Scientific research article / *http://dx.doi.org/10.15446/rcciquifa.v49n3.91347*

Prediction of sulfadiazine solubility in some cosolvent mixtures using non-ideal solution models

Rossember E. Cardenas*, Luz Elena Tinoco, Diana M. Galindres, Alejandro Beltrán, Carlos D. Oviedo, Jhonny Osorio

Grupo de Fisicoquímica y análisis matemático, Facultad de Ciencias y Humanidades, Fundación Universidad de América, Avenida Circunvalar No. 20-53, Bogotá D.C., Colombia.

*Corresponding author: rossember.cardenas@profesores.uamerica.edu.co

Received: 19 September 2020

Revised: 28 September 2020

Accepted: 30 September 2020

Summary

The experimental data of sulfadiazine in (methanol + water), (ethanol + water) and (1-propanol + water) cosolvent mixtures at some temperatures were correlated using non-ideal solution models, namely, the modified Apelblat and Buchowski-Ksiazaczak equations and the van't Hoff equation. The calculated results agreed well with the experimental data. According to the Buchowski equation, the solubility of sulfadiazine in the three co-solvent mixtures shows important deviations from ideality, which is consistent with the literature.

Key words: Sulfadiazine, solubility, van't Hoff model, Buchowski-Ksiazaczak λh model, Apelblat model.

Resumen

Predicción de la solubilidad de la sulfadiazina en algunas mezclas cosolventes utilizando modelos de solución no ideales

Los datos experimentales de sulfadiazina en mezclas de cosolvente de (metanol + agua), (etanol + agua) y (1-propanol + agua) a algunas temperaturas se correlacionaron utilizando modelos de solución no ideales, a saber, las ecuaciones modificadas de Apelblat y Buchowski y la ecuación de van't Hoff. Los resultados calculados coincidieron bien con los datos experimentales. Según la ecuación de Buchowski, la solubilidad de la sulfadiazina en las tres mezclas de cosolventes muestra importantes desviaciones de la idealidad, lo que concuerda con la literatura.

Palabras clave: Sulfadiazina, solubilidad, modelo de van't Hoff, modelo de Buchowski-Ksiazaczak λh, modelo de Apelblat.

Introduction

Sulfadiazine (N^1-2-pyrimidinylsulfanilamide) (figure 1) is a member of the sulfonamide family [1]. As one of the earliest antibacterial drugs used in the prevention and treatment of bacterial infections, sulfonamides are widely used in the medical and livestock industries due to their broad antibacterial spectrum, stability and low-cost [2-4], however, sulfadiazine solubility in ambient water is very low and it is considered as practically insoluble [5-8]. Although the solid dosage form of sulfadiazine has been widely used in therapeutics, the development of liquid dosage forms is important to administer the drug to special groups of patients. To increase the solubility of sulfadiazine some cosolvents have been added to water [9, 10]. The analysis of sulfadiazine in the pharmaceutical industry typically involves high-performance liquid chromatograph that consumes a large quantity of hazardous organic solvents and its waste needs to be properly disposed of [11, 12].

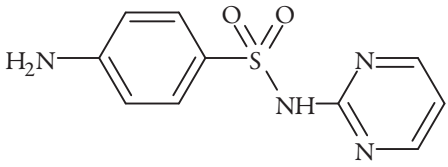

Figure 1. Molecular structure of sulfadiazine.

However, solubility measurement and optimization of the solvent composition for dissolving a desired amount of a drug in a given volume of the solution in most of the cases is a laborious and time consuming procedure which may cause some limitations in discovering and development of new drugs [13, 14]. Mathematical model, as an alternative method, could be used to estimate drug's solubility especially when the solid–liquid equilibrium measurements become impractical. Various numerical models proposed for the estimation of the solubility of drug and/or drug like compounds in the cosolvency systems which in order of appearance include van't Hoff equation [15], Yalkowsky model [5, 16, 17], the mixture response surface model, the double log-log model, the modified Wilson model[18], the Jouyban-Acree model [19-21], the Jouyban-Acree-van't Hoff model, and modified Jouyban-Acree-van't Hoff model. Van't Hoff equation predicts solubility at different temperatures in each solvent composition [22, 23], whereas Yalkowsky model, the modified Wilson model [18], the double log-log model and mixture response surface model predict solubility at different solvent mixtures. Whereas, the Jouyban-Acree [24] and Jouyban-Acree-van't Hoff models [25] predict the solubility in various solvent composition at different temperatures.

The objective of the present work is to evaluate the application of the van't Hoff, Buchowski-Ksiazaczak λh, and modified Apelblat models to the solubility of sulfadiazine in three cosolvent systems.

Theoretical

Modified Apelblat equation

From the Williamson equation, the solubility of non-electrolytes is expressed as [26]:

$$\frac{\partial \ln\left(m/m^{o}\right)}{\partial T^{-1}} = \frac{\Delta_{\text{soln}} H(T)}{R\left[1-0.001hM_1 m\right] f}, f = 1 + \left\{ \frac{\partial \ln \gamma_3}{\partial \ln\left(m/m^{o}\right)} \right\}_T, \tag{1}$$

where h denotes a number of water molecules in the hydrate, $\Delta_{\text{soln}}H(T)$ is the molar enthalpy of solution, γ_3 is the activity coefficient of the solute, M_1 is the molar mass of solvent, R is the gas constant and $m^{\circ} = 1$ mol.kg^{-1}.

If it is assumed that the enthalpy of solution depends linearly on the temperature, the integral form of equation (1) is [27]:

$$\ln\left(m/m^{\circ}\right) = A + BT^{-1} + C\ln T \tag{2}$$

So, expressing the solubility in mole fraction, the modified Apelblat equation, which is a semi-empirical model derived from solid-liquid equilibrium is [28]:

$$\ln x_3 = A + BT^{-1} + C\ln T \tag{3}$$

x_1 refers to measured mole fraction solubility of drug in selected solvent at absolute temperature T; A and B reflect the variation in the solution activity coefficient; C represents the influence of temperature on enthalpy of fusion [29, 30]; The above three parameters and experimental prediction values can be obtained by the nonlinear regression method in Python.

Van't Hoff equation

The van't Hoff equation is also a semi-empirical equation, which reveals the relationship between the mole fraction solubility and the temperature in an ideal solution by taking the solvent effect into account. The formula is shown as equation (4).

$$\ln x_3 = A + \frac{B}{T} \tag{4}$$

A and B are parameters, which can be related to thermodynamic parameters such as dissolution enthalpy and dissolution entropy [22]. The above can be shown from the two mathematical expressions for the Gibbs energy [31-34]:

$$\Delta_{soln} G^\circ = -RT \ln x_3 \tag{5}$$

$$\Delta_{soln} G^\circ = \Delta_{soln} H^\circ - T\Delta_{soln} S^\circ \tag{6}$$

Solving for $\Delta_{soln} G^\circ$ from equation (5), subsequently replacing $\Delta_{soln} G^\circ$ from equation (6), we obtain,

$$\ln x_3 = -\frac{\Delta_{soln} G^\circ}{RT} = \frac{\Delta_{soln} H^\circ - T\Delta_{soln} S^\circ}{RT} \tag{7}$$

$$\ln x_3 = -\frac{\Delta_{soln} H^\circ}{RT} + \frac{\Delta_{soln} S^\circ}{R} \tag{8}$$

So,

$$A = -\frac{\Delta_{soln} H^\circ}{RT}; B = \frac{\Delta_{soln} S^\circ}{R} \tag{9}$$

Buchowski-Ksiazaczak λh model

In 1980, based on the generalized relationship, the Buchowski-Ksiazaczak λh equation was first proposed, which contains two parameters and is widely used to correlate solubility data. The Buchowski-Ksiazaczak λh equation is shown in equation (10).

$$\ln\left[1 + \frac{\lambda(1 - x_3)}{x_3}\right] = \lambda h\left(\frac{1}{T} - \frac{1}{T_f}\right) \tag{10}$$

where λ and h are the two parameters of the λh model, and T_f represents the melting point of drug [35-37]. The model can be tested starting from the following identity [38]:

$$\frac{\partial \ln(1 - a_1)}{\partial \ln a_1} = \frac{-a_1}{1 - a_1} \tag{11}$$

Integrating the identity –equation (11)– into the equation of into the Gibbs-Duhem equation, we obtain,

$$\frac{-a_1}{1-a_1}\frac{x_3}{x_1}=\left(\frac{\partial \ln(1-a_1)}{\partial \ln a_3}\right)_T \equiv \lambda \tag{12}$$

In this way λ is related to activity and therefore to the concept of ideality.

Buchowski showed that when graphing $\ln(1-a)$ vs $1/T$, a linear function was obtained whose slope is λh

$$\frac{\partial \ln(1-a_3)}{\partial T^{-1}}=\lambda h \tag{13}$$

Integration of equation (13) from T_m to T gives equation (14).

$$-\ln(1-a_3)_{sat}=\lambda h\left(\frac{1}{T}-\frac{1}{T_m}\right) \tag{14}$$

where T_m is the melting temperature.

For the solubility curve, equation (14) is rearranged as:

$$\frac{\lambda(1-x_3)}{x_3}=\frac{a_1}{1-a_1} \tag{15}$$

Hence,

$$-\ln(1-a_1)=\ln\left[1+\lambda(1-x_3)/x_3\right] \tag{16}$$

So, equations (14) and (16) give the solubility curve:

$$\ln\left[1+\frac{\lambda(1-x_3)}{x_3}\right]_{sat}=\lambda h\left(\frac{1}{T}-\frac{1}{T_m}\right) \tag{17}$$

Equation (17) is equal to equation (10).

Results and discussion

The solubilities of sulfadiazine in mixtures of (methanol + water), (ethanol + water) and (1-propanol + water) were provided by Delgado and Martínez [6-8].

The experimental solubility data were correlated with the van't Hoff equation, Apelblat equation and Buchowski–Ksiazaczak λh equation, using the software with the Python version 3.8 using pandas and NumPy library, the parameters of the models were calculated with SciPy library and plots were made with Plotly library.

Table 1 shows the parameters of the equations of λh, van't Hoff and Apelblat, for the solubility of SD in (methanol + water) co-solvent mixtures. Although Delgado and Martínez implements the van't Hoff equation, the purpose is to calculate the thermodynamic functions as shown in other references [39-42], and not, to use the equation to calculate the solubility at different temperatures regarding the experimental ones [43, 44]. The melting temperature data, necessary for the development of the λh model, was taken from the literature (259.5 °C) [6].

Table 1. The λh, van't Hoff and Apelblat equations parameters for sulfadiazine in (methanol + water) cosolvent mixtures.

w_1	λh		van't Hoff		Apelblat		
	λ	h	a	b	A	B	C
0.0	0.012	453579.478	-5240.132	5.381	721.839	-37592.530	-106.700
0.1	0.024	231338.674	-5471.214	6.531	-450.653	15179.951	68.083
0.2	0.048	117837.137	-5637.581	7.547	-245.459	5818.116	37.662
0.3	0.102	55545.250	-5641.050	8.306	-873.483	34189.980	131.315
0.4	0.091	58195.968	-5271.480	7.499	127.882	-10687.332	-17.940
0.5	0.071	67026.233	-4794.893	6.372	-636.382	24238.424	95.718
0.6	0.065	68272.846	-4436.498	5.607	-453.188	16284.888	68.325
0.7	0.055	74423.661	-4130.908	4.883	-1134.337	47356.976	169.635
0.8	0.048	80928.039	-3886.460	4.284	-591.953	23047.998	88.790
0.9	0.042	87512.255	-3735.108	3.886	-461.868	17310.056	69.356
1.0	0.033	105595.312	-3502.490	3.205	44.861	-5385.482	-6.203

Table 2 shows the calculated solubility using each of the exposed models, and the relative deviation, calculated using equation (18) [45-48].

$$DR = 100\left(\left|x_3^{Exp} - x_3^{Cal}\right|\right)\left(x_3^{Exp}\right)^{-1} \quad (18)$$

Table 2. Calculated solubility of sulfadiazine in (methanol + water) mixtures expressed in mole fraction ($10^4 x_3$), from equations of λh, van't Hoff and Apelblat.

Buchowski–Ksiazaczak λh equation										
w_1	**293.15 K**	**RD**	**298.15 K**	**RD**	303.15 K	**RD**	**308.15 K**	**RD**	**313.15 K**	**RD**
0.0	0.375	1.326	0.506	5.195	0.676	4.788	0.895	1.771	1.174	2.988
0.1	0.538	1.459	0.736	0.185	0.996	2.230	1.335	1.045	1.772	1.603
0.2	0.843	0.841	1.163	1.791	1.589	0.202	2.149	2.153	2.878	0.960
0.3	1.780	6.404	2.457	4.582	3.357	4.038	4.540	0.833	6.082	2.702
0.4	2.801	1.866	3.786	2.549	5.068	0.200	6.720	0.015	8.831	0.557
0.5	4.613	2.671	6.068	0.347	7.911	3.472	10.226	1.072	13.111	2.139
0.6	7.291	2.672	9.396	0.525	12.008	4.118	15.227	0.660	19.165	1.223
0.7	10.019	3.404	12.686	1.356	15.940	4.728	19.883	4.183	24.632	3.907
0.8	12.674	2.996	15.824	1.819	19.617	1.607	24.153	1.704	29.547	2.066
0.9	14.267	0.861	17.659	1.638	21.708	2.939	26.513	1.268	32.183	1.657
1.0	15.960	1.356	19.493	1.955	23.657	0.316	28.538	1.515	34.229	0.633
van't Hoff equation										
0.0	0.375	1.328	0.506	5.199	0.676	4.784	0.895	1.769	1.174	2.980
0.1	0.538	1.464	0.736	0.185	0.996	2.234	1.335	1.049	1.772	1.605
0.2	0.843	0.838	1.163	1.790	1.589	0.199	2.149	2.155	2.878	0.962
0.3	1.779	6.410	2.457	4.582	3.357	4.041	4.540	0.836	6.082	2.701
0.4	2.800	1.862	3.786	2.546	5.068	0.204	6.720	0.013	8.831	0.551
0.5	4.613	2.684	6.068	0.347	7.912	3.479	10.227	1.079	13.111	2.140
0.6	7.290	2.689	9.396	0.526	12.010	4.129	15.228	0.650	19.164	1.226
0.7	10.015	3.438	12.685	1.360	15.942	4.742	19.887	4.201	24.633	3.902
0.8	12.670	3.028	15.825	1.820	19.620	1.625	24.157	1.721	29.546	2.070
0.9	14.262	0.893	17.659	1.635	21.713	2.960	26.518	1.285	32.180	1.665
1.0	15.955	1.384	19.495	1.965	23.663	0.341	28.542	1.501	34.221	0.610

(*Continued*)

Table 2. Calculated solubility of sulfadiazine in (methanol + water) mixtures expressed in mole fraction ($10^4 x_3$), from equations of λh, van't Hoff and Apelblat.

w_1	**293.15 K**	**RD**	**298.15 K**	**RD**	303.15 K	**RD**	**308.15 K**	**RD**	**313.15 K**	**RD**
Apelblat equation										
0.0	0.363	4.561	0.513	6.566	0.695	2.070	0.908	0.361	1.143	0.253
0.1	0.550	0.694	0.730	1.007	0.978	0.371	1.322	0.048	1.801	0.032
0.2	0.857	2.502	1.161	1.990	1.574	1.133	2.135	1.499	2.895	0.350
0.3	1.855	2.451	2.417	2.888	3.239	0.376	4.452	1.122	6.268	0.276
0.4	2.794	1.624	3.802	2.148	5.095	0.739	6.732	0.159	8.774	0.091
0.5	4.754	0.309	5.997	0.829	7.709	0.823	10.083	0.340	13.404	0.052
0.6	7.446	0.600	9.315	0.338	11.788	2.209	15.077	1.638	19.474	0.373
0.7	10.608	2.280	12.446	3.217	15.224	0.024	19.359	1.436	25.527	0.416
0.8	13.035	0.233	15.655	0.728	19.153	0.796	23.839	0.382	30.151	0.065
0.9	14.594	1.411	17.519	2.416	21.310	1.050	26.239	0.221	32.676	0.149
1.0	15.919	1.605	19.506	2.024	23.700	0.500	28.567	1.412	34.175	0.472

In all cases, the DR of the data calculated with respect to the experimental data is less than 7%. which indicates that the three models predict the solubility of SD in (methanol + water) cosolvent mixtures with good precision. When graphing the experimental data *vs.* the calculated data (figures 2, 3 y 4), linear holdings are obtained with correlation coefficients equal to 0.99, corroborating that these models show good agreement with the experimental solubility data.

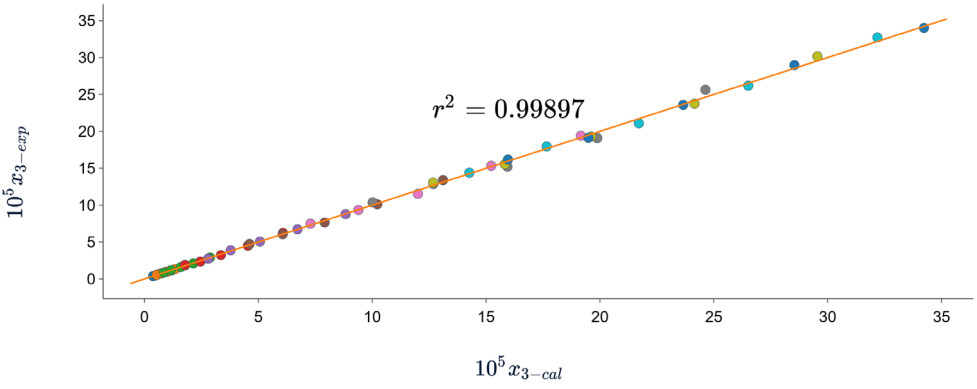

Figure 2. Experimental solubility *vs* calculated solubility by λh model of sulfadiazine in (methanol + water) mixtures.

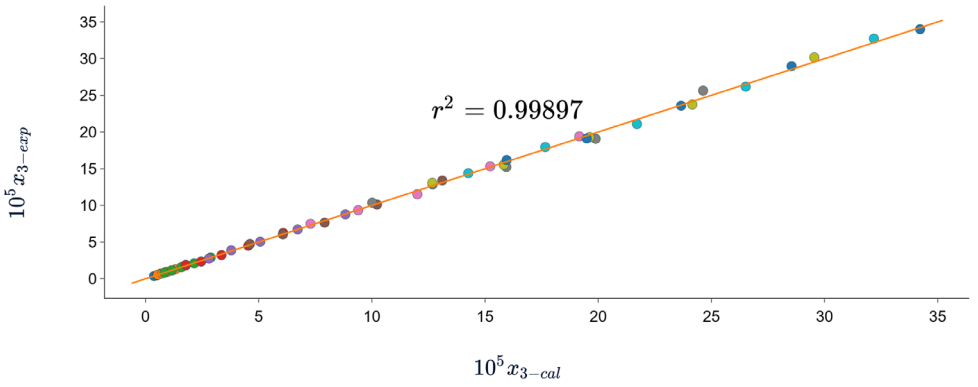

Figure 3. Experimental solubility *vs* calculated solubility by van't Hoff model of sulfadiazine in (methanol + water) mixtures.

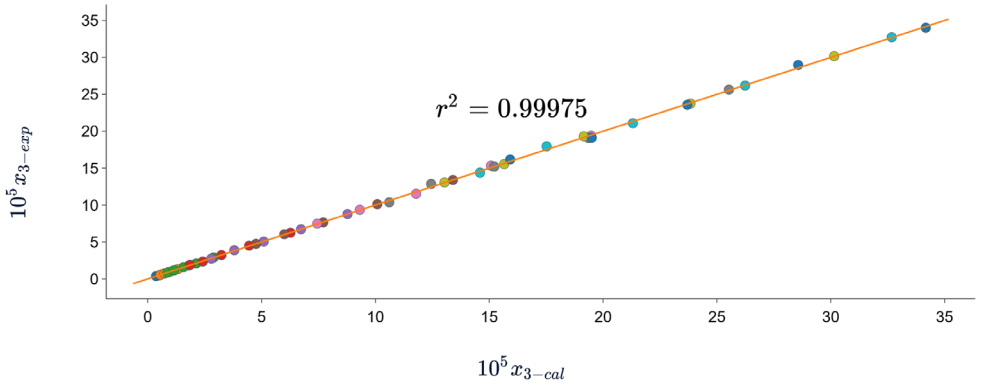

Figure 4. Experimental solubility *vs* calculated solubility by Apelblat model of sulfadiazine in (methanol + water) mixtures.

Table 3 shows the parameters of the equations of λh, van't Hoff and Apelblat, for the solubility of SD in (ethanol + water) cosolvent mixtures and table 4 shows the calculated solubility using each of the exposed models, and the relative deviation. As in the (methanol + water) cosolvent mixtures, the three models predict the solubility data of the SD, with good precision, in this case, the DR are less than 5%.

Table 3. The λh, van't Hoff and Apelblat equations parameters for sulfadiazine in (ethanol + water) cosolvent mixtures.

w_1	λh		van't Hoff		Apelblat		
	λ	h	a	b	A	B	C
0.0	0.012	452082.860	-5242.737	5.390	713.032	-37197.056	-105.387
0.1	0.017	298576.937	-5212.287	5.742	-48.821	-2742.779	8.123
0.2	0.052	105393.552	-5505.28	7.387	-459.017	15545.968	69.466
0.3	0.083	64173.623	-5324.945	7.512	-363.930	11469.983	55.305
0.4	0.041	108496.176	-4467.030	5.208	-203.729	4971.161	31.114
0.5	0.033	120784.624	-4031.583	4.188	-266.243	8182.280	40.273
0.6	0.035	110275.998	-3904.101	4.011	-190.160	4868.094	28.915
0.7	0.042	91475.436	-3893.641	4.175	312.345	-17810.217	-45.894
0.8	0.042	92808.419	-3869.417	4.110	-118.671	1681.403	18.282
0.9	0.031	123363.288	-3815.112	3.710	257.067	-15252.485	-37.734
1.0	0.016	220875.617	-3652.567	2.785	193.870	-12282.134	-28.457

Table 4. Calculated solubility of sulfadiazine in (ethanol + water) mixtures expressed in mole fraction ($10^4 x_3$), from equations of λh, van't Hoff and Apelblat.

	Buchowski–Ksiazaczak λh equation									
w_1	293.15 K	RD	298.15 K	RD	303.15 K	RD	308.15 K	RD	313.15 K	RD
0.0	0.375	1.341	0.506	5.196	0.676	4.771	0.895	1.736	1.175	2.948
0.1	0.592	0.462	0.797	1.131	1.063	1.363	1.405	1.017	1.841	0.305
0.2	1.128	4.139	1.545	2.761	2.095	3.675	2.814	0.790	3.742	1.354
0.3	2.364	0.262	3.205	0.558	4.303	0.203	5.722	2.533	7.541	1.481
0.4	4.406	0.515	5.687	1.153	7.281	2.692	9.248	0.449	11.658	0.544
0.5	7.022	0.893	8.841	0.464	11.048	2.141	13.710	0.087	16.898	0.855
0.6	9.082	0.400	11.351	0.003	14.086	0.039	17.360	1.221	21.258	0.854
0.7	11.087	0.162	13.849	0.058	17.177	0.968	21.159	2.789	25.896	1.773
0.8	11.285	0.351	14.077	1.180	17.435	0.594	21.449	0.785	26.218	0.540
0.9	9.107	0.090	11.325	1.677	13.985	2.169	17.155	0.429	20.911	1.058

(*Continued*)

Table 4. Calculated solubility of sulfadiazine in (ethanol + water) mixtures expressed in mole fraction ($10^4 x_3$), from equations of λh, van't Hoff and Apelblat.

w_1	**293.15 K**	**RD**	**298.15 K**	**RD**	303.15 K	**RD**	**308.15 K**	**RD**	**313.15 K**	**RD**
1.0	6.284	0.304	7.741	0.023	9.474	0.135	11.521	1.406	13.926	1.008
van't Hoff equation										
0.0	0.375	1.344	0.506	5.199	0.676	4.766	0.895	1.735	1.175	2.940
0.1	0.591	0.467	0.797	1.133	1.063	1.358	1.405	1.020	1.841	0.310
0.2	1.128	4.145	1.545	2.761	2.096	3.679	2.814	0.786	3.742	1.355
0.3	2.364	0.267	3.205	0.557	4.303	0.199	5.722	2.536	7.540	1.483
0.4	4.405	0.528	5.688	1.150	7.282	2.702	9.249	0.442	11.657	0.551
0.5	7.020	0.915	8.841	0.460	11.050	2.157	13.711	0.099	16.897	0.865
0.6	9.080	0.422	11.352	0.003	14.088	0.056	17.362	1.233	21.255	0.867
0.7	11.085	0.148	13.851	0.049	17.180	0.985	21.160	2.781	25.891	1.752
0.8	11.283	0.330	14.078	1.174	17.439	0.612	21.451	0.797	26.214	0.555
0.9	9.105	0.105	11.326	1.688	13.988	2.151	17.156	0.421	20.906	1.034
1.0	6.282	0.285	7.742	0.012	9.476	0.157	11.522	1.395	13.923	0.982
Apelblat equation										
0.0	0.363	4.561	0.513	6.566	0.695	2.070	0.908	0.361	1.143	0.253
0.1	0.550	0.694	0.730	1.007	0.978	0.371	1.322	0.048	1.801	0.032
0.2	0.857	2.502	1.161	1.990	1.574	1.133	2.135	1.499	2.895	0.350
0.3	1.855	2.451	2.417	2.888	3.239	0.376	4.452	1.122	6.268	0.276
0.4	2.794	1.624	3.802	2.148	5.095	0.739	6.732	0.159	8.774	0.091
0.5	4.754	0.309	5.997	0.829	7.709	0.823	10.083	0.340	13.404	0.052
0.6	7.446	0.600	9.315	0.338	11.788	2.209	15.077	1.638	19.474	0.373
0.7	10.608	2.280	12.446	3.217	15.224	0.024	19.359	1.436	25.527	0.416
0.8	13.035	0.233	15.655	0.728	19.153	0.796	23.839	0.382	30.151	0.065
0.9	14.594	1.411	17.519	2.416	21.310	1.050	26.239	0.221	32.676	0.149
1.0	15.919	1.605	19.506	2.024	23.700	0.500	28.567	1.412	34.175	0.472

Figures 5, 6 and 7 show the correlation between the experimental solubility data of SD in (ethanol + water) cosolvent mixtures and those calculated with the three models, in all cases the correlation coefficients are equal to or greater than 0.99.

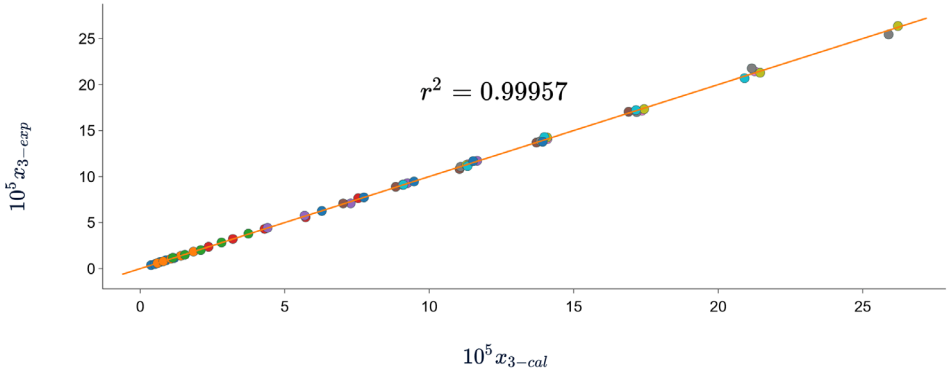

Figure 5. Experimental solubility *vs* calculated solubility by λh model of sulfadiazine in (ethanol + water) mixtures.

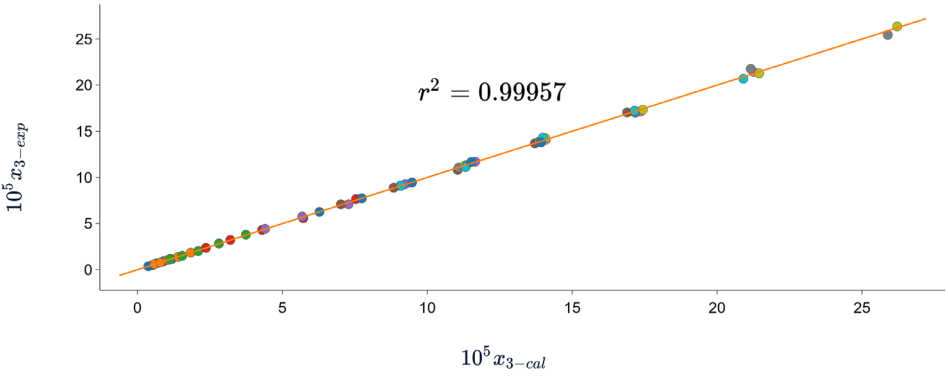

Figure 6. Experimental solubility *vs* calculated solubility by van't Hoff model of sulfadiazine in (ethanol + water) mixtures.

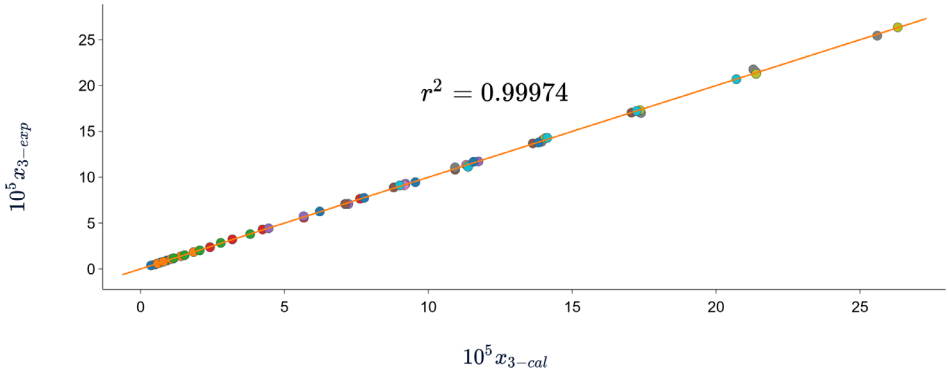

Figure 7. Experimental solubility *vs* calculated solubility by Apelblat model of sulfadiazine in (ethanol + water) mixtures.

Table 5 shows the parameters of the equations of λh, van't Hoff and Apelblat, for the solubility of SD in (1-propanol + water) cosolvent mixtures and table 6 shows the calculated solubility using each of the exposed models, and the relative deviation.

Table 5. The regression parameters of the Apelblat, van't Hoff, and λh model for sulfadiazine in (1-propanol + water) mixtures.

w_1	λh		van't Hoff		Apelblat		
	λ	h	a	b	A	B	C
0.0	0.012	451771.183	-5243.218	5.392	712.964	-37194.385	-105.377
0.1	0.016	314684.946	-4894.286	5.032	371.415	-21443.827	-54.561
0.2	0.022	214826.896	-4760.884	5.136	94.695	-8770.827	-13.357
0.3	0.043	107306.471	-4636.504	5.572	373.823	-21276.670	-54.836
0.4	0.055	83741.522	-4605.045	5.754	-172.781	3454.943	26.590
0.5	0.067	67398.827	-4537.686	5.831	-69.720	-1123.467	11.250
0.6	0.074	59687.244	-4436.373	5.741	166.048	-11686.808	-23.867
0.7	0.056	73997.588	-4171.041	4.970	-39.879	-2132.985	6.672
0.8	0.045	88738.406	-3996.161	4.422	-175.520	4134.765	26.795
0.9	0.029	132531.458	-3874.517	3.764	165.295	-11166.077	-24.058
1.0	0.016	248491.514	-3949.778	3.296	-427.185	15494.320	64.107

Table 6. Calculated solubility of sulfadiazine in (1-propanol + water) mixtures expressed in mole fraction ($10^4 x_3$), from equations of λh, van't Hoff and Apelblat.

	Buchowski–Ksiazaczak λh equation									
w_1	293.15 K	RD	298.15 K	RD	303.15 K	RD	308.15 K	RD	313.15 K	RD
0.0	0.375	1.342	0.506	5.197	0.676	4.770	0.895	1.736	1.175	2.948
0.1	0.860	0.856	1.138	0.643	1.491	0.373	1.938	2.213	2.498	1.678
0.2	1.505	1.653	1.976	1.035	2.572	3.044	3.318	2.431	4.247	0.091
0.3	3.556	0.135	4.635	0.915	5.990	0.090	7.678	2.591	9.764	1.774
0.4	4.753	1.420	6.184	1.561	7.978	0.055	10.208	0.461	12.961	0.645
0.5	6.455	2.143	8.368	3.534	10.754	1.629	13.711	0.533	17.348	0.214
0.6	8.334	1.577	10.740	2.261	13.726	0.651	17.406	2.347	21.908	1.072
0.7	9.537	0.496	12.105	1.541	15.245	2.492	19.059	1.882	23.662	0.382

(*Continued*)

Table 6. Calculated solubility of sulfadiazine in (1-propanol + water) mixtures expressed in mole fraction ($10^4 x_3$), from equations of λh, van't Hoff and Apelblat.

Buchowski–Ksiazaczak λh equation										
w_1	**293.15 K**	**RD**	**298.15 K**	**RD**	303.15 K	**RD**	**308.15 K**	**RD**	**313.15 K**	**RD**
0.8	10.006	1.358	12.573	1.946	15.681	1.178	19.422	1.384	23.896	0.761
0.9	7.849	1.704	9.795	3.547	12.135	1.733	14.933	1.002	18.258	0.980
1.0	3.801	1.935	4.764	1.137	5.926	0.934	7.321	1.486	8.986	1.596
van't Hoff equation										
0.0	0.375	1.344	0.506	5.200	0.676	4.766	0.895	1.735	1.175	2.940
0.1	0.860	0.851	1.138	0.640	1.492	0.380	1.938	2.210	2.498	1.669
0.2	1.505	1.648	1.976	1.031	2.572	3.037	3.318	2.435	4.247	0.082
0.3	3.555	0.142	4.635	0.919	5.991	0.098	7.678	2.587	9.763	1.764
0.4	4.752	1.431	6.184	1.563	7.979	0.064	10.209	0.468	12.960	0.651
0.5	6.455	2.154	8.368	3.537	10.755	1.620	13.712	0.539	17.347	0.221
0.6	8.333	1.587	10.740	2.265	13.728	0.661	17.407	2.341	21.906	1.063
0.7	9.536	0.510	12.105	1.546	15.247	2.479	19.061	1.890	23.659	0.394
0.8	10.004	1.378	12.573	1.951	15.684	1.162	19.424	1.395	23.893	0.772
0.9	7.848	1.721	9.795	3.556	12.137	1.716	14.934	0.993	18.254	0.960
1.0	3.800	1.962	4.764	1.140	5.927	0.952	7.322	1.500	8.985	1.603
Apelblat equation										
0.0	0.363	4.536	0.512	6.551	0.695	2.086	0.908	0.343	1.144	0.248
0.1	0.845	0.911	1.145	0.006	1.513	1.841	1.953	1.455	2.465	0.356
0.2	1.507	1.769	1.986	0.566	2.583	2.612	3.320	2.485	4.218	0.589
0.3	3.490	1.992	4.662	1.508	6.077	1.546	7.739	1.810	9.642	0.504
0.4	4.789	0.662	6.162	1.196	7.921	0.661	10.171	0.097	13.046	0.013
0.5	6.479	1.787	8.357	3.401	10.722	1.923	13.688	0.360	17.388	0.016
0.6	8.256	2.490	10.761	2.460	13.811	1.272	17.471	1.981	21.801	0.579
0.7	9.573	0.116	12.108	1.567	15.223	2.633	19.032	1.735	23.666	0.367
0.8	10.094	0.492	12.535	1.642	15.571	1.871	19.345	0.984	24.035	0.183
0.9	7.793	2.416	9.826	3.882	12.215	1.084	14.981	0.683	18.140	0.327
1.0	3.878	0.039	4.726	0.341	5.825	0.789	7.254	0.551	9.121	0.120

According to the results shown in table 6 and figures 8, 9 and 10, in which the experimental and calculated solubility are compared. the three solubility models, including Apelblat model, Buchowski-Ksiazaczak λh equation and van't Hoff model, were applied to fit with experimental data obtaining a good predictability of the experimental data, since the DR values do not exceed 5%.

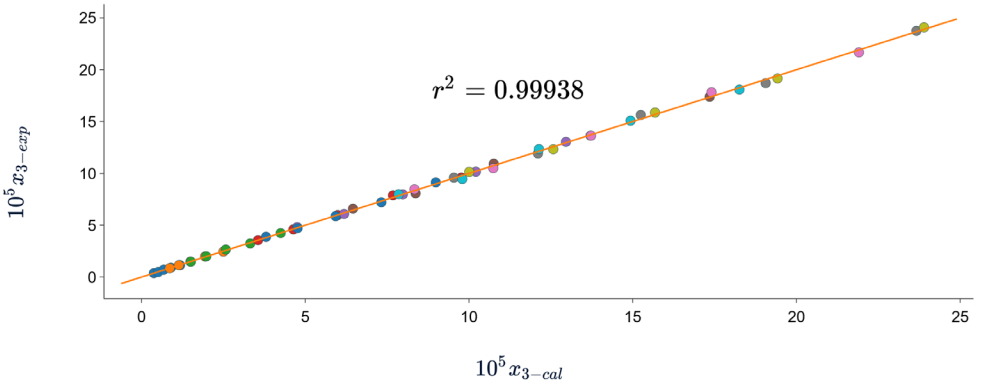

Figure 8. Experimental solubility *vs* calculated solubility by λh model of sulfadiazine in (1-propanol + water mixtures) mixtures.

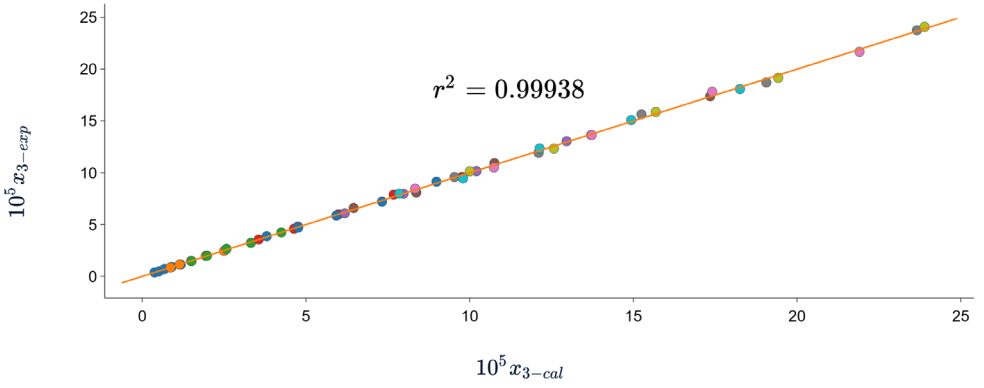

Figure 9. Experimental solubility *vs* calculated solubility by van't Hoff model of sulfadiazine in (1-propanol+ water) mixtures.

In general terms, from the results shown in tables 2, 4, 6 and figures 2-10, it can be observed that the Apelblat model, Buchowski-Ksiazaczak λh equation and van't Hoff model gave almost the same goodness of fit to the experimental data. Error percentages of the predicted solubility values obtained from calculations using both models were below 5%, except for one point of SD solubility in (methanol + water) mixtures

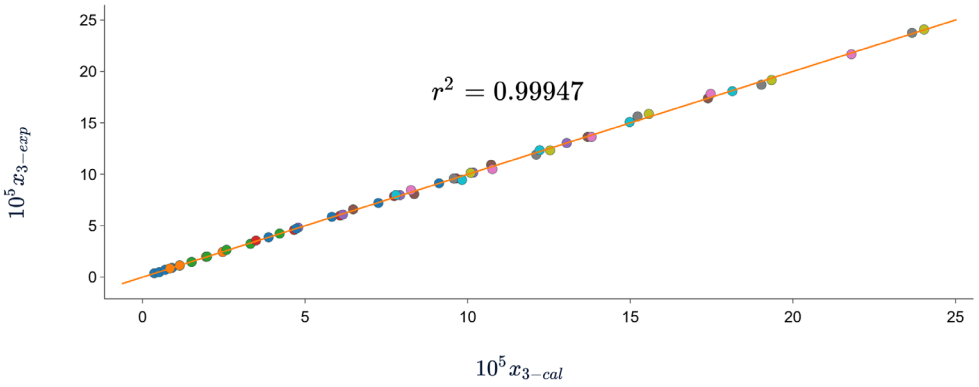

Figure 10. Experimental solubility *vs* calculated solubility by Apelblat model of sulfadiazine in (1-propanol+ water) mixtures.

(w_3 at 293.15 K). The goodness of fit of these equations can also be seen from the r^2 values listed in figures 2-10, which are almost unity. Buchowski *et al.* [38] stated that in an ideal solution, the value of λ equals to 1. The values of the obtained equation parameter (λ) in tables 2, 4 and 6 showed that the SD in (methanol + water), (ethanol + water) and (1-propanol + water) cosolvent mixtures, understandably were nonideal. This agrees with Delgado and Martínez [6-8], who reported that solution of SD in some cosolvent mixtures are highly non-ideal.

Acknowledgements

The authors gratefully acknowledge support from the Faculty of Science and Humanities and Research Direction of the Fundación Universidad de América.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

1. R.S. Vardanyan, V.J. Hruby, *Synthesis of Essential Drugs*, Elsevier, Amsterdam (Netherlands), 2006, pp. 499-523.

2. H. Li, L. Duan, H. Wang, Y. Chen, F. Wang, S. Zhang, Photolysis of sulfadiazine under UV radiation: Effects of the initial sulfadiazine concentration, pH, NO^{3-} and Cd^{2+}, *Chem. Phys. Lett.*, **739**, 136949 (2020).

3. K. Kümmerer, A. Al-Ahmad, V. Mersch-Sundermann, Biodegradability of some antibiotics, elimination of the genotoxicity and affection of wastewater bacteria in a simple test, *Chemosphere*, **40**, 701-710 (2000).

4. D.R. Delgado, F. Martínez, Solubility and solution thermodynamics of sulfamerazine and sulfamethazine in some ethanol + water mixtures, *Fluid Phase Equilib.*, **360**, 88-96 (2013).

5. S.H. Yalkowsky, *Solubility and solubilization in aqueous media*, American Chemical Society and Oxford University Press, New York (NY), 1999.

6. D.R. Delgado, F. Martínez, Solution thermodynamics of sulfadiazine in some ethanol + water mixtures, *J. Mol. Liq.*, **187**, 99-105 (2013).

7. D.R. Delgado, F. Martínez, Solubility and solution thermodynamics of some sulfonamides in 1-propanol + water mixtures, *J. Solution Chem.*, **43**, 836-852 (2014).

8. D.R. Delgado, F. Martínez, Solubility and preferential solvation of sulfadiazine in methanol + water mixtures at several temperatures, *Fluid Phase Equilib.*, **379**, 128-138 (2014).

9. D.M. Jiménez, Z.J. Cárdenas, D.R. Delgado, M.A. Peña, F. Martínez, Solubility temperature dependence and preferential solvation of sulfadiazine in 1,4-dioxane + water co-solvent mixtures, *Fluid Phase Equilib.*, **397**, 26-36 (2015).

10. M.M. Muñoz, D.R. Delgado, M.Á. Peña, A. Jouyban, F. Martínez, Solubility and preferential solvation of sulfadiazine, sulfamerazine and sulfamethazine in propylene glycol + water mixtures at 298.15 K, *J. Mol. Liq.*, **204**, 132-136 (2015).

11. S. Akay, B. Kayan, D. Cunbin, J. Wang, Y. Yang, Research of sulfadiazine using subcritical water and water + alcohol mixtures as the solvent: Solubility and thermodynamic property, *J. Mol. Liq.*, **253**, 270-276 (2018).

12. D.R. Delgado, G.A. Rodríguez, J.A. Martínez, J.H. Rojas, F. Martínez, Validación de una metodología analítica empleando espectrofotometría ultravioleta para el estudio de la solubilidad de algunas sulfonamidas en mezclas cosolventes alcohol + agua, *Rev. Colomb. Quim.*, **42**, 31-40 (2013).

13. S. Zadaliasghar, E. Rahimpour, T. Ghafourian, F. Martínez, M. Barzegar-Jalali, A. Jouyban, Measurement and mathematical modeling of ketoconazole solubility in propylene glycol + water mixtures at various temperatures, *J. Mol. Liq.*, **291**, 111246 (2019).

14. H. Kishi, Y. Hashimoto, Evaluation of the procedures for the measurement of water solubility and n-octanol/water partition coefficient of chemicals results of a ring test in Japan, *Chemosphere*, **18**, 1749-1759 (1989).

15. A.Y. Lin, K.T. Cheng, S.C. Chen, H.W. Tsui, Effect of solvent composition on the van't Hoff enthalpic curve using amylose 3,5-dichlorophenylcarbamate-based sorbent, *J. Chromatogr. A*, **1515**, 179-186 (2017).

16. F. Shakeel, N. Haq, N.A. Siddiqui, F.K. Alanazi, I.A. Alsarra, Thermodynamics of the solubility of reserpine in {2-(2-ethoxyethoxy)ethanol + water} mixed solvent systems at different temperatures, *J. Chem. Thermodyn.*, **85**, 57-60 (2015).

17. M.A. Ruidiaz, D.R. Delgado, F. Martínez, Performance of the Jouyban-Acree and Yalkowsky-Roseman models for estimating the solubility of indomethacin in ethanol+ water mixtures, *Rev. Acad. Colomb. Cienc.*, **35**, 329-336 (2011).

18. X. Hu, Y. Tian, Z. Cao, J. Sha, Z. Huang, Y. Li, T. Li, B. Ren, Solubility measurement, Hansen solubility parameter and thermodynamic modeling of etodolac in four binary solvents from 278.15 K to 323.15 K, *J. Mol. Liq.*, **318**, 114155 (2020).

19. D.R. Delgado, G.A. Rodríguez, A.R. Holguín, F. Martínez, A. Jouyban, Solubility of sulfapyridine in propylene glycol + water mixtures and correlation with the Jouyban-Acree model, *Fluid Phase Equilib.*, **341**, 86-95 (2013).

20. G.A. Rodríguez, D.R. Delgado, F. Martínez, A. Jouyban, W.E. Acree Jr., Solubility of naproxen in ethyl acetate+ethanol mixtures at several temperatures and correlation with the Jouyban-Acree model, *Fluid Phase Equilib.*, **320**, 49-55 (2012).

21. I.P. Osorio, F. Martínez, D.R. Delgado, A. Jouyban, W.E. Acree Jr., Solubility of sulfacetamide in aqueous propylene glycol mixtures: Measurement, correlation, dissolution thermodynamics, preferential solvation and solute volumetric contribution at saturation, *J. Mol. Liq.*, **297**, 111889 (2020).

22. D.J.W. Grant, M. Mehdizadeh, A.H.L. Chow, J.E. Fairbrother, Non-linear van't Hoff solubility-temperature plots and their pharmaceutical interpretation, *Int. J. Pharm.*, **18**, 25-38 (1984).

23. G.A.M. Areiza-Aldana, A. Cuellar-Lozano, N.A. Peña-Carmona, D.I. Caviedes-Rubio, A. Mehrdad, A. Hossein-Miri, G.A. Rodríguez-Rodríguez, D.R. Delgado, Solution thermodynamics and preferential solvation of 3-chloro-*N*-phenylphthalimide in acetone + methanol mixtures, *Rev. Colomb. Cienc. Quím. Farm.*, **45**, 256-274 (2016).

24. D.R. Delgado, M.A. Peña, F. Martínez, A. Jouyban, W.E. Acree Jr., Further numerical analyses on the solubility of sulfapyridine in ethanol + water mixtures, *Pharm. Sci. (Tabriz)*, **22**, 143-152 (2016).

25. A.M. Romero-Nieto, N.E. Cerquera, D.R. Delgado, Measurement and correlation of solubility of ethylparaben in pure and binary solvents and thermodynamic properties of solution, *Rev. Colomb. Cienc. Quím. Farm.*, **48**, 332-347 (2019).

26. A.T. Williamson, The exact calculation of heats of solution from solubility data, *Trans. Faraday Soc.*, **40**, 421-436 (1944).

27. A. Apelblat, E. Manzurola, N.A. Balal, The solubilities of benzene polycarboxylic acids in water, *J. Chem. Thermodyn.*, **38**, 565-571 (2006).

28. A. Noubigh, M.H. Oueslati, Measurement and modeling of the solubility of vanillin constituent of olive mill wastewater in binary water + ethanol solvents mixtures between 278.15 K and 308.15 K, *Austr. J. Basic Appl. Sci.*, **8**, 396-403 (2014).

29. R. Heryanto, M. Hasan, E.C. Abdullah, A.C. Kumoro, Solubility of stearic acid in various organic solvents and its prediction using non-ideal solution models, *ScienceAsia*, **33**, 469-472 (2007).

30. J. Cuevas-Valenzuela, Á. González-Rojas, J. Wisniak, A. Apelblat, J.R. Pérez-Correa, Solubility of (+)-catechin in water and water-ethanol mixtures within the temperature range 277.6-331.2 K: Fundamental data to design polyphenol extraction processes, *Fluid Phase Equilib.*, **382**, 279-285 (2015).

31. A.M. Romero-Nieto, D.I. Caviedes-Rubio, J. Polania-Orozco, N.E. Cerquera, D.R. Delgado, Temperature and cosolvent composition effects in the solubility of methylparaben in acetonitrile + water mixtures, *Phys. Chem. Liq.*, Forthcoming 2020, doi: 10.1080/00319104.2019.1636379.

32. D.R. Delgado, A. Holguin, F. Martínez, Solution thermodynamics of triclosan and triclocarban in some volatile organic solvents, *Vitae, Rev. Fac. Quim. Farm.*, **19**, 79-92 (2012).

33. D.M. Jiménez, Z.J. Cárdenas, D.R. Delgado, A. Jouyban, F. Martínez, Solubility and solution thermodynamics of meloxicam in 1,4-dioxane and water mixtures, *Ind. Eng. Chem. Res.*, **53**, 16550-16558 (2014).

34. E.A. Ahumada, D.R. Delgado, F. Martínez, Solution thermodynamics of acetaminophen in some PEG 400 + water mixtures, *Fluid Phase Equilib.*, **332**, 120-127 (2012).

35. A. Ksiazczak, J.J. Kosinski, Vapour pressure of binary, three-phase (S-L-V) systems and solubility, *Fluid Phase Equilib.*, **44**, 211-236 (1988).

36. A. Ksiazczak, K. Moorthi, I. Nagata, Solid-solid transition and solubility of even n-alkanes, *Fluid Phase Equilib.*, **95**, 15-29 (1994).

37. S. Krajangsod, S. Chotikamas, A. Tawai, M. Sriariyanun, Measurement and thermodynamic modelling of erythritol solubility in aqueous solvents, *Oriental J. Chem.*, **34**, 265-275 (2018).

38. H. Buchowski, A. Ksiazczak, S. Pietrzyk, Solvent activity along a saturation line and solubility of hydrogen-bonding solids, *J. Phys. Chem.*, **84**, 975-979 (1980).

39. D.R. Delgado, M.A. Ruidiaz, S.M. Gómez, M. Gantiva, F. Martínez, Thermodynamic study of the solubility of sodium naproxen in some ethanol + water mixtures, *Quim. Nova*, **33**, 1923-1927 (2010).

40. A.R. Holguín, D.R. Delgado, F. Martínez, Thermodynamic study of the solubility of triclocarban in ethanol + propylene glycol mixtures, *Quim. Nova*, **35**, 280-285 (2012).

41. K.C. Mercado, G.A. Rodríguez, D.R. Delgado, F. Martínez, A. Romdhani, Solution thermodynamics of methocarbamol in some ethanol + water mixtures, *Quim. Nova*, **35**, 1967-1972 (2012).

42. J.H. Blanco-Márquez, Y.A. Quigua-Medina, J.D. García-Murillo, J.K. Castro-Camacho, C.P. Ortiz, N.E. Cerquera, D.R. Delgado, Thermodynamic analysis and applications of the Abraham solvation parameter model in the study of the solubility of some sulfonamides, *Rev. Colomb. Cienc. Quím. Farm.*, **49**, 234-255 (2020).

43. C. Holm, M. Zaman, Regulating audit quality: Restoring trust and legitimacy, *Account. Forum*, **36**, 51-61 (2012).

44. J. Tritschler, *Audit quality: Association between published reporting errors and audit firm characteristics*, (Ph. D. thesis, University of Innsbruck, 2013), Springer-Gabler, 2014.

45. M.A. Ruidiaz, D.R. Delgado, F. Martínez, Indomethacin solubility estimation in 1,4-dioxane + water mixtures by the extended Hildebrand solubility approach, *Quim. Nova*, **34**, 1569-1574 (2011).

46. D.R. Delgado, M.Á. Peña, F. Martínez, Extended Hildebrand solubility approach applied to sulphadiazine, sulphamerazine and sulphamethazine in some {1-propanol (1) + water (2)} mixtures at 298.15 K, *Phys. Chem. Liq.*, **57**, 388-400 (2019).

47. M. Ruidiaz, D.R. Delgado, F. Martínez, Correlating the solubility of indomethacin in 1,4-dioxane + water mixtures by means of the Jouyban-Acree model, *Rev. Colomb. Cienc. Quím. Farm.*, **39**, 211-226 (2010).

48. F. Almanza, A.R. Holguín, D.R. Delgado, F. Martínez, A. Jouyban, Solution thermodynamics of sodium diclofenac in ethanol + water mixtures and correlation with the Jouyban-Acree model, *Lat. Am. J. Pharm.*, **31**, 427-436 (2012).

How to cite this article

R.E. Cardenas, L.E. Tinoco, D.M. Galindres, A. Beltrán, C.D. Oviedo, J. Osorio, Prediction of sulfadiazine solubility in some cosolvent mixtures using non-ideal solution models, *Rev. Colomb. Cienc. Quím. Farm.*, **49**(3), 822-842 (2020).