethanol, etc) are lower than most of the listed hydrophilic NADES, but higher than hydrophobic systems. This would be expected due to the high polarizability provided by the components of hydrophilic NADES.

3.6. Surface tension

Along with density, viscosity and refractive index, surface tension has been one of most studied physical properties in eutectic mixture fields. The experimental values of surface tensions are presented in Table 5, which also includes the results from the predictive method, as well some data found available in the literature. Despite their being insufficient data to do such a comparison, it can still be noted that the results of refractive indexes and surface tensions obtained in this work are consistent with those reported in the literature. On the other hand, contrarily to what was observed previously in densitys prediction
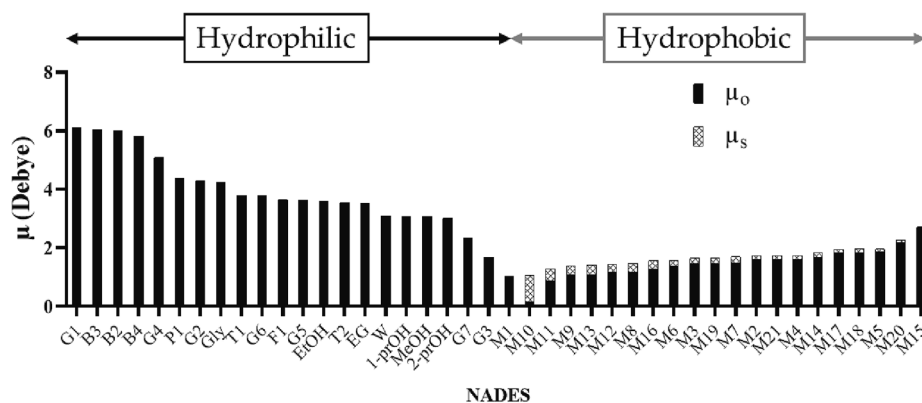
Fig. 6. Dipole moments of NADES estimated using the models of Onsager (μ_O, [36]) and Salem (μ_S, [37]).
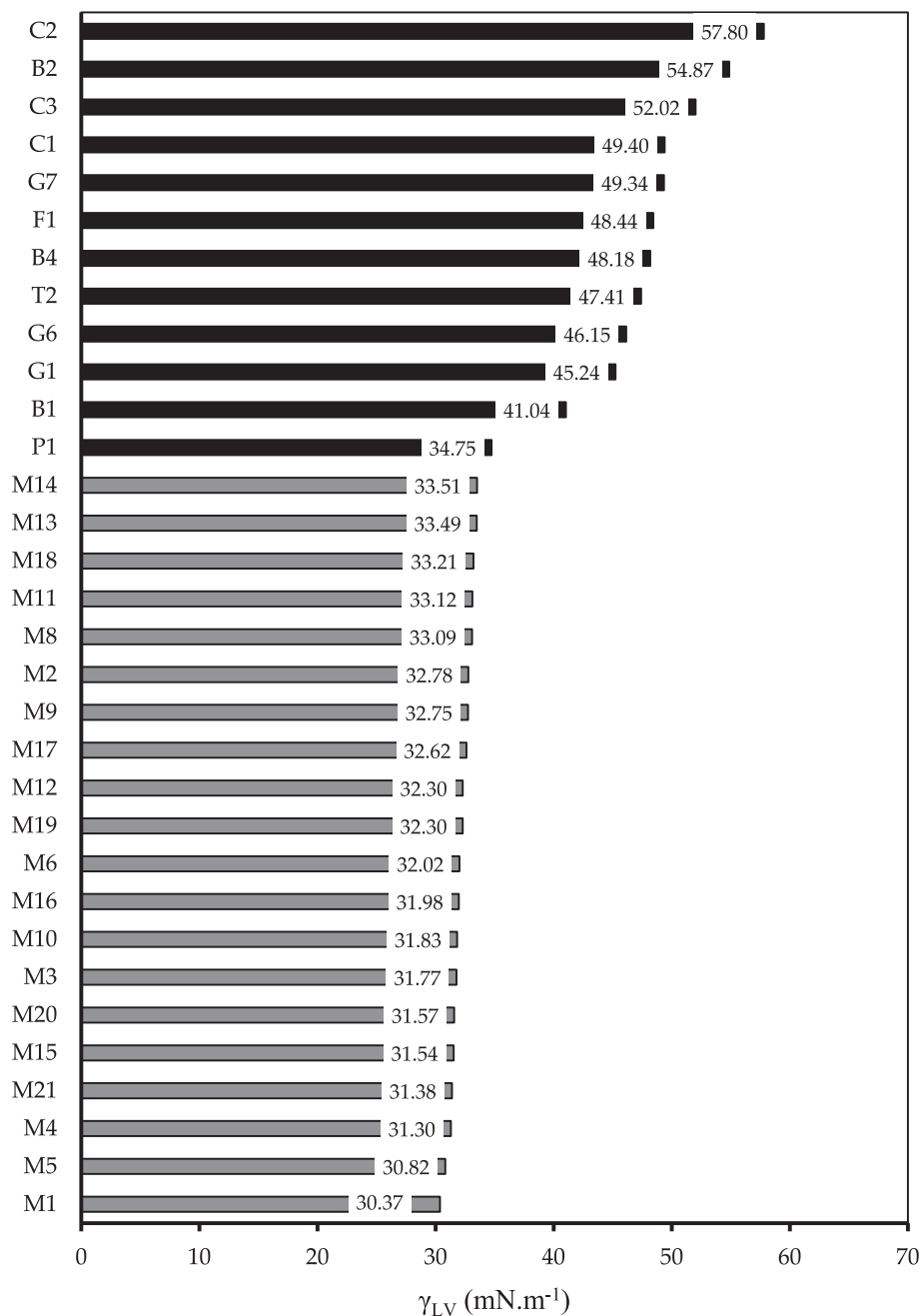
Fig. 7. Measured surface tensions (γ_{LV}, in mN.m-1) of investigated NADES at the temperature of 296.15 K. The data for the systems C1, C2 and C3 were obtained from literature (from de references [68,70;72], respectively).

Table 6

Maximum absorption wavelength of the used probes obtained experimentally (at 293.15 K) and used to calculate the solvatochromic parameters, polarity (E_{NR}), polarizability (π^*), acidity (α) and basicity (β) of a set of organic solvents and the listed NADES.

| N°/ID	Organic solvent/ NADES	λ_{max} NR	DM4N	4NA	Ref.	E_{NR}	π^*	α	β	Ref.
1	Water	583.3 ± 0.3	421.3 ± 0.6	380.0 ± 0.0	This work	49.01	1.14 [a] 1.19[b]	0.33 [a] 1.00[b]	0.21 [a] 0.32[b]	This work
		593.2	N/A	N/A	[73]	48.21	1.09	1.17	0.18	[73,74]
		585.4	N/A	N/A	[26]	48.90	1.14	1.23	0.29	[26,75]
		584.5	N/A	N/A	[76]	N/A	N/A	N/A	N/A	N/A
2	Methanol	555.0 ± 0.1	392.0 ± 0.0	371.3 ± 0.6	This work	51.52	0.69 [a] 0.63[b]	0.82 [a] 0.81[b]	0.75 [a] 0.75[b]	This work
		549.6	N/A	N/A	[73]	52.02	0.60	0.93	0.62	[73,77]
		559.5	N/A	N/A	[26]	51.10	N/A	N/A	N/A	[26]
3	Ethanol	550.0 ± 0.0	388.0 ± 0.0	372.0 ± 0.0	This work	52.00	0.62 [a] 0.55[b]	0.90 [a] 0.74[b]	0.89 [a] 0.87[b]	This work
		548.3	N/A	N/A	[9]	52.15	0.54	0.83	0.77	[9,75]
		552.3	N/A	N/A	[26]	51.76	N/A	N/A	N/A	[26]
		539.8	N/A	N/A	[76]	N/A	N/A	N/A	N/A	N/A
4	1-propanol	549.0 ± 0.1	387.7 ± 0.6	375.3 ± 1.2	This work	52.08	0.62 [a] 0.54[b]	0.91 [a] 0.74[b]	1.01 [a] 0.96[b]	This work
		545.6	N/A	N/A	[73]	52.40	0.53	0.84	0.85	[73,74]
		549.70	N/A	N/A	[26]	52.02	0.52	0.78	NA	[26,75]
5	Ethylene glycol	571.0 ± 0.1	406.0 ± 0.0	375.3 ± 2.3	This work	50.07	0.91 [a] 0.91[b]	0.56 [a] 0.95[b]	0.47 [a] 0.53[b]	This work
		565.2	N/A	N/A	[77]	50.58	0.92	0.90	0.52	[77,78]
		557.3	N/A	N/A	[76]	N/A	N/A	N/A	N/A	N/A
6	Glycerol	578.0 ± 0.0	415.3 ± 0.6	386.7 ± 1.2	This work	49.47	1.05 [a] 1.08[b]	0.43 [a] 0.97[b]	0.58 [a] 0.61[b]	This work
		580.4	N/A	N/A	[74]	49.88	1.04	0.93	0.67	[74]
7	DMSO	562.3 ± 0.1	412.0 ± 0.0	389.7 ± 0.6	This work	50.84	1.00 [a] 1.02[b]	0.55 [a] 0.71[b]	0.76 [a] 0.75[b]	This work
		544.0	N/A	N/A	[76]	N/A	1.00	0.00	0.76	[75]
8	Cyclohexane	510.0 ± 0.0	358 ± 0.0	329.3 ± 1.2	This work	56.06	0.08 [a] −0.13[b]	1.55 [a] 0.31[b]	0.28 [a] 0.42[b]	This work
		487.6	N/A	N/A	[73]	58.63	0.00	0.00	0.00	[73,75]
		459.0	N/A	N/A	[76]	N/A	N/A	N/A	N/A	N/A
9	Hexane	506.0 ± 0.0	354.0 ± 0.0	319.7 ± 0.6	This work	56.50	0.00 [a] −0.23[b]	1.64 [a] 0.27[b]	0.00 [a] 0.21[b]	This work
		484.4	N/A	N/A	[73]	59.02	−0.08	0.00	0.00	[73,75]
B1	Bet:Glc:W (5:2:10)	572.0 ± 0.0	419.0 ± 1.4	388.0 ± 0.0	This work	49.99	1.10 [a] 1.15[b]	0.42 [a] 0.81[b]	0.52 [a] 0.56[b]	This work
B2	Bet:Gly:Suc:W (2:3:1:5)	572.0 ± 0.0	418.7 ± 1.2	390.0 ± 2.0	This work	49.49	1.10 [a] 1.14[b]	0.39 [a] 0.92[b]	0.59 [a] 0.61[b]	This work
B3	Bet:sorb:W (3:1:10)	567.2 ± 0.4	420.0 ± 0.0	389.0 ± 1.4	This work	50.41	1.12 [a] 1.17[b]	0.44 [a] 0.71[b]	0.53 [a] 0.56[b]	This work
B4	Bet:Suc:Pro:W (5:2:2:21)	583.3 ± 0.3	419.7 ± 0.6	390.7 ± 1.2	This work	49.01	1.11 [a] 1.16[b]	0.35 [a] 1.02[b]	0.59 [a] 0.61[b]	This work
C1	Chcl:EG (1:2)	563.7 ± 0.1	412.3 ± 0.6	387.3 ± 1.2	This work	50.72	1.00 [a] 1.03[b]	0.54 [a] 0.73[b]	0.68 [a] 0.69[b]	This work
						N/A	1.11	0.89	0.64	[24]
C2	Chcl:Gly (1:2)	598.0 ± 0.0	415.5 ± 0.7	386.0 ± 0.0	This work	47.81	1.05 [a] 1.08[b]	0.32 [a] 1.33[b]	0.55 [a] 0.59[b]	This work
						N/A	1.11	1.49	0.52	[24]
C3	Chcl:Ure (1:2)	584.0 ± 0.0	418.0 ± 0.0	388.0 ± 0.0	This work	48.96	1.09 [a] 1.13[b]	0.36 [a] 1.05[b]	0.55 [a] 0.58[b]	This work
						N/A	1.14	1.42	0.50	[24]
F1	Fru:Glc:Suc:W (1:1:1:10)	597.3 ± 0.1	425.3 ± 1.2	387.3 ± 1.2	This work	47.87	1.19 [a] 1.26[b]	0.22 [a] 1.20[b]	0.34 [a] 0.41[b]	This work
G1	Glc:Pro:Gly:W (3:5:3:20)	588.3 ± 0.3	420.7 ± 0.6	388.7 ± 1.2	This work	48.60	1.13 [a] 1.18[b]	0.31 [a] 1.10[b]	0.50 [a] 0.54[b]	This work
G2	Gly:Fru (4:1)	579.3 ± 0.7	415.0 ± 1.4	388.0 ± 0.0	This work	49.35	1.04 [a] 1.08[b]	0.42 [a] 1.00[b]	0.63 [a] 0.65[b]	This work
G3	Gly:Fru:Sorb:W (1:1:1:3)	585.0 ± 0.1	421.0 ± 0.0	392.0 ± 0.0	This work	48.87	1.13 [a] 1.18[b]	0.33 [a] 1.03[b]	0.59 [a] 0.61[b]	This work
G4	Gly:Glc (4:1)	583.0 ± 0.1	418.0 ± 2	418.0 ± 2	This work	49.04	1.09 [a] 1.13[b]	0.37 [a] 1.03[b]	0.53 [a] 0.57[b]	This work
G5	Gly:Glc:Sorb:W (1:1:1:3)	589.0 ± 0.1	425.0 ± 1.4	390.0 ± 0.0	This work	48.54	1.19 [a] 1.25[b]	0.27 [a] 1.06[b]	0.43 [a] 0.48[b]	This work
G6	Gly:Suc:Sorb:W (2:1:2:10)	592.3 ± 0.2	424.3 ± 0.6	388.0 ± 0.0	This work	48.27	1.18 [a] 1.24[b]	0.25 [a] 1.13[b]	0.38 [a] 0.45[b]	This work
G7	Gly:Tre:Sorb:W (2:1:2:10)	586.0 ± 0.0	424.5 ± 0.7	388.0 ± 0.0	This work	48.79	1.18 [a] 1.24[b]	0.29 [a] 1.01[b]	0.38 [a] 0.45[b]	This work
P1	Pro:Gly:Sorb:W (1:1:1:13)	584.7 ± 0.1	424.3 ± 0.6	389.7 ± 0.6	This work	48.90	1.18 [a] 1.24[b]	0.30 [a] 0.99[b]	0.43 [a] 0.49[b]	This work
T1	Tre:Fru:W (1:2:13)	592.0 ± 0.3	426.0 ± 0.0	390.5 ± 0.7	This work	48.30	1.20 [a] 1.27[b]	0.24 [a] 1.10[b]	0.42 [a] 0.47[b]	This work

(continued on next page)

Table 6 (*continued*)

N°/ ID	Organic solvent/ NADES	λ_{max} NR	DM4N	4NA	Ref.	E_{NR}	π^*	α	β	Ref.
T2	**Tre:Glc:W (1:2:13)**	592.0 ± 0.3	428.0 ± 0.0	389.5 ± 0.7	This work	48.30	1.23 [a]	0.22 [a]	0.34 [a]	This work
							1.30 [b]	1.08 [b]	0.41 [b]	
M1	**Men:AcetA (1:1)**	548.3 ± 0.1	386.0 ± 0.0	364.0 ± 2.0	This work	52.14	0.59 [a]	0.93 [a]	0.68 [a]	This work
							0.51 [b]	0.75 [b]	0.71 [b]	
						N/A	0.53	1.64	0.60	[39]
M2	**Men:Bor (7:2)**	N/A	382.0 ± 0.0	367.3 ± 1.2	This work	52.91	0.52 [a]	1.03 [a]	0.92 [a]	This work
		540.3 ± 0.1	N/A	N/A	[26]		0.42 [b]	0.64 [b]	0.90 [b]	
M3	**Men:DecA (1:1)**	534.7 ± 0.1	377.0 ± 1.4	354.5 ± 0.7	This work	53.48	0.43 [a]	1.13 [a]	0.62 [a]	This work
							0.31 [b]	0.59 [b]	0.67 [b]	
M4	**Men:DecA (2:1)**	N/A	376.0 ± 0.7	360.0 ± 0.0	This work	53.14	0.42 [a]	1.12 [a]	0.86 [a]	This work
		538.0 ± 0.0	N/A	N/A	[26]		0.29 [b]	0.67 [b]	0.85 [b]	
M5	**Men:DecA (4:1)**	536.7 ± 0.1	378.5 ± 0.7	359.0 ± 1.4	This work	53.28	0.46 [a]	1.10 [a]	0.74 [a]	This work
							0.35 [b]	0.61 [b]	0.76 [b]	
M6	**Men:DecA (7:2)**	N/A	377.0 ± 1.4	363.0 ± 1.4	This work	53.28	0.43 [a]	1.12 [a]	0.93 [a]	This work
		536.7 ± 0.1	N/A	N/A	[26]		0.31	0.63	0.91	
M7	**Men:LauA (2.7:1)**	536.7 ± 0.1	378.0 ± 0.0	360.0 ± 0.0	This work	53.28	0.45 [a]	1.10 [a]	0.79 [a]	This work
							0.33 [b]	0.62 [b]	0.80 [b]	
M8	**Men:LauA (2:1)**	535.3 ± 0.1	378.0 ± 0.0	359.3 ± 0.6	This work	53.41	0.45 [a]	1.11 [a]	0.77 [a]	This work
							0.33 [b]	0.59 [b]	0.78 [b]	
M9	**Men:LauA (4.5:1)**	536.3 ± 0.1	378.5 ± 0.7	378.5 ± 0.7	This work	53.31	0.46 [a]	1.10 [a]	0.81 [a]	This work
							0.35 [b]	0.60 [b]	0.82 [b]	
M10	**Men:LauA (4:1)**	539.6 ± 0.1	379.0 ± 1.0	364.0 ± 0.0	This work	52.99	0.47 [a]	1.07 [a]	0.90 [a]	This work
							0.36 [b]	0.66 [b]	0.88 [b]	
M11	**Men:LauA (5.3:1)**	536.3 ± 0.2	378.0 ± 0.0	362.5 ± 0.7	This work	53.31	0.45 [a]	1.10 [a]	0.88 [a]	This work
							0.33 [b]	0.61 [b]	0.87 [b]	
M12	**Men:LauA (8:1)**	N/A	380.0 ± 0.0	366.0 ± 0.0	This work	53.10	0.49 [a]	1.07 [a]	0.94 [a]	This work
		538.4 ± 0.1	N/A	N/A	[26]		0.38 [b]	0.63 [b]	0.91 [b]	
M13	**Men:LauA:DecA (2:1:1)**	N/A	376.3 ± 0.6	353.3 ± 0.6	This work	53.44	0.42 [a]	1.13 [a]	0.60 [a]	This work
		535.0 ± 0.1	N/A	N/A	[26]		0.30 [b]	0.60 [b]	0.66 [b]	
M14	**Men:LauA:DecA (4:1:1)**	N/A	378.3 ± 0.6	358.3 ± 0.6	This work	53.24	0.46 [a]	1.10 [a]	0.72 [a]	This work
		537.0 ± 0.1	N/A	N/A	[26]		0.34 [b]	0.62 [b]	0.75 [b]	
M15	**Men:LevA (1:1)**	555.7 ± 0.1	392.0 ± 0.0	368.0 ± 0.0	This work	51.45	0.69 [a]	0.81 [a]	0.63 [a]	This work
							0.63 [b]	0.82 [b]	0.67 [b]	
						N/A	0.66	1.56	0.58	[114]
M16	**Men:MyrA (4:1)**	N/A	379.0 ± 1.0	360.0 ± 2.0	This work	53.18	0.47 [a]	1.08 [a]	0.76 [a]	This work
		537.7 ± 0.1	N/A	N/A	[26]		0.36 [b]	0.62 [b]	0.78 [b]	
M17	**Men:MyrA (8:1)**	539.0 ± 0.1	379.5 ± 0.7	368.0 ± 0.0	This work	53.05	0.48 [a]	1.07 [a]	1.02 [a]	This work
							0.37 [b]	0.64 [b]	0.98 [b]	
M18	**Men:Thy (1:1)**	N/A	400.0 ± 0.0	369.5 ± 0.7	This work	50.90	0.82 [a]	0.69 [a]	0.45 [a]	This work
		561.7 ± 0.1	N/A	N/A	[26]		0.79 [b]	0.84 [b]	0.52 [b]	
M19	**Men:Thy (2:1)**	N/A	395.5 ± 0.7	368.0 ± 0.0	This work	51.67	0.75 [a]	0.79 [a]	0.53 [a]	This work
		553.3 ± 0.1	N/A	N/A	[26]		0.70 [b]	0.73 [b]	0.58 [b]	
M20	**Men:Thy (4:1)**	N/A	390.5 ± 0.7	369.0 ± 1.4	This work	52.08	0.66 [a]	0.87 [a]	0.71 [a]	This work
		549.0 ± 0.1	N/A	N/A	[26]		0.60 [b]	0.71 [b]	0.73 [b]	
M20	**Men:Thy (8:1)**	N/A	386.5 ± 0.7	366.5 ± 0.7	This work	52.40	0.60 [a]	0.94 [a]	0.75 [a]	This work
		545.7 ± 0.1	N/A	N/A	[26]		0.52 [b]	0.69 [b]	0.76 [b]	

[a] π^*, α, and β that were calculated using the equations **eqn. (4)**, **eqn. (6)** and **eqn. (8)**, respectively.

[b] π^*, α, and β that were calculated using the equations **eqn. (5)**, **eqn. (7)** and **eqn. (9)**, respectively.

(section 3.1.2), the models used to calculate the refractive index and surface tension show to work relatively better in hydrophobic NADES than hydrophilic ones (except for Chcl-based systems). This is because the ARD% related to the prediction these two parameters for hydrophobic systems are much lower than those found in hydrophilic case. It is also important to mention that the empirical models used here, despite being indeed very useful tool to compliment the investigated NADÉs physicochemical characterization, they are not the focus of this work, therefore no deep discussion will be done.

Some studies reported that in eutectic combinations based on choline chloride (e.g., Chcl:EG, also called ethaline), choline chloride acts as a surfactant agent and decreases the surface tension of the system [2]. Analysing the surface tensions of the investigated NADES, listed in Fig. 7, it is possible to conclude that hydrophilic NADES display highest cohesive energies than hydrophobic ones.

In fact, this would be expected for such highly polar fluids, since all the components of these mixtures contain one or more polar groups that lead to the formation of a vast network of hydrogen bonds, which attracts and holds molecules close to each other and increasing, consequently, the energy that is sent to hold the surface area. The surface tensions values of choline chloride-based NADES (**C1**, **C2** and **C3**)

presented in Fig. 7, were taken from the literature, but as can be seen, they are within the same range of values found for the other hydrophilic systems. Regarding the hydrophobic NADES, it was confirmed by the few data found in the literature that these are as well in the same range of the expected (e.g., **M3**, **M4** and from **M18** to **M20**).

3.7. Solvatochromic parameters

The results from the solvatochromic essays are presented in Table 6. Here, some of the values reported in the literature for the listed organic solvents and a few NADES are also shown.

From these results it is possible to analyse each of the solvatochromic parameters (polarity and Kamlet-Taf parameters) for all the studied systems and understand better their behaviour as a solvent.

3.7.1. Polarity

The values of polarities of investigated NADES were evaluated by the Rile red scale (E_{NR}) and presented in Fig. 8. According to this figure, it was observed that, except for hexane (Hx) and cyclohexane (CHx), most NADES (black bars) exhibit polarities quite similar to the conventional organic solvents (dark upward diagonal stripes) (Fig. 8).

Fig. 8. Polarity of the NADES (black bars) and some organic solvents (dark upward diagonal stripes) organized in descending order (from top to bottom).
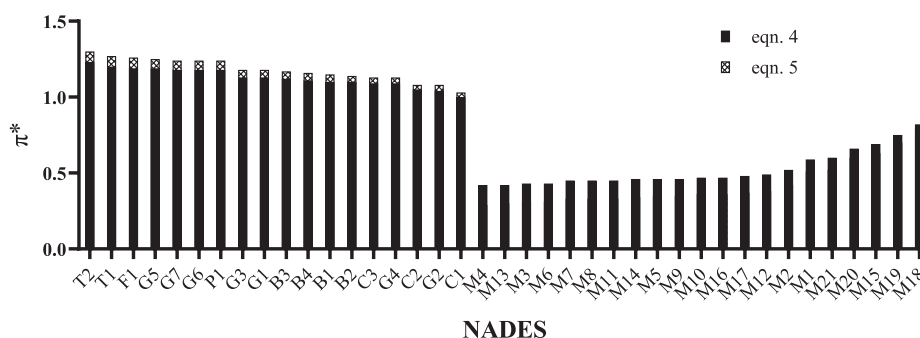
Nile red as dye means that the ground state is better stabilized by hydrophobic solvents, which means an increase in the energy difference between the two states ($\Delta E = E_{excited} - E_{ground}$) and therefore a deviation of the dyés absorption curve to a lower wavelength. Therefore, when **eqn. (3)** is used, the higher values of E_{NR} the lower is the polarity (e.g., cyclohexane (CHx) and hexane (Hx)). So, in this perspective, according to Fig. 8, **C2** (Chcl:Gly (1:2)) and **M3** (Men:DecA (1:1)) are, respectively, the most and less polar systems found in this work.

3.7.2. Kamlet-Taft parameters (KTP)

The outcomes of the NADES polarizability (π^*) calculation using both approaches under study are shown in Fig. 9.

Here, it is possible to observe that despite the small differences found in the values of the hydrophilic systems, in general both models could in fact be used to estimate the π^* parameter. Additionally, as it would be expected, both approaches confirm that the polarizability of hydrophilic NADES are much higher than hydrophobic ones.

In order to understand the applicability and the differences between them, the α parameter of NADES was evaluated using these two equations and the results can be seen in Fig. 10.

Contrarily to the π^* parameter, there is clearly a large difference between the results of the α parameter calculation using **eqn. (6)** and **eqn. (7)**. Such discrepancy is noticeable particularly in the calculations involving the hydrophilic systems. The model proposed by Dwamena *et al.*, (**eqn. (7)**, [34]) suggests that the acidic nature of the presented hydrophilic NADES must be greater than what would be obtained if the evaluation were done using **eqn. (6)**. Furthermore, as can be seen, in some cases the values should even be higher than those of hydrophobic NADES, which nevertheless contain acidic compounds as components of the mixture. However, given the fact that hydrophilic systems components are also constituted by several hydrogen donor groups (OH), the results from **eqn. (7)** should perhaps not be considered incorrect. On the other hand, either **eqn. (6)** or **eqn. (7)** could be applied to estimate the acidity parameter of hydrophobic NADES, as the results obtained are quite similar.

The analysis of the NADES basicity, using these two equations can be made using the graphic shown in Fig. 11.

According to the results, both models could be valid to determine the β parameter, either for hydrophilic or hydrophobic systems. Additionally, hydrophobic NADES exhibit basicity values relatively higher than the hydrophilic ones. Thus, in summary, it can be concluded that, the largest discrepancies between the models used to estimate the three KTPs, are more likely to be found in calculations involving hydrophilic compounds.

3.7.3. Replacement of organic solvents using KTPs

One of the most recent investigations suggests the implementation of KTPs to map organic solvents commonly used in pharmaceutical industries and find potential candidates to replace hazardous solvents, mainly the dipolar aprotic ones such as DMFO, DMSO ACN (acetonitrile) [74,79]. On the other side, solvents such as water, ethanol, methanol,

This is certainly very interesting, as it may be a good indication to, once again, reinforce the concept of the potential of NADES as alternative green solvents and possibly even replace the commonly used harmful or toxic ones, as for example dimethyl sulfoxide (DMSO). Using

Fig. 9. Polarizability parameter of Kamlet-Taft (π^*), calculated using the eqn. (4) and eqn. (5).
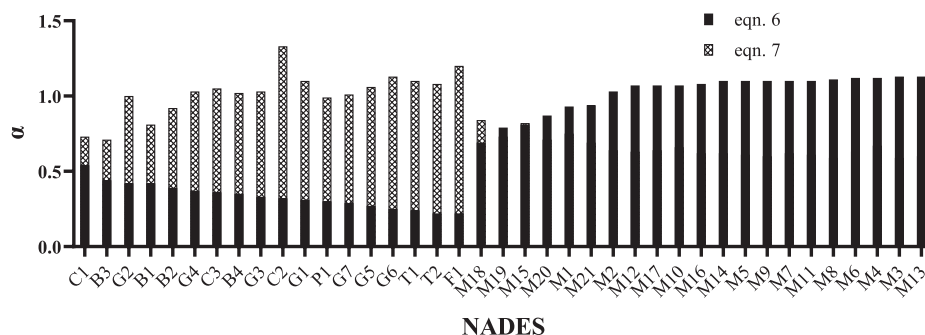
Fig. 10. Acidity Parameter of Kamlet-Taft (α), calculated using the eqn. (6) and eqn. (7).
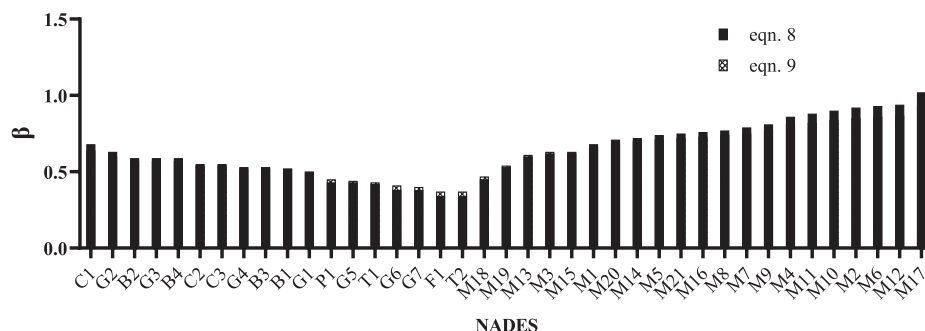
Fig. 11. Basicity parameter of Kamlet-Taft (β) calculated using the eqn. (8) and eqn. (9).
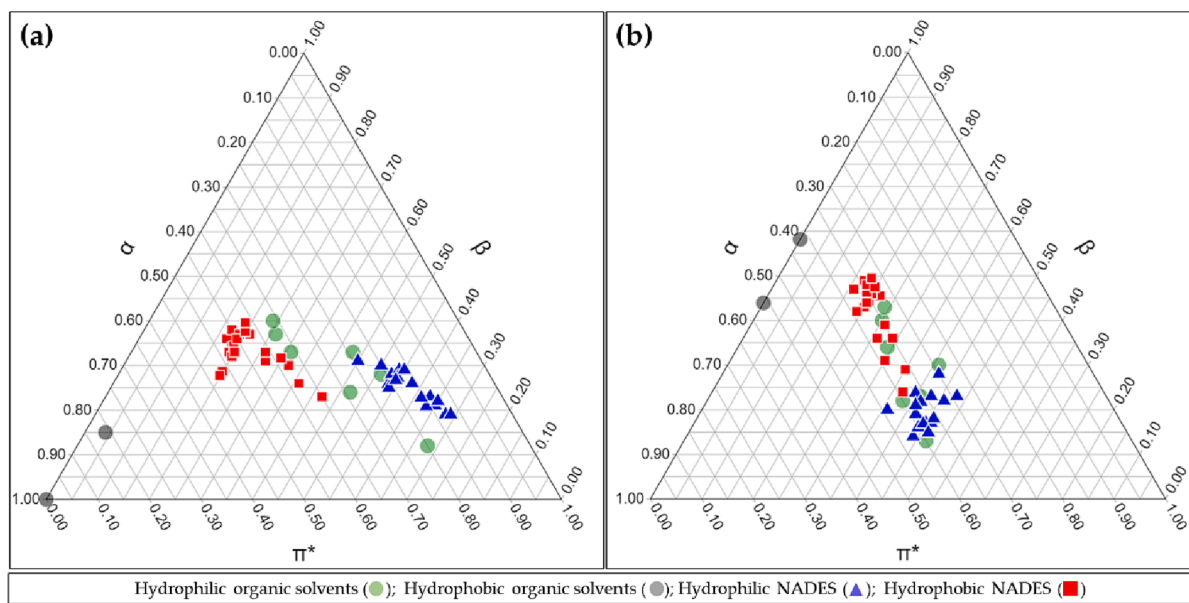
Fig. 12. Ternary plots of KTP (π*, α and β). The values in graphic (a) were obtained by using the eqn. (4), eqn. (6) and eqn. (8) respectively, and graphic (b) using eqn. (5), eqn. (7) and eqn. (9), respectively. The values are written in fractional form.

etc, are often recommended, however, due to their poor solubility properties regarding active pharmaceutical ingredients (APIs), it is necessary, in some cases, to follow an approach such as solvent-pair mixtures [79–81]. In this perspective, NADES can be pointed to as a good object of study. This assessment was made through the ternary plots of the KTPs, demonstrated in Fig. 12. Yet, it is important to mention that the values shown in the plot correspond to the fraction of each parameter.

As it can be noted in Fig. 12, the KTPs of both hydrophobic as well hydrophilic NADES exhibit an activity very similar to the conventional

organic solvents such as water, methanol, ethanol, etc (green circles), reasserting that NADES can be certainly a good alternative to these solvents. Moreover, given the high value of the acidity (α) found for these systems, it can be also good indicative of their potential in replacing hazardous solvents, as, contrarily to NADES, one feature that is said to be characteristic of these solvents is their considerable impassioned ability to donate hydrogen bonds and establish stronger bonds [79].

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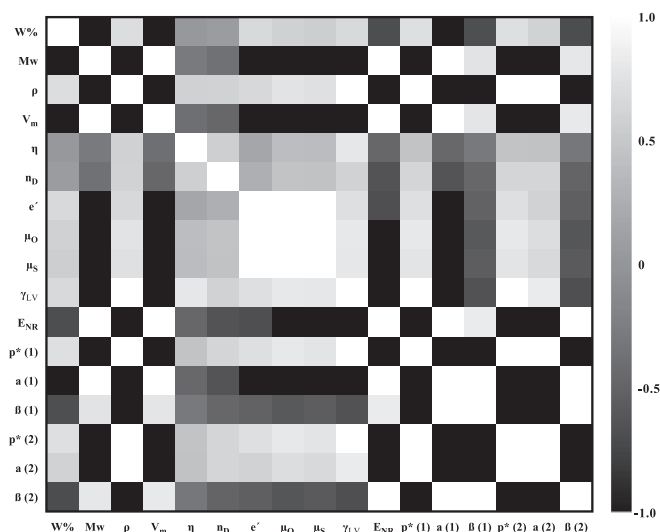
Fig. 13. Heat map of the intercorrelation between all the studied parameters, using the Pearson correlation coefficient (r) of the total list of NADES studied.

3.8. Correlation between the studied properties

One of the simplest ways to discover, a priori, if two or more physicochemical parameters are correlated, is understanding the principle fundamental of each one of them. However, until there are additional tools that may support such a notion, the term "correlation" should not be employed carelessly. Thus, a statistic study was also carried out, in order to understand the type of interrelationship existent between all the studied parameters (see **Table S8 and S9**, in **the Supplementary section**). The Pearson correlation coefficient (r) values were used to create the heat map shown Fig. 13 so that the results could be more clearly understood. This heat map represents the correlations made with the general list of NADES investigated.

In general, the majority of the parameters exhibit strong and statistically significant correlations (*p*-value) with each other (**SI, Table S9**). Taking the water content (W%) as example, it is possible to note that it has strong positive correlations (white squares) with parameters such as density (ρ), dielectric constant (ε'), dipole moments (μ_O and μ_S), surface tension (γ_{LV}), polarizability (π^* (1) and (2)) and acidity (α (1) and (2)); strong negative correlations (black squares) with molecular weight (Mw), molar volume (V_m), polarity (E_{NR}) and basicity (β (1) and (2)); and no significant correlation with properties such as viscosity (η) and refractive index (n_D). In fact, as can be seen in Fig. 13, these last two parameters are clearly the ones that show less correlation with the remaining parameters, and this can be also confirmed by their low statistical significance, as their *p*-value > 0.05 (**SI, Table S9**). Viscosity, for instance, except for the strong positive correlations with the ρ, n_D and γ_{LV}, it shows no significant relationship with the other properties. An overall look at these results, suggests that both density and surface tension stand out among all the other examined parameters as they are the only ones that exhibit strong correlations (positive or negative) with the all the other physical properties. Furthermore, the correlations of both density and surface tension with parameters such as polarity and Kamlet-Taft parameters (mainly polarizability and acidity) also prove to be quite strong. For example, whether in correlations involving hydrophilic and hydrophobic systems separately or with the entire list of NADES investigated, a strong negative correlation between polarity and density is noticeable, although theoretically these two parameters are not directly related. Additionally, looking, yet, solely at the values obtained (in **SI, Table S10 and S11**, and **Table S12 and S13**, respectively) or at the heat maps of hydrophilic and hydrophobic systems (**Fig. S3 and S3, in SI**), it can be concluded that the intensity and direction of the linearity are mostly due to the contribution of correlations found between the parameters of hydrophilic NADES list. Despite the sample size being small, the information found here is undoubtedly particularly important, as it allows identifying potential correlations that could be used in the future to estimate related properties from easier and less laborious methods.

3.9. Evaluation of the effects of molar ratio and water content on NADES physicochemical properties

It is well-known that the physicochemical properties of eutectic mixtures are dependent on different factors including molar ratio, water content, type of HBD, size of chain, temperature, etc [2,59,16]. Therefore, the understanding of how these factors is influencing the physicochemical properties can be also considered a key piece in the studying the behaviour of NADES as solvents. Although the data acquired in this study allow to do a more comprehensive study of these factors, only the effect of the molar ratio and water on fundamental properties such as viscosity, density, refractive index and surface tension, will be further explored. Menthol-based NADES were used as an example in this assessment, as data are available on different molar ratios.

3.9.1. Effect of molar ratio

The type of relationship found between the molar ratio (in terms of molar fraction of menthol, X_{Men}) of the systems Men:DecA (**M3 - M6**), Men:LauA (**M7 - M12**) and Men:Thy (**M18 - M21**), and their physicochemical properties are presented in Fig. 14.

Through the graphs above, it is possible to conclude that for any of the cases (Men:DecA, Men:LauA or Men:Thy), the increase in viscosity of these mixtures is mainly caused by an increasing in the X_{Men} (graphics (a), (e) and (i), respectively). On the other hand, while for the Men:DecA and Men:LauA systems (graphs (c) and (g), respectively), the refractive index increases with the increase of X_{Men}, in the case of Men:Thy (graphic (k)), the relation between these two parameters is inversely proportional. In fact, as can be seen, in relation to the Men:Thy system, with the exception of viscosity, all other properties show a tendency to decrease with the increase of X_{Men}. This suggests that to increase the values of density, refractive index or surface tension it would be necessary whether to decrease the amount of menthol or increase the thymol fraction in the mixture. Furthermore, comparing, in general, the behaviour observed in the graphics of the two acids HBD (DecA (graphics (a) to (d)) and LauA (graphics (e) to (h))) with those of the terpene HBD (Thy (graphics (i) to (l))), it is evident that the relationship between the molar ratio and physicochemical properties is more direct when the HBD is a terpene.

3.9.2. Effect of water content

Contrarily to the hydrophilic systems, the residuals amount of water that are found in hydrophobics ones are commonly considered impurities [13,49]. Despite no elaborate assay was performed in this study to directly evaluate the effect of water content (e.g., by adding intentionally given amount of water in the system), it is still important to evaluate if the small traces of water obtained from Karl-Fischer measurement are somehow related with the physicochemical behaviour of these mixtures. This analysis can be done using the graphics illustrated in Fig. 15.

As it can be seen, except for the profile found in the graphs (e) and slightly in (f) and (g), all the other do not show any significant relationships between water content and the studied properties. Such behaviour suggests that for these kinds of hydrophobic systems, the residual amount of water measured after prepared does not affect substantially the proprieties viscosity, density, refractive index and mainly surface tension. This is somehow expecting, because as can be seen in Table 4 and Table 5, most of the results obtained here are in concordance with those found in the literature, which means that for these specific cases, even with the some variation in the water content, the physicochemical behaviour tend to be retained. However, it is still important to emphasize once more that the main goal of this study was only to
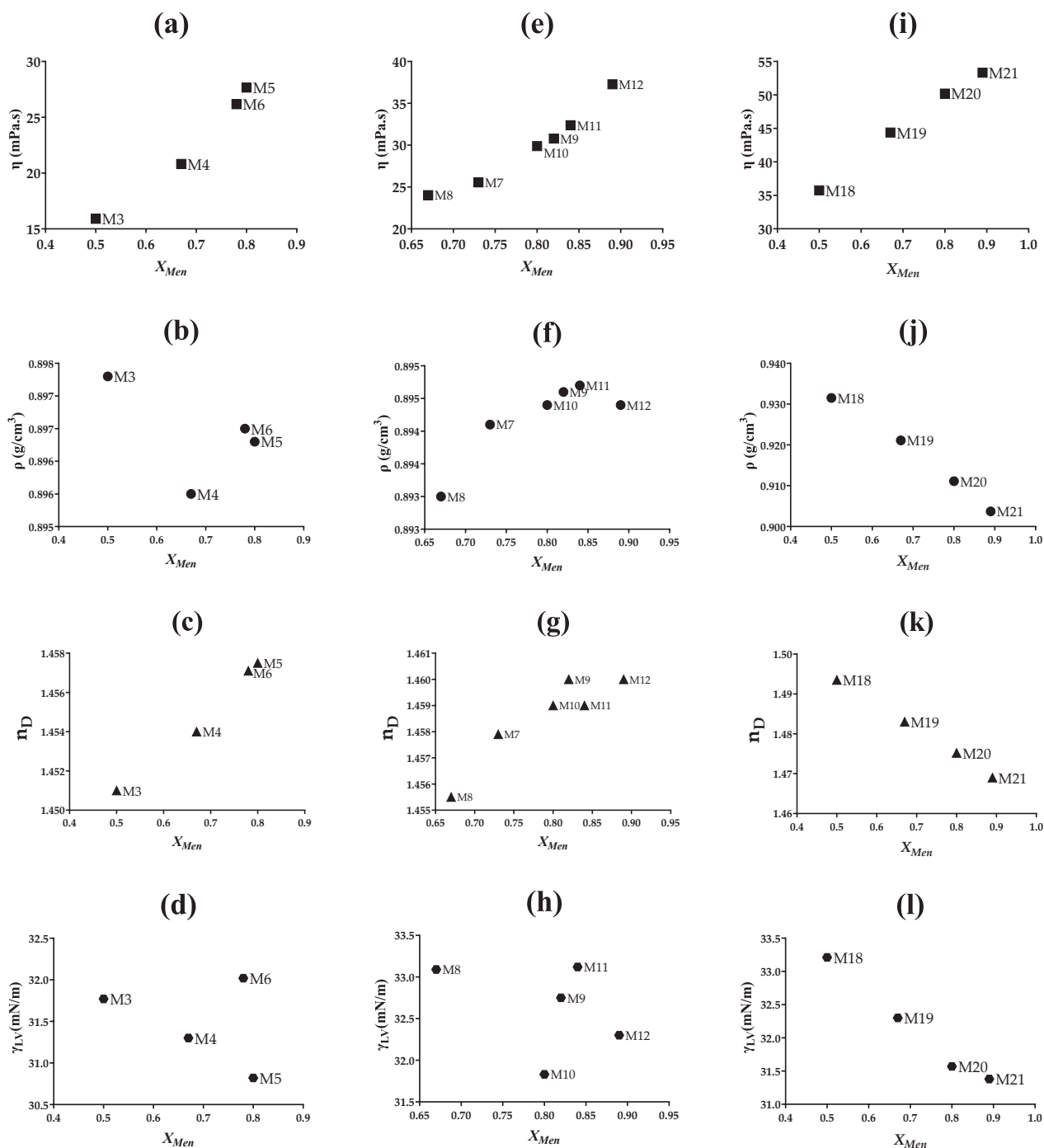
Fig. 14. Relationship between the molar fraction of Menthol (X_{Men}) and properties such as viscosity (η), density(ρ), refractive index (n_D) and surface tension ($γ_{LV}$) for the systems Men:DecA (M3 – M5) (from graphics (a) to (d), respectively), Men:LauA (M7 – M12) (from graphics (e) to (h), respectively) and Men:Thy (M18 – M21) (from graphics (i) to (l), respectively). The indicated ID correspond to the systems: M3 (Men:DecA (1:1)), M4 (Men:DecA (2:1)), M5 (Men:DecA (4:1)), M6 (Men:DecA (7:2)), M7 (Men:LauA (2.7:1)), M8 (Men:LauA (2:1)), M9 (Men:LauA (4.5:1)), M10 (Men:LauA (4:1)), M11 (Men:LauA (5.3:1)), M12 (Men:LauA (8:1M18 (Men:Thy (1:1)), M19 (Men:Thy (2:1)), M20 (Men:Thy (4:1)) and M21 (Men:Thy (8:1)).

characterize physicochemically the selected NADES and evaluate if these properties are related, in order to provide both an indirect way to calculate a desired property, as well understand their behaviour as solvent. Therefore, the real effects of water content, in this case., those would be achieved from specific essays with increase of water content were not evaluated. Hence evaluation regarding the effect of water content here performed was done using exclusively with the water present as component in ternary/quaternary hydrophilic NADES, and the water present as impurity (in case of hydrophobic systems).

4. Conclusions

This work aimed to characterize physicochemically NADES of different nature, hydrophilic and hydrophobic, regarding their water content, viscosity, density, dielectric constant, dipole moment, surface tension, polarity and Kamlet-Taft parameters, as well as exploring the types of correlations between them. Regarding the physicochemical properties, in general, these showed to vary as expected and some even in a similar way to what is described in the literature. Analysing these
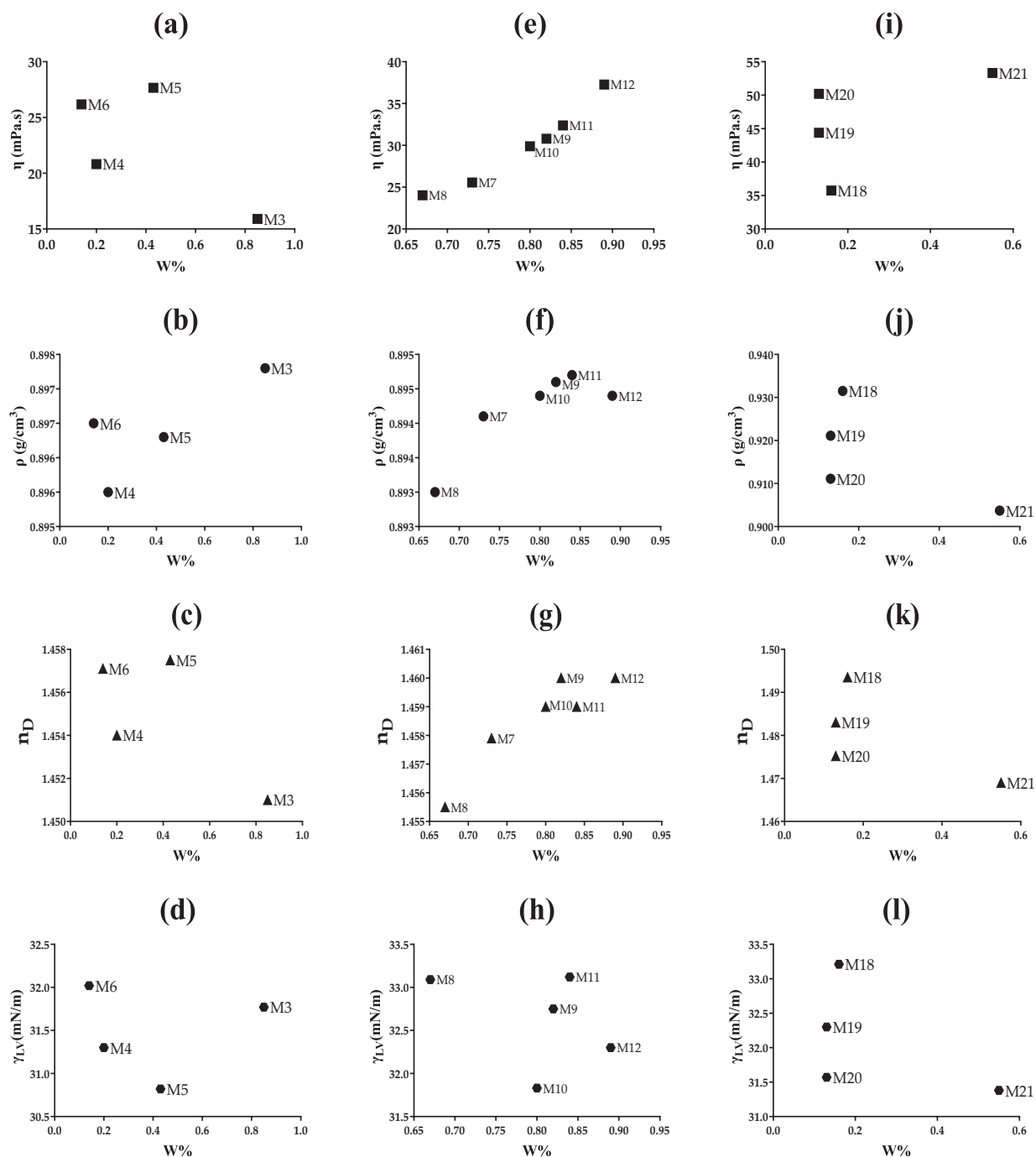
Fig. 15. Relationship between the water contents (W%, in mass%) and properties such as viscosity (η), density(ρ), refractive index (n_D) and surface tension (γ_{LV}) for the systems Men:DecA (M3 – M5) (from graphics (a) to (d), respectively), Men:LauA (M7 – M12) (from graphics (e) to (h), respectively) and Men:Thy (M18 – M21) (from graphics (i) to (l), respectively). The indicated ID correspond to the systems: M3 (Men:DecA (1:1)), M4 (Men:DecA (2:1)), M5 (Men:DecA (4:1)), M6 (Men:DecA (7:2)), M7 (Men:LauA (2.7:1)), M8 (Men:LauA (2:1)), M9 (Men:LauA (4.5:1)), M10 (Men:LauA (4:1)), M11 (Men:LauA (5.3:1)), M12 (Men:LauA (8:1M18 (Men:Thy (1:1)), M19 (Men:Thy (2:1)), M20 (Men:Thy (4:1)) and M21 (Men:Thy (8:1)).

characteristics of NADES solvents, it was found that the behaviour for most of their physical characteristics is somewhat differently from conventional organic solvents and that this mostly depends on of the systems nature. However, it was also confirmed that at the solvatochromic level, the behaviour of most of the studied systems are similar to these conventional solvents, which despite being referred as green ones, continue to have the inherent problems of organic solvents and once again highlights the capacity of NADES as potential green alternatives. Moreover, this study also allowed exploring more about the dielectric properties of NADES and proposing a simpler and faster

method to estimate the dipole moment of these compounds. Finally, answering the question in the title of this work and considering the total list of NADES examined, through statistical analysis, it was observed that most of the studied parameters are strongly correlated either positive and negatively with each other, which means that, in fact, it is possible to take advantage of such relationships and predict, indirectly, the behaviour of NADES. This is indeed a very useful information, as it means that less laborious experimental methods could now be used to understand the behaviour of another one (e.g., use measuring polarity to evaluate the surface tension of NADES), or also, the future development

of new, easy and suitable semi-empirical or empirical models to predict a desire physicochemical property of NADES.

CRediT authorship contribution statement

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.molliq.2023.122280.

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