ISSN 1027-5495. Functional Materials, 31, No.4 (2024), p. 619-629
doi:http://dx.doi.org/10.15407/fm31.04.619

New menthol-based eutectic solvents and their extraction properties towards metal ions

M. Yu. Cherniakova[1], O. V. Vashchenko[2], I. O. Zinchenko[1], V. I. Musatov[1], K. N. Belikov[1,3]

[1] Institute of Functional Materials Chemistry, State Scientific Institution
“Institute for Single Crystals” of National Academy of Sciences of Ukraine,
60 Nauky Ave, 61072 Kharkiv, Ukraine
[2] Institute for Scintillation Materials of National Academy of Sciences of
Ukraine, 60 Nauky Ave, 61072 Kharkiv, Ukraine
[3] School of Chemistry, V. N. Karazin Kharkiv National University, 4 Svobody
Sq., 61022 Kharkiv, Ukraine

Received October 11, 2024.

Deep eutectic solvents are increasingly being used as extraction media as their properties are easily tunable and they can fulfill the green chemistry criteria. In this study, a range of hydrophobic (deep) eutectic solvents was developed as potential extractants of elemental impurities. The experimental results provided insights into the solid-liquid equilibrium of the binary mixtures containing menthol with various organic compounds. The NMR and FTIR spectroscopy were applied to characterize the eutectic compositions. The extraction property towards elemental species was evaluated in the terms of distribution coefficient for 24 elements. It has been shown that the inclusion of a chelating reagent as compnent of the eutectic solvent can significantly increase the group extraction efficiency of metal ions.

Keywords: deep eutectic solvent, liquid extraction, metal ions, green chemistry, supramolecular chemistry, menthol, atomic emission spectrometry

Нові евтектичні розчинники на основі ментолу та їх екстракційні властивості стосовно іонів металів. *М. Ю. Чернякова, О. В. Ващенко, І. О. Зінченко, В. І. Мусатов, К. М. Беліков*

Глибокоевтектичні розчинники набувають активного використання як екстракційні середовища, оскільки їхні властивості легко регулюються і вони можуть задовольняти критеріям «зеленої хімії». У цій роботі було розроблено ряд гідрофобних (глибоко)евтектичних розчинників як потенційних екстрагентів елементних домішок. Експериментально досліджено рівноваги тверда – рідка фаза у бінарних сумішах, що містять ментол з різними органічними сполуками. ЯМР- та ІЧ-спектроскопія були застосовані для характеристики евтектичних складів. Екстракційна властивість по відношенню до елементних форм була оцінена в термінах коефіцієнта розподілу для 24 елементів. Показано, що використання хелатуючого реагенту як компонента евтектичного розчинника може значно підвищити ефективність групової екстракції іонів металів.

1. Introduction

One of the main priorities of modern green analytical chemistry is the search for green extraction systems [1]. Implementing an extraction method at the sample preparation stage can significantly improve the sensitivity of instrumental techniques of analysis and eliminate matrix effects. This is especially important for the determination of ultra-small amounts of analytes, including elemental impurities. The analysis of elemental impurities is essential for the quality control of pharmaceuticals, food, materials for various purposes, and environmental monitoring. In particular, the content of elemental impurities is regulated by ICH Q3D [2] at a low level in both drugs and raw materials for their production.

Deep eutectic solvents (DESs) are proving to be effective extractants and are increasingly used in analytical practice for separation and preconcentration of various organic and inorganic analytes [3,4]. DESs can be considered as liquid supramolecular systems, which are mixtures of substances self-associated via hydrogen bonds. They reveal a depressed eutectic point relative to the theoretical one, which indicates negative deviations from ideality for the components. Since not all mixtures can exhibit such deviations, in a broader sense, DESs are a subclass of eutectic solvents (ESs) [5].

To date, ESs containing organic salts (tetraalkylammonium and imidazolium ones), organic acids (including hydroxy- and polycarboxylic ones), long-chain alcohols, carbamide, and phenolic compounds have been proposed for the separation and preconcentration of elements prior to their analysis in various objects (rock, soil, oil, biological samples, food, and water of different origins) [6–17]. Although in many cases the extraction procedure involves the introduction of a chelating agent.

For the extraction of metal ions and other elemental species from aqueous media, hydrophobic ESs are of great interest, as they consist of substances that are poorly soluble in water [18]. Menthol is a popular component of such ESs due to its properties and natural origin [5]. The ESs containing menthol and long-chain organic acids [19,20] or organic ligand [21] showed the ability to extract some metal ions. Also, binary mixtures of menthol with decanoic and lauric acids were proposed for the microextraction of elemental impurities from drugs [22] and food products [23], respectively.

This work aims to develop and characterize new menthol-containing ESs that can be used as extraction materials for removal and preconcentration of elemental impurities.

2. Experimental

Materials. All chemicals and reagents used in the present work were of analytical grade and supplied by commercial companies.

Preparation of ESs. The mixtures were prepared using the heating and stirring method. For this, an appropriate amount of chemicals was weighed using an analytical balance ABJ-220-4M (Kern&Sohn) and put in the glass vessels. Each sample was heated to 30 - 50 °C on the water bath and mixed on the magnetic stirrer till the liquid was formed. After that, samples were cooled at room temperature.

Differential scanning calorimetry. A Mettler DSC 1 microcalorimeter (Metler-Toledo) was used to acquire thermodynamical characteristics of the ESs. The procedure of the DSC instrument calibration was performed by melting of an indium sample. The samples of 6 – 8 mg were weighed using the Mettler XP 26 (Metler-Toledo) microbalance and placed in a standard 40 μL aluminum pan with a lid. The DSC thermograms were obtained under a heating regime with a scanning rate 5 °C·min^{-1} within the temperature range from 0 to 80 °C for all the systems explored, except for M : OA. For the latter system the temperature scanning was performed within the range of -30 °C to 50 °C preceded by 10 min sample equilibration at -30 °C. The temperatures of the endothermic events were used to plot the binary phase diagrams. The melting temperatures and enthalpies for the individual components were determined on the basis of the corresponding thermograms by means of STARe 11.0 software.

Deviations from ideality of the liquid phase. The ideal liquidous curves were estimated according to the Schröder equation [24,25], which describes the melting curves of pure compounds:

$$\ln\left(x_i\gamma_i\right)=\frac{\Delta_m H}{R}\left(\frac{1}{T_m}-\frac{1}{T}\right), \quad (1)$$

where γ_i is an activity coefficient of the compound i at a certain liquid mole fraction x_i, T is the absolute temperature, T_m and $\Delta_m H$ are the melting temperature and enthalpy of the pure compound, respectively, R is the universal gas constant. γ_i = 1 when assuming the ideality of the liquid phase. The activity coefficients of the components in the mixtures were calculated from the experimental data using the following equation:

$$\gamma_i=\frac{exp\left(\frac{\Delta_m H}{R}\left(\frac{1}{T_m}-\frac{1}{T}\right)\right)}{x_i}. \quad (2)$$

Nuclear magnetic resonance spectroscopy. The Varian MR-400 spectrometer (400 MHz) was used to record ^{1}H NMR spectra in $CDCl_3$ with tetramethylsilane as an internal standard.

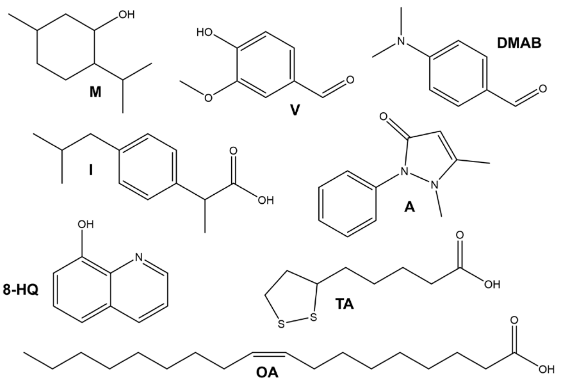

Fig. 1. The structures of compounds used in this work: *L*-menthol (M), vanillin (V), *p*-dimethylaminobenzaldehyde (DMAB), ibuprofen (I), antipyrine (A), 8-hydroxyquinoline (8-HQ), thioctic acid (TA), oleic acid (OA)

Attenuated total refraction – Fourier-transform infrared spectroscopy. The FTIR Shimadzu 8400S instrument was used to obtain ATR-FTIR spectra of pure compounds and their mixtures.

Extraction procedure. Model solutions with the concentration of 1 mg·L^{-1} of each element were prepared by diluting the ICP-OES standard solutions with the concentration of 1 g·L^{-1}. The selected elements were divided into 3 groups based on the background of the standard solutions: Ag, Al, Bi, Cd, Co, Cu, Fe, Hg, Mn, Ni, Pb, Tl, Zn – nitrate anions; Sb, Sn, Ti, Pt, Pd, Au, W – chloride anions; As, V, Cr, Mo – in the form of anionic species. The pH of the model solutions was adjusted with acid (HNO_3 or HCl) and alkali (NaOH) solutions and controlled using the Starter3100 pH-meter (OHAUS). The aliquot of 10 mL of obtained model solution was transferred to the test tube. Then, a certain amount of ES was added and dispersed by shaking for 1 minute in order to form tiny droplets of ES. The ESs were slightly heated prior their withdrawal. Phase separation was performed by centrifugation at 3000 rpm during 10 minutes and the aqueous phase was taken using a syringe. 100 μL of concentrated HNO_3 or HCl were added to prevent the precipitation of analytes.

Inductively coupled plasma optical emission spectrometry. The ICP-OES method was applied to determine the concentrations of elements before and after extraction. The ICP-OES analysis was carried out using the iCAP 6300 Duo (Thermo Scientific) inductively coupled plasma optical emission spectrometer with axial mode of plasma viewing and a cyclonic spray chamber. The ICP-OES measurement parameters were: RF power of 1150 W, auxiliary argon flow rate of 1 L·min^{-1}, nebulizer argon flow rate of 0.5 L·min^{-1}, peristaltic pump rate of 50 rpm, integration time of 15 s, 2 measurement replicates.

Extraction ability. The extraction ability of ESs was evaluated in terms of distribution coefficient:

$$K_D = \frac{C^{in} - C^{aq}}{C^{aq}}, \tag{3}$$

and extraction recovery:

$$R = \frac{C^{in} - C^{aq}}{C^{in}} \cdot 100\%, \tag{4}$$

where C^{in} – the initial concentration of an element in the solution before extraction (mg·L^{-1}), C^{aq} – the concentration of an element in the aqueous phase after extraction (mg·L^{-1}).

3. Results and discussion

Solid-liquid equilibrium. The binary mixtures of *L*-menthol (M) with vanillin (V)/ *p*-dimethylaminobenzaldehyde (DMAB)/ ibuprofen (I)/ antipyrine (A)/ 8-hydroxyquinoline (8-HQ)/ thioctic acid (TA)/ oleic acid

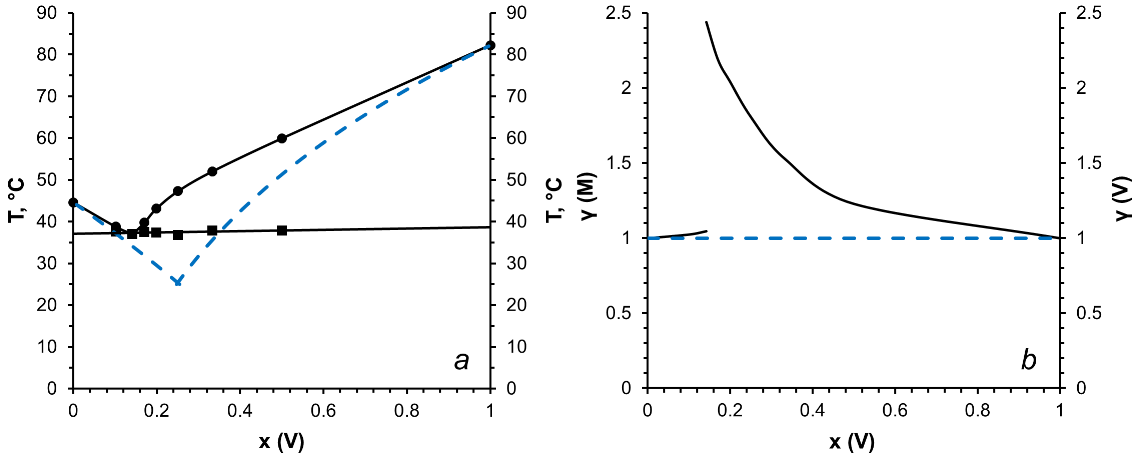

Fig. 2. The phase diagram (a) and activity coefficients of the components (b) of the M : V mixture

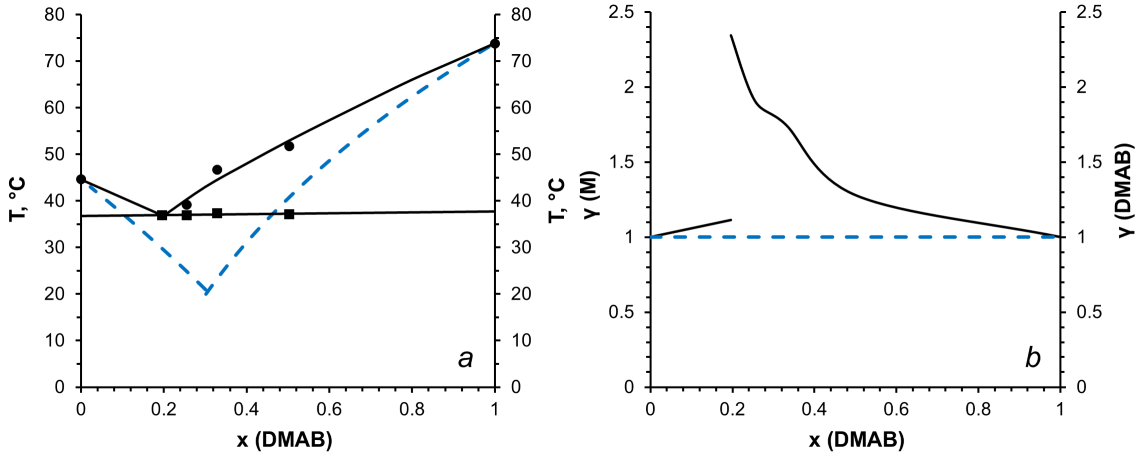

Fig. 3. The phase diagram (a) and activity coefficients of the components (b) of the M : DMAB mixture

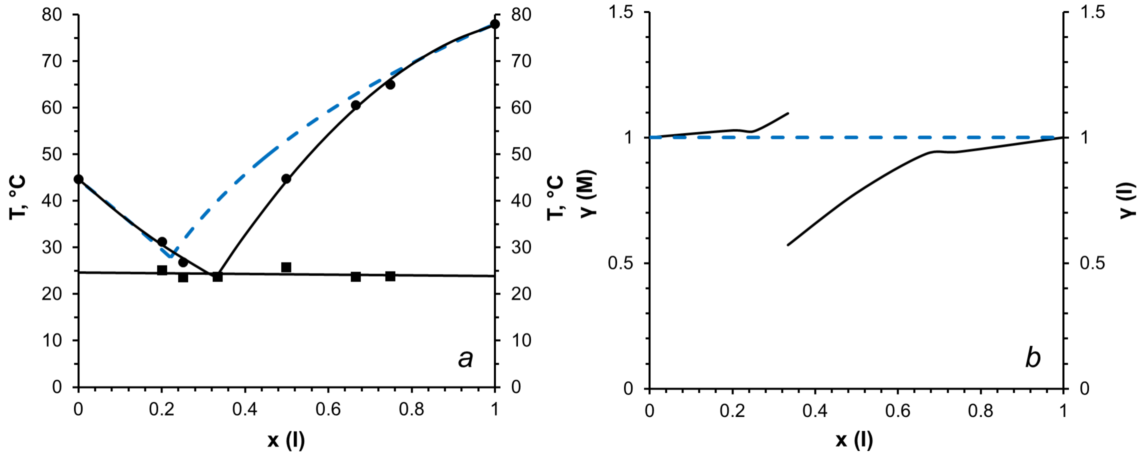

Fig. 4. The phase diagram (a) and activity coefficients of the components (b) of the M : I mixture

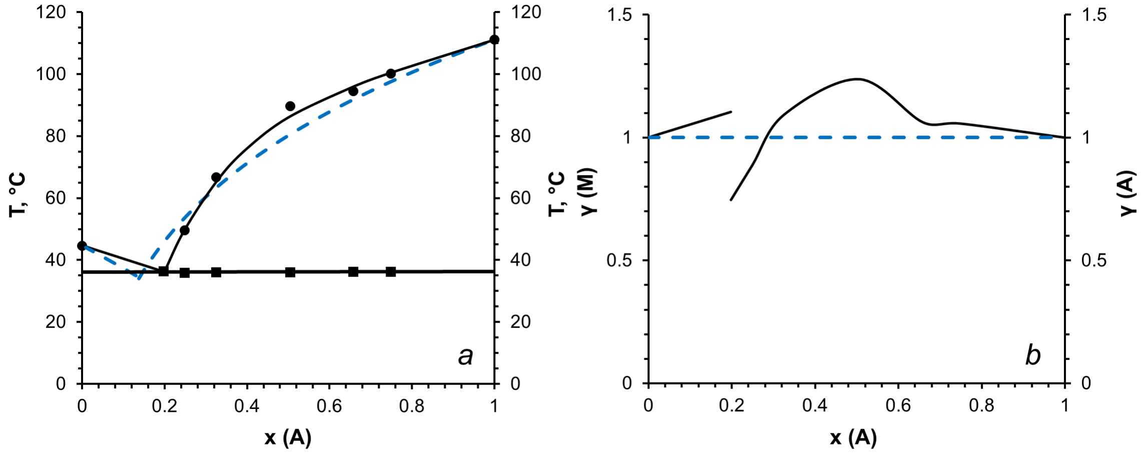

Fig. 5. The phase diagram (a) and activity coefficients of the components (b) of the M : A mixture

(OA) were obtained (Fig. 1). The data on solid-liquid equilibrium of these mixtures (Fig. 2-8 (a)) were obtained with DSC method (represented as dots) and compared with the ideal melting curves of the pure components (represented as blue dashed lines). Also, the activity coefficients of components were derived from the experimental data (Fig. 2-8 (b)). The temperatures and enthalpies of melting for the pure individual compounds determined in this work were used to calculate the ideal melting curves and activity coefficients (Table 1).

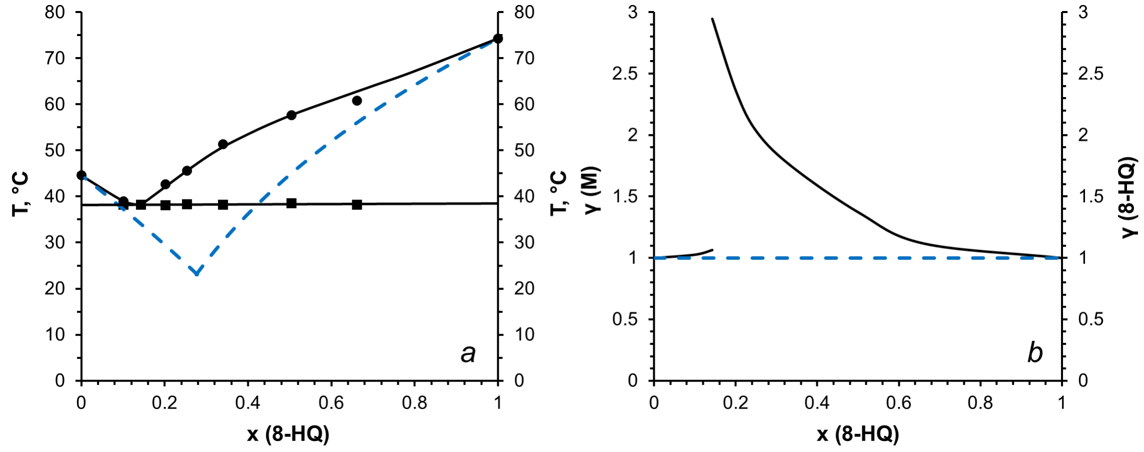

Fig. 6. The phase diagram (a) and activity coefficients of the components (b) of the M : 8-HQ mixture

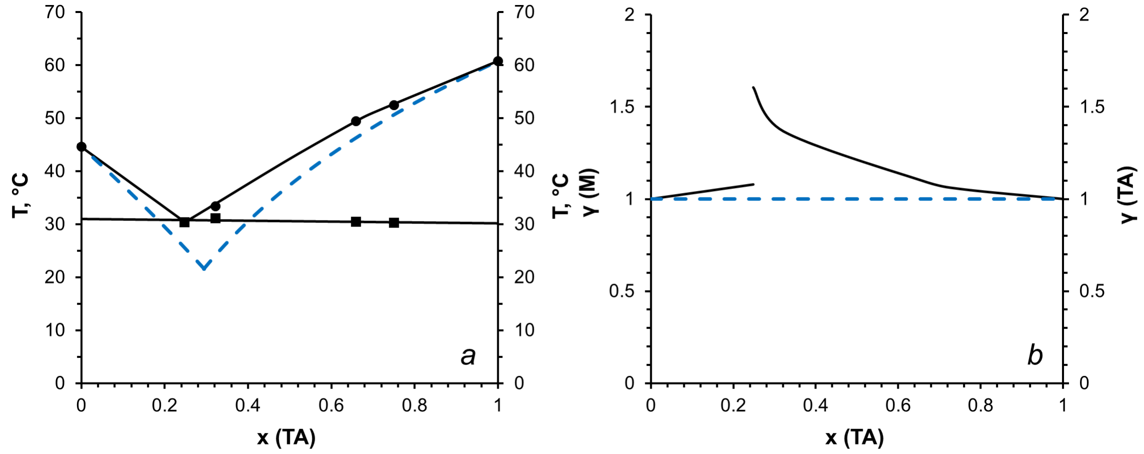

Fig. 7. The phase diagram (a) and activity coefficients of the components (b) of the M : TA mixture

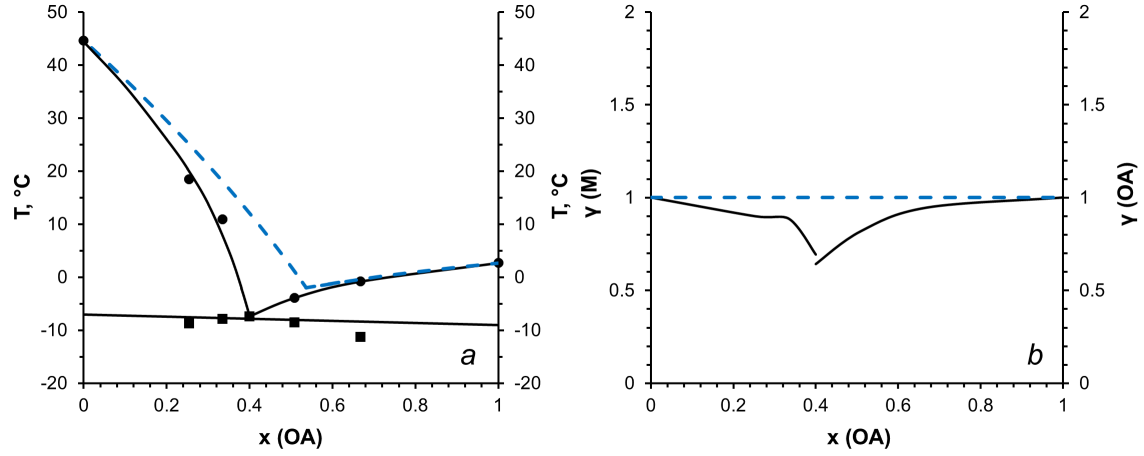

Fig. 8. The phase diagram (a) and activity coefficients of the components (b) of the M : OA mixture

The obtained phase diagram for the M : I mixture corrects the data on eutectic point from the work [26]. In this system, ibuprofen exhibits negative deviations from ideality reaching the value of activity coefficient of 0.57 in the eutectic point. This means that the intermolecular interactions between ibuprofen and menthol are stronger than in pure ibuprofen, therefore, M : I system is a DES [27]. Also, the M : OA system can be recognized as a DES because of the negative deviations for both components (γ_M = 0.69 and γ_{OA} = 0.69 in

Table 1. The temperatures and enthalpies of melting of pure individual compounds

	T_m, °C	$\Delta_m H$, kJ/mol
L-menthol (M)	44.6	11.8
Vanillin (V)	82.2	21.5
p-Dimethylaminobenzaldehyde (DMAB)	73.8	18.8
Ibuprofen (I)	78.0	26.4
Antipyrine (A)	111.1	25.3
8-Hydroxyquinoline (8-HQ)	74.3	21.5
Thioctic acid (TA)	60.8	25.5
Oleic acid (OA)	2.7	82.0

the eutectic point). The solid-liquid equilibrium data for the M : OA system are in good agreement with those available in the literature [28], though *DL*-menthol was used there.

The activity coefficients of antipyrine have values both greater and smaller than 1, depending on the molar composition of the mixture M : A, but they do not get beyond values above 1.24 and below 0.75. This system has a quasi-ideal liquid phase behavior, which is similar to that observed for long-chain acids (lauric, myristic etc.) in their mixtures with menthol [29]. This suggests that the intermolecular interactions established in the mixture are not significantly different in intensity to those present in the individual compounds. Taking into account the classification by eutecticity [5], the system M : A could be defined as a normal eutectic solvent (NES).

The other systems, M : V, M : DMAB, M : 8-HQ, and M : TA, reveal a quasi-ideal behavior for menthol and positive deviations from the ideality for other components (γ_V=2.45, γ_{DMAB} = 2.34, γ_{8-HQ}=2.94, and γ_{TA}=1.61 in the eutectic point). The positive deviations also occur in eutectic mixtures [3] and, for those exhibiting such behavior, the term "shallow eutectic solvents" (SESs) is appropriate. [5].

The experimental eutectic points of the studied systems (Table 2) do not exceed 40 °C. This makes them suitable for use in extraction, where the ES phase can be separated by simple cooling to room temperature.

Table 2. The experimental eutectic points of the ESs

System	Molar ratio	T_e, °C
M : V	6.1:1	37.0
M : DMAB	4:1	36.9
M : I	2:1	23.7
M : A	4:1	36.3
M : 8-HQ	6:1	38.2
M : TA	3:1	30.4
M : OA	1.5:1	-7.4

Hydrogen bonding. There are various intermolecular interactions between components in eutectic mixtures, the main and the strongest of which is hydrogen bonding. The NMR spectroscopy can reveal the formation of hydrogen bonds due to decrease in the peak intensity and a shift of the resonance signals of protons of the functional groups involved in the hydrogen bonding, particularly the OH group proton. However, on the spectra of compounds with OH groups of sufficiently high acidity, the signal of OH group proton is not always present due to the rapid hydrogen exchange with the deute-rated solvent or residual water. In contrast, the formation of intermolecular hydrogen bonds may prevent this process since access of solvent or water molecules to OH group proton is impeded by steric hindrances.

The ^{1}H NMR spectra for the pure components and their mixtures were obtained in the polar solvent, $CDCl_3$ (Fig. 9). In the spectrum of menthol, signal for the OH group proton can be identified at 1.4 ppm. The presence of this signal in the spectrum is explained by the rather low acidity of the OH group of menthol.

The molecules of antipyrine and *p*-dimethylaminobenzaldehyde do not have OH group, but contain carbonyl and aldehyde groups, respectively. These groups, as hydrogen bond acceptors, may interact with the OH group of menthol. However, in the spectra of the M : A (4:1) and M : DMAB (4:1) mixtures, the location of the signal for the OH group proton of menthol does not change.

In the spectrum of pure vanillin, due to weak dissociation of OH group, signal of its

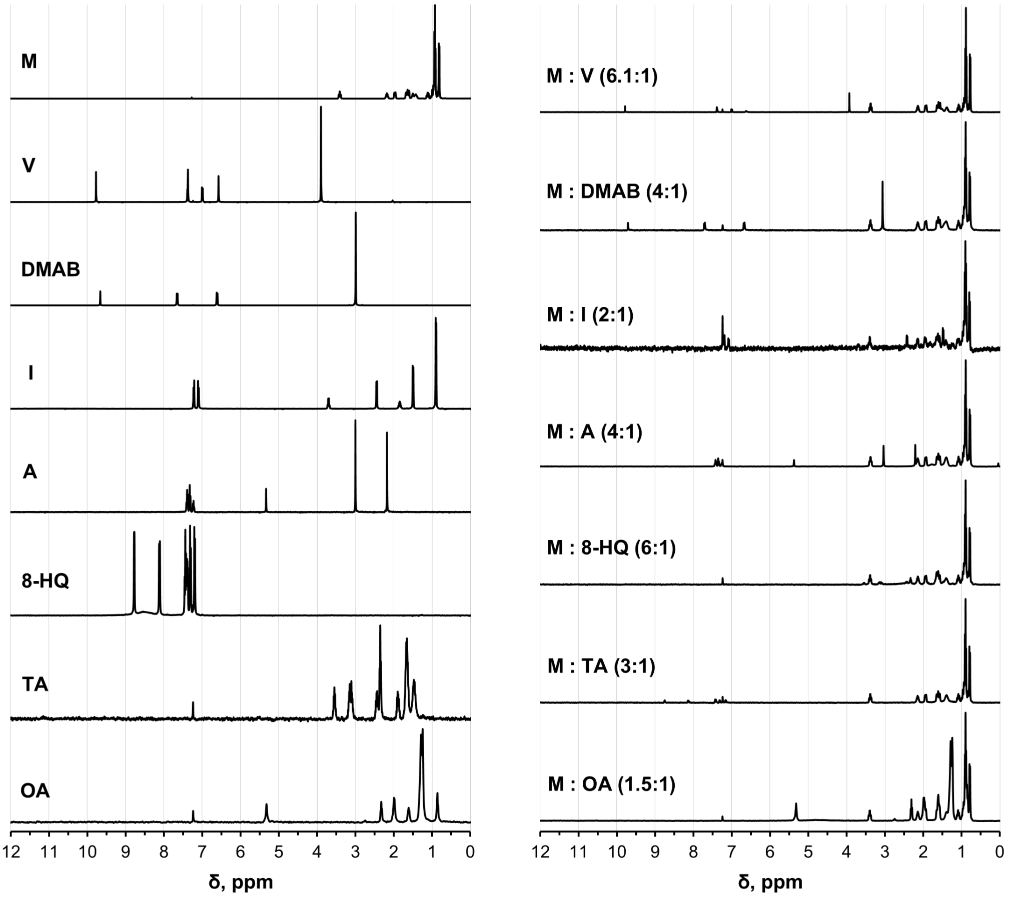

Fig. 9. The ^{1}H NMR spectra of individual compounds and ESs obtained in $CDCl_3$

proton occurs at 6.6 ppm. The spectrum of the M : V (6.1:1) mixture exhibit signals for the OH groups protons of both compounds, the location of which has not changed. These data suggest that the interaction of molecules of vanillin with menthol is less favorable than with other vanillin molecules.

Signal for the OH group proton is not detected in the spectra of 8-hydroxyquinoline and thioctic acid, as well as in their mixtures with menthol. However, in the spectrum of the M : 8-HQ (6:1) mixture, the whole signal set for protons of 8-hydroxyquinoline is upfield shifted (more shielded protons). The opposite situation occurs in the spectrum of the M : TA (3:1) mixture – the whole signal set for protons of thioctic acid is downfield shifted (protons are less shielded).

It is known that long-chain carboxylic acids can form dimers, but this does not occur significantly under these conditions for oleic acid. The minor signal at 2.8 ppm can be attributed to proton of the OH group of oleic acid, but the intensity of this signal indicates that dimerization process is negligible.

The spectrum of ibuprofen also does not reveal signal of proton of the OH group due to its high lability and ability to be exchanged. However, there is no signal of the OH group proton found in the spectra of M : I (2:1) mixture, despite the presence of negative deviations in this system.

The FTIR spectroscopy can also be useful in detecting the presence of hydrogen bonding. Lowering the frequency of OH stretching vibration and broadening of its peak is a result of the formation of both intra- and intermolecular hydrogen bonds.

The analysis of the FTIR spectra of individual compounds (Fig. 10) yielded the following data: the OH stretching vibrations were observed in a range 3250-3000 cm^{-1} as broad absorption bands for menthol, vanillin, 8-hydroxyquinoline, ibuprofen, and thioctic acid. All the compounds have the CH stretching vibrations in the 3100-2600 cm^{-1} region. Vanillin, *p*-dimethylaminobenzaldehyde, antipyrine, ibuprofen, thioctic acid, and oleic acid demonstrated the C=O vibrations located at 1710–1650 cm^{-1}. Also, the C=C

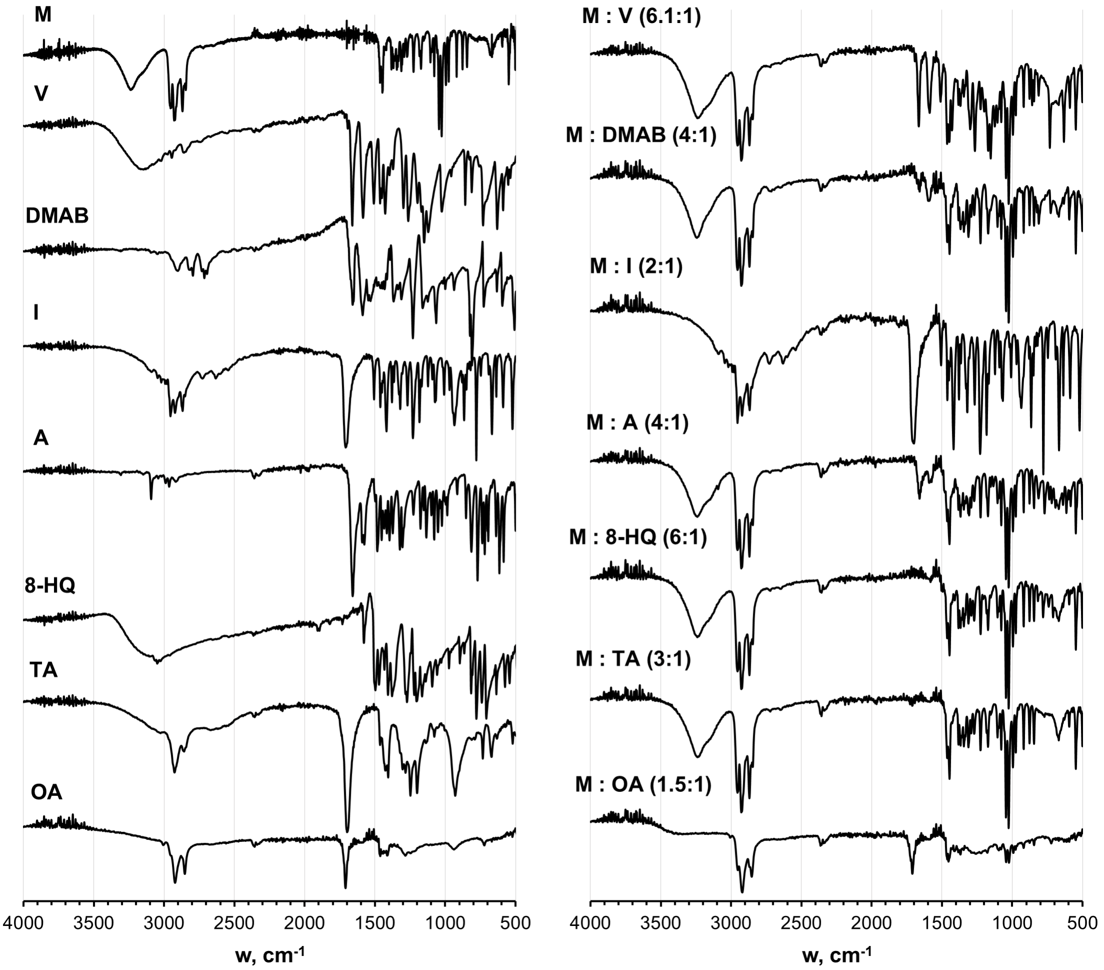

Fig. 10. The ATR-FTIR spectra of individual compounds and ESs

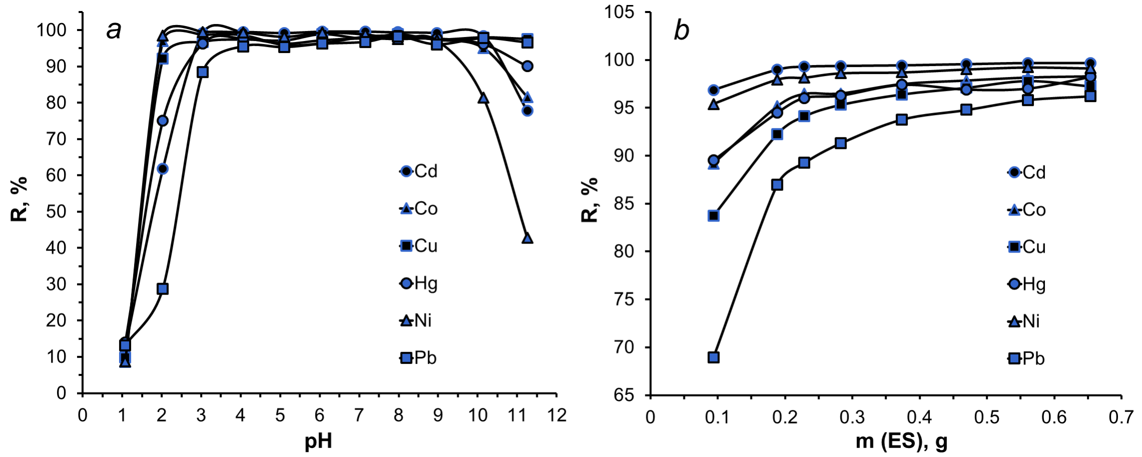

Fig. 11. The dependence of extraction recovery on pH of the solution using 500 µL of the M : 8-HQ (6:1) (a) and on the amount of the M : 8-HQ (6:1) at pH 5 (b)

vibration at 1591–1575 cm^{-1} have been found for antipyrine. It is difficult to detect OH vibration band for oleic acid, probably because it has a small intensity and is very broadened. The position and shape of OH vibrations may suggest the presence of hydrogen bonding in pure compounds.

The spectra of the eutectic M : V (6.1:1), M : DMAB (4:1), M : A (4:1), M : 8-HQ (6:1), and M : TA (3:1) mixtures (Fig. 10) exhibit the OH

Table 3. The distribution coefficients of elemental species at pH 3

Elements	Predominant species* at pH 3	M : V (6.1:1)	M : DMAB (4:1)	M : I (2:1)	M : A (4:1)	M : Ox (6:1)	M : OA (1.5:1)
Ag	Ag^+	3.31	4.93	2.29	3.18	7.05	3.45
Al	Al^{3+}	0.08	0.31	0.07	0.25	10.10	0.11
Bi	$BiOH^{2+}$ (20%), $Bi(OH)_2^+$ (80%)	3.47	7.51	17.50	5.02	19.49	53.79
Cd	Cd^{2+}	0.01	0.02	0.02	0.11	127.6	0.03
Co	Co^{2+}	0.03	0.13	0.05	0.10	56.89	0.10
Cu	Cu^{2+}	0.02	0.15	0.01	0.12	25.27	0.04
Fe	Fe^{3+} (10%), $FeOH^{2+}$ (77%), $Fe(OH)_2^+$ (13%)	0.21	0.47	4.91	0.43	14.96	5.77
Hg	Hg^{2+} (52%), $HgOH^+$ (18%), $Hg(OH)_2$ (30%)	0.07	0.74	-0.24	-0.15	10.11	0.17
Mn	Mn^{2+}	0.07	0.26	0.28	0.25	7.33	0.35
Ni	Ni^{2+}	-0.01	0.07	-0.02	0.03	117.2	0.03
Pb	Pb^{2+}	-0.02	0.08	0.00	0.09	11.37	0.03
Tl	Tl^{1+}	0.00	0.09	-0.01	0.11	0.05	0.04
Zn	Zn^{2+}	-0.05	0.05	-0.08	0.00	37.36	0.01
Sb	$Sb(OH)_2^+$ (2%), $Sb(OH)_3$ (98%)	0.55	0.65	0.56	0.68	1.48	0.35
Sn	Sn^{4+}	1.82	2.06	1.38	2.73	4.26	1.43
Ti	$Ti(OH)_3^+$ (6%), $Ti(OH)_4$ (94%)	1.41	1.71	1.16	2.04	24.18	1.25
Pt	$[PtCl(H_2O)_3]^-$ (3%), $PtCl_2(H_2O)_2$ (59%), $[PtCl_3(H_2O)]^-$ (35%), $[PtCl_4]^{2-}$ (3%) [30]	0.05	0.06	0.01	0.13	0.03	0.04
Pd	Pd^{2+} (3%), $PdOH^+$ (5%), $PdCl^+$ (57%), $PdCl_2$ (35%)	0.10	0.34	0.11	0.21	72.26	0.35
Au	Au^{3+} (3%), $AuOH_2^+$ (92%), $Au(OH)_4^-$ (5%)	14.93	5.58	0.18	31.97	9.59	1.86
W	$WO_3(H_2O)_3$	-0.10	1.99	0.62	4.35	2.87	0.05
As	$H_2AsO_4^-$ (84%), H_3AsO_4 (16%)	-0.04	-0.01	-0.02	-0.05	-0.01	0.00
V	VO_2^+ (93%), $H_2VO_4^-$ (7%)	5.83	5.97	8.17	4.83	0.89	2.65
Cr	$HCrO_4^-$	0.16	0.16	0.11	0.18	0.21	0.13
Mo	MoO_4^-	0.11	0.12	0.12	0.32	5.15	0.13

* calculated using Visual MINTEQ software

peaks belonging to menthol evidencing an absence of strong hydrogen bonding between menthol and other components. However, it is necessary to take into account the relatively high content of menthol in these mixtures, causing an overlapping of their absorption bands.

In contrast, the spectra of the M : OA (1.5:1) and M : I (2:1) mixtures do not have a clearly distinct OH band of menthol. Some changes occur in the 3400-3200 cm^{-1} region for the M : OA (1.5:1) mixture and it seems that only ibuprofen appears to affect the M : I (2:1) spectra shape. These changes may indicate the formation of hydrogen bonds.

Extraction properties. The developed hydrophobic ESs were examined for their ability to extract elemental ions from aqueous solutions. The extraction properties of the M : TA mixture have not been studied because it appears to be very viscous which complicates its withdrawal. Even though M : OA and M : I mixtures were reported in the literature [26,28], they have not been used in the extraction of elemental impurities before.

The evaluation of distribution coefficients (K_D) was carried out at pH 3, which was chosen from the viewpoint of suppression of dissociation of ESs components and hydrolysis of metal cations. Also, these extraction experiments were conducted using 500 µL of ESs. It should be noted that the K_D value depends on the extraction conditions, such as the initial concentration of the element, amount of extractant, and presence of background influences in the cumulative element solutions.

The obtained K_D of elemental species between the organic and aqueous phases (Table 3) demonstrate the ability of the

ESs to completely (K_D>19) and partially (1<K_D<19) remove some elements at a given pH. The high K_D values are observed for Au using the M : A (4:1) and for Bi – with the M : OA (1.5:1). Nonetheless, the M : V (6.1:1) and M : I (2:1) also appeared to be promising for extraction of Au and Bi, respectively. The M : 8-HQ (6:1) (Fig. 11) has a high ability to extract the range of metal ions: Al, Bi, Cd, Co, Cu, Fe, Hg, Ni, Pb, Zn, Ti, Pd. This is explained by the fact that this mixture contains 8-hydroxyquinoline, a well-known chelating reagent. The employment of a complexing reagent as a component of ES (DES) was introduced as a novel approach to the development of designer solvents [21].

The M : 8-HQ (6:1) mixture has a potential to be applied as an extraction system for the group separation and preconcentration of metal ions. Therefore, its extraction efficiency was studied towards Cd(II), Hg(II), and Pb(II) which belong to class 1 according to ICH Q3D, Co(II) and Ni(II) – class 2, and Cu(II) – class 3. The effect of the solution pH on the extraction recovery (R) of these metal ions was investigated using 500 µL of the M : 8-HQ (6:1) (Fig. 11 (a)). The high R values for each metal are observed over a wide pH range from 4 to 9. By studying the effect of the M : 8-HQ (6:1) amount at pH 5 (Fig. 11 (b)), it was found that 0.55 g (~600 µL) are sufficient. Also, the following affinity towards metal ions is observed: Pb(II)< Cu(II)< Co(II), Hg(II)< Ni(II)< Cd(II).

4. Conclusions

The mixtures of *L*-menthol with vanillin/ *p*-dimethylaminobenzaldehyde/ ibuprofen/ antipyrine/ 8-hydroxyquinoline/ thioctic acid/ oleic acid have been characterized by solid-liquid phase diagrams and classified as different types of ESs on the basis of deviations from ideality of liquid phase. The NMR and ATR-FTIR spectroscopy did not confirm the presence of strong hydrogen bonding in the mixtures that do not show negative deviations. The ability to extract metal ions is controlled by the nature of the ES constituents rather than the presence of deep eutecticity. As demonstrated with the M : 8-HQ, the introduction of a chelating reagent notably increases extraction efficiency. Overall, this work demonstrates the viability of menthol-based ESs as green, efficient, and tunable extraction systems for analytical applications, particularly for the extraction of elemental impurities. These findings contribute to the ongoing search for sustainable solvents in green analytical chemistry and open up new possibilities for developing designer solvents.

Acknowledgement

The work was supported with the project of the National Academy of Sciences of Ukraine "Novel approaches for solving the chemical-analytical problems of the study of the composition of functional materials and quality control of pharmaceutical drugs" (0122U002561). The authors thank all brave defenders of Ukraine who allow us to continue our scientific work.

References

1. S. Armenta, S. Garrigues, F. A. Esteve-Turrillas *et al. TrAC - Trends Anal. Chem.* **116**, 248 (2019).
2. International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use. *ICH Harmonised Guideline: Guideline for Elemental Impurities Q3D(R2). Europeans Medicines Agency* 1 (2022).
3. J. Bintanel-Cenis, M. A. Fernández, B. Gómara *et al. Talanta* **270**, 125599 (2024).
4. T. Khezeli, M. Ghaedi, S. Bahrani *et al.* in *New Generation Green Solvents for Separation and Preconcentration of Organic and Inorganic Species* 381 (2020).
5. M. Cherniakova, V. Varchenko, K. Belikov. *Chem. Rec.* **24**, e202300267 (2023).
6. S. Sadeghi, A. Davami. *J. Mol. Liq.* **291**, 111242 (2019).
7. S. M. Sorouraddin, M. A. Farajzadeh, T. Okhravi. *J. Food Compos. Anal.* **93**, 103590 (2020).
8. M. Karimi, S. Dadfarnia, A. M. H. Shabani *et al. Talanta* **144**, 648 (2015).
9. R. Akramipour, M. R. Golpayegani, S. Gheini *et al. Talanta* **186**, 17 (2018).
10. R. A. Zounr, M. Tuzen, N. Deligonul *et al. Food Chem.* **253**, 277 (2018).
11. M. H. Habibollahi, K.A. Karimyan, N. Mirzaei *et al. J. Sci. Food Agric.* **99**, 656 (2019).
12. J. M. Matong, L. Nyaba, P. N. Nomngongo. *Ecotoxicol. Environ. Saf.* **135**, 152 (2017).
13. R. A. Zounr, M. Tuzen, M. Y. Khuhawar. *J. Mol. Liq.* **242**, 441 (2017).
14. E. Yilmaz, M. Soylak. *Talanta* **136**, 170 (2015).
15. M. Soylak, M. Koksal. *Microchem. J.* **147**, 832 (2019).
16. H. U. Haq, M. Balal, R. Castro-Muñoz *et al. J. Mol. Liq.* **333**, 1 (2021).
17. K. Ghanemi, M. A. Navidi, M. Fallah-Mehrjardi *et al. Anal. Methods* **6**, 1774 (2014).
18. P. Makoś, E. Słupek, J. Gębicki. *Microchem. J.* **152**, 104384 (2020).

19. E. E. Tereshatov, M. Y. Boltoeva, C. M. Folden. *Green Chem.* **18**, 4616 (2016).
20. N. Schaeffer, M. A. R. Martins, C. M. S. S. Neves *et al. Chem. Commun.* **54**, 8104 (2018).
21. M. Y. Cherniakova, O. V. Vashchenko, J. M. Stolper *et al. New J. Chem.* **48**, 14527 (2024).
22. F. C. Pinheiro, M. Á. Aguirre, J. A. Nóbrega *et al. Anal. Chim. Acta* **1185**, 339052 (2021).
23. N. Altunay, M. Tuzen. *Food Chem.* **364**, 130371 (2021).
24. M. J. Blandamer, J. C. R. Reis. *A Notebook for Topics in Thermodynamics of Solutions and Liquid Mixtures* (2024).
25. J. M. Prausnitz, R. N. Lichtenthaler, E. G. de Azevedo. *Molecular Thermodynamics of Fluid-phase Equilibria* (1999).
26. P. Stott. *J. Control. Release* **50**, 297 (1998).
27. M. A. R. S. P. Martins, Pinho, J. A. P. Coutinho. *J. Solution Chem.* **48**, 962 (2019).
28. W. Pitacco, C. Samorì, L. Pezzolesi *et al. Food Chem.* **379**, 132156 (2022).
29. M. A. R. Martins, E. A. Crespo, P. V. A. Pontes *et al. ACS Sustain. Chem. Eng.* **6**, 8836 (2018).
30. F. Mahlamvana, R. J. Kriek. *Appl. Catal. B Environ.* **148–149**, 387 (2014).