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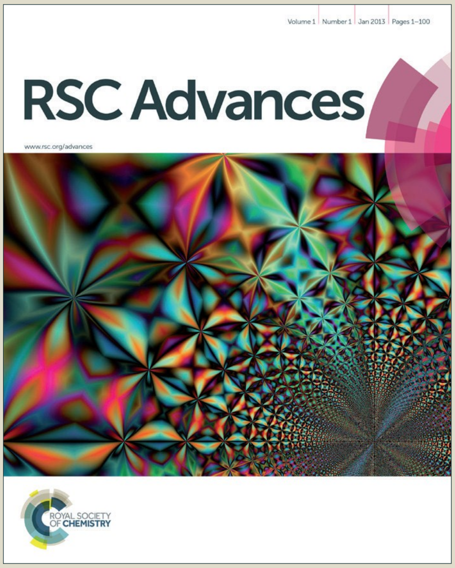

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SOLUTE-INDUCED PERTURBATION OF METHANOL-WATER ASSOCIATION

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This article addresses experimental evidences on the changing in the equilibrium constant of methanol-water association induced by solutes. The behavior of four solutes (solvatochromic dyes) in methanol-water binary mixtures are probed using augmentation of infrared and UV-Vis spectroscopy methods followed by multivariate analysis. In order to get a more reliable concentration and spectral profiles, with fewer ambiguities, complementarity and coupling theorems has been utilized. A ternary system was resolved by multivariate analysis on the noted augmented data for each chemical probe. Resultant concentration profiles showed unique behavior of each solute in the binary-solvent system. Therefore, individual association constant for the formation of the methanol-water association was achieved for each solvatochromic probe. Indeed, different solutes can change solvent-solvent interaction based on their hydrogen binding affinity. Diverse hydrogen binding affinities for different solutes were investigated by charge distribution analysis via the molecular electrostatic potential (MEP) calculations as well as atomic charge on oxygen atom. In addition, obtained spectral profiles of standard solvatochromic probeswere used to calculate solvatochromic parameters of dipolarity/ polarizability and hydrogen-bonding basicity of three resolved components (i.e. methanol, water and methanol–water complex surrounded probes).

Introduction

Solvent-solute and solvent-solvent interactions are of vital importance in studying chemical, environmental, industrial, and biological processes in liquid phase. solvents-induced changes of the dynamic and equilibria of such processes (known as preferential salvation) has been well understood.[1–5]

Methanol-water binary solvents, as the widely used solvents in liquid chromatography, have been studied in the past using both theoretical and experimental methods. In this regard, multivariate curve resolution (MCR) as a powerful chemometrics technique has been used to analyze the spectroscopic and physicochemical data of solvents alone or in the presence of solutes.[6–9] It has now been accepted that, in the binary mixtures of methanol and water, a methanol-water association (or cluster) is formed.[6–12] However, all of the previous studies ignored the solute effects on the structure of this association. This led to the inconsistency between the obtained results by different authors. There is no agreement between the stoichiometric ratio(s) of the associate(s)[6–9,11–13]and also the reported equilibrium constants for even the same association model, e.g. 1:1 molar ratio association, are largely different.[9,12,13]

Besides to the pronounced effect of solvent on the structure and function of solutes, recently Ben-Amotz and coworkers discovered the effect of solute on the structure of solvent.[14–21] Using Raman spectroscopy and multivariate curve resolution, they could identify the changes in the structure and hydrogen-bonding network of water in the presence of different solutes including ions[17,19] as well as polar and nonpolar molecules.[15] However, nothing has been reported regarding solute effect on the structure of mixed solvents.

Here, we demonstrate the effect of solute on the methanol-water association in their binary mixtures. In the past, both native FTIR spectra of the pure solvents as well as the mixed solvents[10–12] and the spectra of solvatochromic dyes in the pure and mixed solvents.[2,6,22–24]have been used to monitor the methanol-water association. However, the changes in absorbance spectra of the solvatochromic dyes can also provide some indirect measurement of the solvent-solvent association. Thus, in this work, we used both techniques simultaneously for following the solute effects in dynamic parameters of binary solvents.

To do so, the ATR-FTIR and visible electronic absorbance spectra of methanol-water mixtures in the presence of different solvatochromic dyes as probes had been analyzed by chemometrics methods.[9] The results revealed changes in the equilibrium constant of methanol-water association through

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Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/x0xx00000x perturbing of the hydrogen bonding interactions between the solvents.

Although, MCR method has been used in many methanol-water mixture studying, [6–9,25], because of existence of a range of feasible solutions (so-called rotational ambiguity) in this system, a unique and appropriate analysis could not be achieved. [26]

Here, we aim to use a more reliable method with fewer ambiguities to investigate solutes effects. In this regard, complementarity and coupling theorems have been used as a soft model. In this method, any additional information on the system could be utilized to reduce this ambiguity. Complementarity and coupling theory has a solid mathematical foundation and can be formulated in terms of linear and affine linear subspaces to which certain concentration profiles and spectra are restricted. This theory allows formulating restrictions on the feasible concentration profiles if information on the spectra is available and vice versa.[27,28]

Additionally, it had been shown that the dipolarity/polarizability and hydrogen acidity/ basicity of the solutes depend strongly on the composition and properties of solvent mixture and mobile phases.[6,8] Therefore, as well as the dynamic parameters, the resolved spectra are used to estimate the dipolarity/polarizability parameter (π^*)[29] and the hydrogen-bonding basicity (β)[30] parameter for the pure solvent species and also for the solvent- water complexes.

Experimental

Chemicals and Materials. N,N-Dimethyl-4-nitroaniline (DMA), 4-nitroanisol (NAS), Indigo carmine (ICM), and 4-nitroaniline (NAL) were purchased from sigma-Aldrich. Merck supplied indigo carmine. Water (chromatography grade) and methanol (Spectroscopy grade) were from Sigma Chemical Co. and were used directly without any further purification.

UV−vis absorptions were studied by Shimadzu 1601 UV–Vis spectrometer, using quartz analytical cells of 1 cm path length.

IR spectra were recorded on a FT-IR Perkin Elmer FTIR spectrometer-spectrum RX1 equipped with a Perkin Elmer ZnSe ATR sampler accessory.

Binary solvent mixtures of methanol and water of variable mole fractions (21 binary solvents) were prepared by mixing of the desire weights of the pure solvents. Also, mole fraction compositions in IR spectroscopy were as same as the absorption spectroscopy.

The concentrations for all the dyes in the solvent mixtures were kept constant at 2×10^{-5} M. For each solute, the IR and UV-Vis spectra of the resulting solutions in methanol-water binary solvents of various compositions were recorded. The temperature was fixed at 25°C. The collected spectra were converted to ASCII format and transferred to MATLAB (Mathwork, Inc.) environment. The data were analyzed with programs written in the MATLAB programming environment.

Data Analysis Method. Data matrices were constructed for each dye solvent mixture by collecting the digitized spectra of the dye in solvent mixtures at compositions ranging from 100% to 0% organic phase. For each solute and each spectroscopic method, absorbance data matrix **D** of size ($m \times n$) was obtained, where $\boldsymbol{m}$ is the number of different solvent compositions at which spectra are measured and $\boldsymbol{n}$ is the number of absorbance reading per spectrum.

According to the bilinear Lambert-Beer law, the absorbance data matrix **D** equals the product **CA** with **C** being the matrix of concentration profiles and **A** being the matrix of pure component spectra. Usually the concentration profiles are taken along the time axis, but here these values correspond to the different bulk solvent compositions.

The starting point is a singular value decomposition (SVD) of **D** with the form $\mathbf{D} = \mathbf{U\Sigma V^T}$. The number of significant singular values indicates the number of independent components. Then the first **s** columns of **U** (left singular vectors) and the first s columns of **V** (right singular vectors) are used for the expansion of an approximate factorization with $\mathbf{C} = \mathbf{U\Sigma T^{-1}}$ and $\mathbf{A} = \mathbf{TV^T}$. Therein **T** is a regular $\mathbf{s} \times \mathbf{s}$ matrix. In general the matrix T is not unique, but many nonnegative factorizations exist. The term rotational ambiguity paraphrases the non-uniqueness of **T**. In order to extract the chemically most meaningful and hopefully correct solution, hard and soft models can be used as constraints on the factors **C** and **A**. [31–33]

Whenever additional information on the pure component factors is available, it should be used in order to reduce the rotational ambiguity; see e.g. the complementarity and coupling theory. [27,28]

Results and Discussion

Factor numbers

Four standard solvatochromic indicators[34] including N,N-dimethyl-4-nitroaniline (DMA), 4-nitroanisol (NAS), 4-nitroaniline (NAL) and indigo carmine (ICM) were used to probe methanol-water association. A fixed amount of each dye was dissolved in the methanol-water binary solvents and then the ATR-FTIR as well as UV-Vis absorbance spectra of the resultant solutions were recorded. The resulting spectra are shown in electronic supplementary information (ESI) (Fig. S1 and S2 (ESI).). To ignore the concentration effect, the same concentration of dyes was used for all dyes. For each dye and for each spectroscopic method, an absorbance data matrix **D**, each row of which was the digitized absorbance spectrum at a specified methanol-water composition, was provided. Then, for each dye, the data matrices obtained from two spectroscopic methods were augmented in a column-wise manner[35] to monitor the manner of solutes in binary solvents by both IR and absorption spectroscopy techniques.

First step in analysis of methanol-water mixture, is the determination of the number of significant principal components in the mixture. Both singular value decomposition (SVD) and evolving factor analysis (EFA) were employed to determine the number of the significant principal components, attributing to the number of the solvated complex in the systems. Eigen-value (EV) plot (obtained from SVD)) and the results of EFA vs. number of principal components as a function of the eigenvalue numbers were shown in Fig. S3. In addition, we used reduced eigenvalue (REV), root mean square (RMS) and residual standard deviation (RSD) as mathematical criteria to determine the number of factors.[36] The results of SVD analysis are summarized in Table S1. In summary, Principal component analysis (PCA)[37] of the data matrices of all dyes revealed the presence of three significant chemical species (see ESI section, Fig. S3 and Table S1 for details), attributed to the pure methanol, pure water and a methanol-water association.[6–9] The same results were obtained when PCA was run on the extended data matrix obtained by stacking the data matrices of all dyes under each other (Table S1).

Pure contribution of species and stoichiometric analysis.

The detection of three principal components by PCA suggested that when a dye is dissolved in a binary methanol-water solvent, it can be solvated by three solvent components and hence there are three different solvated states of each dye. According to the Beer-Lambert law of absorbance additives, the absorbance of each dye in the binary mixtures can be assumed as the summation of the absorbance of dyes in its three different states. So, the absorbance data matrix of each dye can be discomposed into the contribution of each solvated state of the dye:

$$\mathbf{D} = \mathbf{D_m} + \mathbf{D_w} + \mathbf{D_{mw}} = \mathbf{c_m s_m} + \mathbf{c_w s_w} + \mathbf{c_{mw} s_{mw}} = [\mathbf{c_m c_w c_{mw}}]\ [\mathbf{s_m}; \mathbf{s_w}; \mathbf{s_{mw}}] = \mathbf{CS} \qquad (1)$$

The indices m, w and mw denotes pure methanol, pure water and methanol-water association, respectively. The column vectors $\mathbf{c_m}$, $\mathbf{c_w}$ and $\mathbf{c_{mw}}$ correspond to the concentration profile of each solvent species as function of the bulk solvent composition. The row vectors $\mathbf{s_m}$, $\mathbf{s_w}$ and $\mathbf{s_{mw}}$ denote the pure spectrum of different states of the solvated dye. The same explanations apply for the FTIR spectra of the solvents. The recorded FTIR absorbance spectrum at a specified methanol-water mole fraction can be assumed as the summation of the absorbance of three solvent species.

Generally multivariate curve resolution (MCR) as a soft-modeling method have been used to decompose the data matrix **D** into the pure contribution of each species (to obtain estimates of **C** and **S** as matrices of concentration profiles and pure spectra, respectively).[38] Comparing the obtained concentration profiles of different solvent species in the presence of different solutes will reveal the effect of solute on the methanol-water association. But, one major drawback inherent to all MCR methods is rotational ambiguity, which usually lead to obtaining a range of feasible solution instead of unique solution for **C** and **S**.[26,39] Since the effect of solutes on solvent structure is very small, there might be an overlap between the ranges of solutions of different dyes and, hence, the comparison might not be meaningful. So, obtaining a unique solution is a key in comparing the effects of solutes. The recent works conducted by Sawall and Neymeyr allow to extract unique solutions for the given three component system.[27,28] In this regard, the data analysis combines classical MCR techniques with the relatively new complementarity theory. The spectral data matrices for all our experiments indicate three-component systems. In all cases two of the three pure component spectra are available. By means of the complementarity theorem,[27] this allows to compute the concentration profile of the third component. In order to supply the missing information for the remaining pure component spectra and concentration profiles, an additional soft constraint is used in the form of a mass balance for the three components. This constraint maximizes the smoothness of the concentration profiles of the two remaining components; mathematically the norm of the discretized second derivatives of these concentration profiles is minimized.[27,28]

The resultant concentration profiles for augmented matrices by complementarity and coupling theorems are given in Fig. 1. The starting point for these computations is the known pure component spectra of water and methanol. So the three component system has only two degrees of freedom, which is a result of the representation of the rotational ambiguity of the factorization for a three component system.[32]

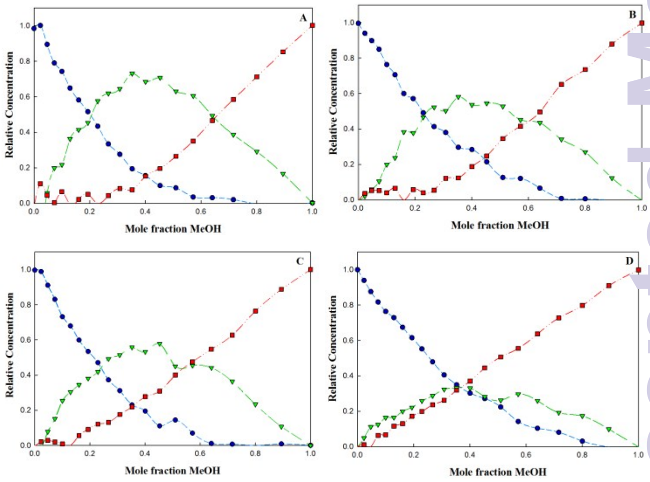

Fig. 1 Results of complementarity and coupling theorems: concentration profiles of augmented spectra of UV-Vis and IR for dyes as solvatochromic probes. Dyes involve 4-nitroanisol (A), 4-nitroaniline (B), N, N dimethyl- 4- nitroaniline (C) and indigo carmine (D) in methanol- water mixture. For all experiments, water solvated solutes (blue, (●)), methanol solvated solutes (red, (■)) and methanol-water solvated solutes (green, (▲)) were shown in the graphs.

In order to reduce the remaining two-parameter ambiguity, two soft-constraint functions (namely, on the mass balance and on the smoothness of the concentration profiles) have been used.[31] The concentration profiles are similar for all studied dyes. All show a single association model. The methanol-water associated solvent reaches to its maximum concentration value at bulk molar ratio of about 0.5. This suggests a 1:1 stoichiometric ratio of methanol-water in the associated solvent.

Determination of the Complex Association Constant

As shown in Fig. 1, four dyes has the similar ternary contribution in the methanol-water mixed solvents. However, the concentrations of the associated solvent change as dyes vary. The observed differences can be attributed to the changing in the equilibrium constant of the association model with the form:

$$\mathbf{M + W \leftrightarrows MW} \qquad (2)$$

The association constant can be estimated by nonlinear fitting of the concentration profiles to association model of Eq. (2). As it is observed from Table 1, there is a large difference in the estimated association constants for different solutes. The largest association constant (2.32 M^{-1}) has been obtained in the presence of NAS whereas the smallest value (0.10 M^{-1}) has been found in the presence of ICM. The major difference between these compounds is their polarity and their ability for hydrogen-bonding. Indigo carmine is a large polyanionic compounds capable of forming hydrogen bonding with both methanol and water, whereas 4-nitroanisole as a small molecule with fewer donor functional groups have lower ability of forming hydrogen bond

So, the lower instability of the methanol-water association in the presence of ICM can be attributed to the perturbation of methanol-water interaction (mostly because of hydrogen bonding) by the polar groups of ICM. On the other hand, the estimated association constant in the presence of DMA and NAL were in intermediate levels with 0.54 M^{-1} and 0.64 M^{-1} association constant, respectively. These compounds could be considered as lower polarity relative to NAS and higher polarity relative to ICM. It should be noted that there are two reports on estimating of association constant of MW in the absence of solute. Using bulk properties of binary mixtures such as volume changes on mixing, refractive index and density, an association constant of 5.04 has been suggested by Katz et al.[40] In addition, by chemometrics analysis of various solvent properties, Hemmateenejad reported an association constant of 13.7.[9] Interestingly, both values are larger than those found in the presence of solutes. This confirms instability of methanol-water association in the presence of solutes.

In order to confirm the solutes preferential hydrogen binding in methanol- water mixture, charge distributions and molecular electrostatic potential analysis have been performed in following.

Table1 Association constant of methanol– water complex by using various dyes

Dye	Association constant	ssq
4-nitroanisol (NAS)	2.32 ± 0.0003	1.60
4-nitroaniline (NAL)	0.64 ± 0.0007	0.35
N,N dimethyl 4-nitroaniline (DMA)	0.54 ± 0.0013	0.82
Indigo carmine (ICM)	0.10± 0.0043	0.34

Meanwhile, to be assure about the 1:1 association model, other association models like 2:1, 1:2 or 3:2 were also examined and the resultant concentration profiles were fitted to these models. The results revealed that, none of these models could be fitted as good as the 1:1 model, i.e., the standard errors of fitting for these models were much larger than that for 1:1 association model**.**

Charge distribution analysis

In order to get a deeper insight into the role of structural properties of solutes affecting the stability of methanol-water association, we performed the charge distribution analysis via the molecular electrostatic potential (MEP) calculations.[41] The electrostatic potential for the nuclei and electrons of a molecule create in the surrounding space is well established as a guide to the interpretation and prediction of molecular reactive behavior. This quantity is a useful tool in studying both electrophilic and nucleophilic processes, including hydrogen-bonding interactions and, in particular, to be well suited for studies that involve the identification of key features necessary for the "recognition" of one molecule by another.[42,43] In this context, the structures of all solutes were optimized in the framework of density functional theory using the B3LYP method. All calculations were performed with 6-31G +(d) basis set by means of the Gaussian 09 suite of programs.[44] Natural population analysis was also employed to describe charge distribution in each solute.[45] The resulting electrostatic potential maps of all considered solutes are plotted in Fig. 2. Clearly, a negative electrostatic potential (red color) is present in the O end of the NO_2 group whereas a positive one (blue color) is observed around the hydrogen atoms.

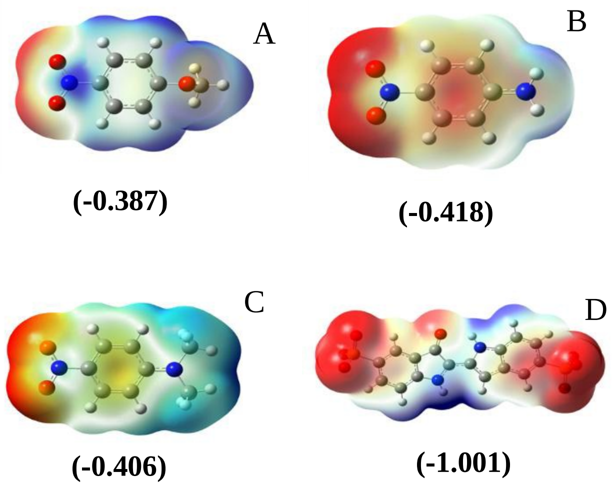

Fig. 2 Electrostatic potentials isosurfaces (0.025 au) of 4-nitroanisol (A), 4-nitroaniline (B), N, N dimethyl- 4-nitroaniline (C) and indigo carmine (D). The red and blue colors represent the negative and positive molecular electrostatic potentials; respectively. Natural Charges on oxygen atoms have been shown below the figures.

Inspection of the MEP plots in Fig. 2 and the computed atomic charge on oxygen atom in different solutes reveal that the polarizability of oxygen atom and its tendency to participate in hydrogen bonding interaction, exhibiting the following order: ICM>>NAL > DMA > NAS. This trend is consistent with the association constant of the methanol- water complex in the presence of mentioned solutes (Table 1). The only exception is the relative position of NAL and DMA. The association constants in the presence of these compounds are very close and the differences in values of the association constants are in the range of experimental error.

Pure spectra of the species

Besides to concentration profile, complementarity and coupling theorems gives the pure spectra of the species contributing to the system under study. We have two set of spectra data individually; the UV/Vis absorbance spectra of the solutes and the FTIR spectra of the solvents.

The resolved FTIR spectral data are attributed to the solvents and comparing the pure spectra obtained in the presence of different solutes gives information on the solute-induced perturbation of solvent spectrum (or, in the better word, the solvent structure). Whilst the solute-induced changes of the spectral profiles of pure solvents have already been studied, the effect of solute on the spectral characteristic of methanol-water associate has not been investigated yet. Therefore, an interesting point is to compare the pure spectrum of each solvent species in the present of different solutes. Comparison of the resolved IR spectra (over the OH stretching frequencies) of each solvent species in the presence of different solutes clearly shows the perturbation of solvent spectra by the solutes.

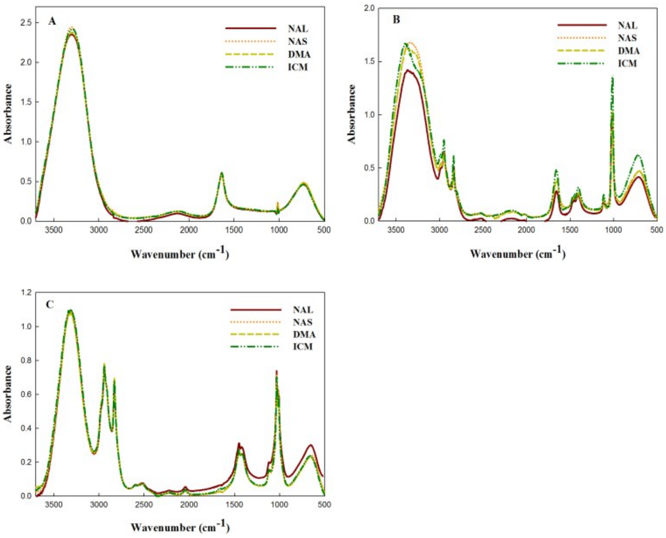

Fig. 3 Infrared spectra obtained with complementarity and coupling theorems for solvents solvated four dyes (solutes). water solvated solutes (A), methanol-water solvated solutes (B) and methanol solvated solutes (C).

This effect is minute for water and methanol (Fig.. 3 A and C). However, significant solute-induced perturbation of IR spectra is observed for methanol-water association (Fig. 3B).

Solvatochromic Parameter

The extracted UV/Vis pure spectra profiles are related to the solutes solvated by different solvent species (i.e. pure methanol, pure water and methanol-water cluster) (Fig. 4). One can use these spectral profiles to calculate the solvatohromic parameters of the solvents.

Kamlet–Taft solvatochromic parameters are the most comprehensive and commonly used quantitative measurement of solvent properties. These parameters are the hydrogen bond basicity (β), the hydrogen bond acidity (α) and the dipolarity-polarizability (π*). Important information about the polarity and hydrogen bonding ability of the formed methanol- water complexes, let to predict solvent properties as a function of composition. This information can be useful in analyzing of retention models in chromatography.

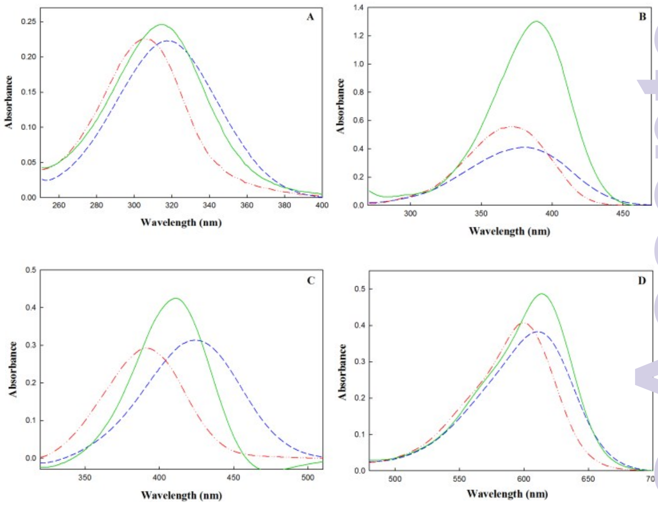

Fig. 4 Estimated spectra profiles obtained by complementarity and coupling theorems of UV-Vis spectra for four probes, 4-nitroanisol (A),4-nitroaniline (B), N, N dimethyl- 4-nitroaniline (C) and indigo carmine (D) in methanol- water mixtures. For all experiments, water solvated solutes (blue, (●)), methanol solvated solutes (red, (■)) and methanol-water solvated solutes (green, (▲)) were shown in the graphs.

The solvatochromic property of pure methanol and pure water can be simply measured by recording the absorbance spectrum of the solute in the pure solvents. However, the spectral data of solutes in methanol-water associate could not be determined experimentally. An interesting application of complementarity and coupling theorems analysis is estimating the spectral profiles of the solutes in methanol-water associate. The calculated solvatochromic parameters of the methanol-water associate and the pure solvents, using the resolved spectral profiles of the standard solutes, are listed in Table 2 and are compared with previous literature values.

Table 2 π* and β values of three species of dyes in methanol- water mixture,calculatedbycomplementarity and coupling theorems

	π* Standard Dye					**β Standard Dye**		
	N,N dimethyl4-nitroaniline		**4-nitroanisol**			**4-nitroaniline**		
	Exp value	**Our theorem**	**Exp value**	**Our theorem**	**literature**	**Exp value**	**Our theorem**	**literature**
Water	1.46	1.46	1.14	1.09	1.14[46] 1.09[47] 1.35[6]	0.48	0.48	0. 47[2]
Methanol -Water complex	–	1.18	–	0.97	1.21[6]	–	0.81	1.09[14]
Methanol	0.77	0.75	0.61	0.61	0.60[47] 0.78[6]	0.79	0.79	0.70[47]

The estimated values of π*[29] using dyes N, N-dimethyl-4-nitroaniline and 4-nitroanisol (Fig. 4 A and C) which solvated with methanol- water complex are 0.97 and 1.18, respectively.

The two probes confirm that dipolarity/ polarizability is closer to water than methanol. The differences in the various π* scales are caused by the different mixture of dipolarity and polarizability measured by the respective indicator.[2] In this regard, average value of 1.07 is suggested for π*.

The β parameter[30] obtained from the estimated profiles has been compared with the experimental values in Table 2. The β values of 0.84 have been obtained for the methanol- water complex. The solute 4-nitroaniline solvated by methanol-water complex represents larger bathochromic shift than water. Therefore, its β value for the methanol-water complex is higher than that of both pure methanol and water. Tendency of the methanol- water complex to hydrogen bonding accepting is more than pure solvents. It can be related to enhancement of the hydrogen bonding basicity of complex compared to the unmixed methanol and water. The results can be in agreement with previous studies about α parameter.[6,46]

As seen, a good agreement is observed between our results and the reported values. The polarity/polarizability index of methanol-water association is in the intermediate of that of the pure solvents.

Conclusions

In conclusion, we illustrate the ability of different solute in perturbation of methanol- water solvent association by applying a unique method, complementarity and coupling theorem. Each solute gives an individual association constant for methanol-water association. These constants can be related to the affinity of variant electron donor/acceptor functional groups toward hydrogen bonding.

Therefore, attributing a fix and invariant association constant to binary solvent association is not acceptable and even the type of solute should be considered.

In addition, the spectra profiles of three components have been used for determination of solvatochromic parameters Dipolarity/ polarizability (π*), and hydrogen-bonding basicity (β), have been defined for all three components of methanol-water system separately. The average π* values for the methanol- water is 1.07.The β parameter was achieved 0.58 for the complex species.

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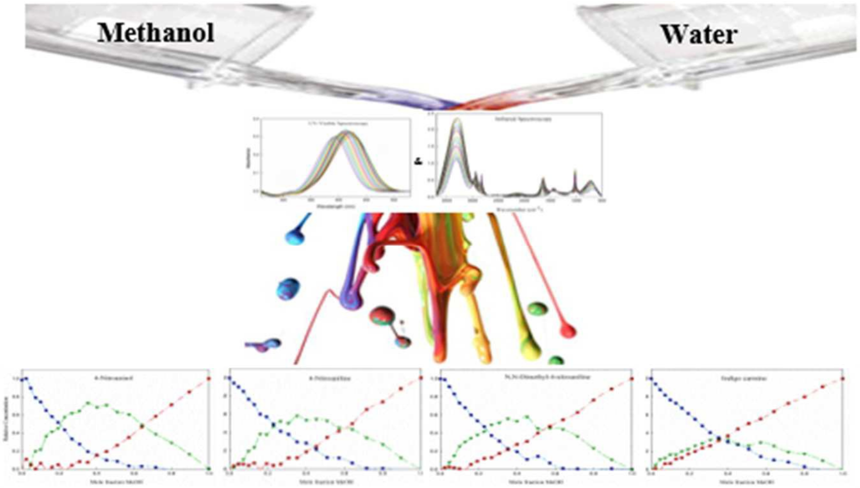

Chemometrics analysis of the IR and UV-Vis absorbance data revealed the pronounced effect of stability of the associated methanol-water cluster in the mixtures of the solvents.