Scientific research article / *http://dx.doi.org/10.15446/rcciquifa.v50n3.100240*

Extended Hildebrand solubility approach and Yalkowsky-Roseman model for estimating the solubility of sulfadiazine and sulfamethazine in some {ethylene glycol (1) + water (2)} mixtures at several temperatures

Martha Sofía Vargas-Santana[1,2], Ana María Cruz-González[1,2], Nestor Enrique Cerquera[3], Alana Sofia Escobar Rodriguez[2], Rossember E. Cardenas[4], Omar Calderón-Losada[4], Claudia Patricia Ortiz[5], Daniel Ricardo Delgado[6*]

[1] Environmental Management and Engineering, Universidad Surcolombiana, Colombia.

[2] Sifati Group Ingeniería S.A.S., Grupo de Investigaciones Ciencia, Ingeniería e Innovación, Palermo, Huila, Colombia.

[3] Universidad Surcolombiana, Faculty of Engineering, Agricultural Engineering Program, Hydro Engineering and Agricultural Development Research Group (GHIDA), Avenida Pastrana Borrero-Carrera 1, Neiva, Huila, Colombia.

[4] Grupo de Fisicoquímica y Análisis Matemático, Facultad de Ciencias y Humanidades, Fundación Universidad de América, Avenida Circunvalar N.° 20-53, Bogotá D.C., Colombia.

[5] Corporación Universitaria Minuto de Dios-UNIMINUTO, Programa de Administración en Salud Ocupacional, Grupo de Investigación en Seguridad y Salud en el Trabajo, Neiva, Huila, Colombia.

[6] Universidad Cooperativa de Colombia, Department of Engineering, Grupo de Investigación de Ingenierías UCC-Neiva, Calle 11 N.° 1-51, Neiva, Huila, Colombia.

*Address for correspondence: danielr.delgado@campusucc.edu.co

Received: March 22, 2021

Corrected: April 27, 2021

Accepted: May 4, 2021

Summary

Aim: extended Hildebrand Solubility Approach (EHSA) and Yalkowsky Roseman (YR) were applied to evaluate the solubility of sulfadiazine, and sulfamethazine in ethylene glycol + water mixtures. **Methodology:** reported experimental equilibrium solubilities and some fusion properties of these drugs were used for the calculations.

Results: a good predictive character of EHSA (with mean deviations lower than 3.0%) were found by using regular polynomials in order two correlating the interaction parameter *W* with the Hildebrand solubility parameter of solvent mixtures without drug; however, the results obtained from YR model show relatively high deviations greater than 50%.

Key-words: Sulfadiazine, sulfamethazine, extended Hildebrand model, Yalkowsky-Roseman, solubility, cosolvent mixtures.

Resumen

Método extendido de Hildebrand y modelo de Yalkowsky-Roseman en la estimación de la solubilidad de sulfadiazina y sulfametazina en algunas mezclas {etilenglicol (1) + agua (2)} a varias temperaturas

Objetivo: aplicar los enfoques de los modelos de Solubilidad Extendido de Hildebrand (EHSA) y Yalkowsky Roseman (YR) para evaluar la solubilidad de sulfadiazina y sulfametazina en mezclas de etilenglicol + agua. **Metodología:** para los cálculos se utilizaron las solubilidades experimentales en equilibrio reportadas y algunas propiedades de fusión de estos fármacos. **Resultados:** en particular, se encontró un buen carácter predictivo de EHSA (con desviaciones medias inferiores al 3,0%) utilizando polinomios regulares en orden dos correlacionando el parámetro de interacción *W* con el parámetro de solubilidad de Hildebrand de mezclas de disolventes sin fármaco; sin embargo, los resultados obtenidos del modelo YR muestran desviaciones relativamente altas superiores al 50%.

Palabras clave: Sulfadiazina, sulfametazina, método extendido de Hildebrand, Yalkowsky-Roseman, solubilidad, mezclas cosolventes.

Resumo

Método de Hildebrand estendido e modelo de Yalkowsky-Roseman na estimativa da solubilidade de sulfadiazina e sulfametazina em algumas misturas {etileno glicol (1) + água (2)} em várias temperaturas

Objetivo: aplicar as abordagens dos modelos de Solubilidade Estendida de Hildebrand (EHSA) e Yalkowsky Roseman (YR) para avaliar a solubilidade de sulfadiazina e sulfametazina em misturas de etilenoglicol + água. **Metodologia:** as solubilidades de equilíbrio experimental relatadas e algumas propriedades de fusão dessas drogas foram usadas para os cálculos. **Resultados:** em particular, foi encontrado um bom caráter preditivo de EHSA (com desvios médios menores que 3,0%) usando polinômios regulares na ordem dois, correlacionando o parâmetro de interação *W* com o parâmetro de solubilidade de Hildebrand de misturas de solventes sem fármaco; no entanto, os resultados obtidos com o modelo YR mostram desvios relativamente altos superiores a 50%.

Palavras-chave: Sulfadiazina, sulfametazina, método estendido de Hildebrand, Yalkowsky-Roseman, solubilidade, misturas de cossolventes.

Introduction

Sulfonamides are a group of synthetic organic compounds that have played an important role as effective chemotherapeutics in bacterial and protozoal infections in veterinary medicine. Indications for sulfonamides are wide against both Gram negative and Gram-positive bacteria, owing to their wide spectrum of activity. Sulfonamides are used to treat infectious diseases of the digestive and respiratory tracts, secondary infections, mastitis, metritis, and foot rot [1-3]. All drugs of the sulfonamide group are currently included in Council Regulation (EEC) N.°2377/90 of 26 June 1990 laying down a community procedure for the establishment of maximum residue limits of veterinary medicinal products in foodstuffs of animal origin [4]. So, the existing EU Maximum Residue Levels (MRLs) for all drugs of the sulfonamide group is 100 μg/kg in all food-producing species [5].

Sulfadiazine (SD, 4-amino-N-2-pyrimidinylbenzenesulphonamide, molar mass 250.28 $g.mol^{-1}$, CAS number 68–35-9, molecular structure shown in figure 1) is a sulfonamide drug employed sometimes in human and veterinarian therapeutics because it exhibits a wide spectrum against most gram-positive and gram-negative organisms [6-9]. It inhibits the multiplication of bacteria by acting as a competitive inhibitor of p-aminobenzoic acid in the folic acid metabolism cycle [1, 10-12]. In spite of its continuous therapeutical use its equilibrium solubility data in aqueous-cosolvent mixtures is not yet complete [13].

Sulfamethazine, (SMT, *N*1-(4,6-dimethyl-2-pyrimidinyl) sulfanilamide, figure 1), is broadly used in veterinary medicine to treat infectious diseases. SMT abuse in veterinary practice may lead to the presence of SMT residues in food; these residues are harmful to consumers because of their carcinogenic potential and risk of developing antibiotic resistance [14-16].

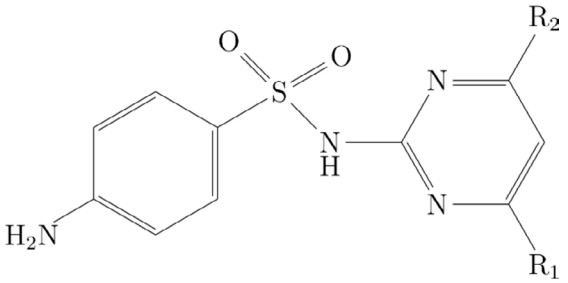

Figure 1. Molecular structure of the sulfonamides considered. Sulfadiazine: R_1 and R_2 = H.

Sulfamethazine: R_1 and R_2 = CH_3.

SMT has a low aqueous solubility, so solubility studies of this therapeutic agent are important. And within research related to solubility, co-solvency is perhaps the most relevant strategy to increase the solubility of a drug.

The other hand, that predictive methods of physicochemical properties of drugs, in particular those intended for estimating their solubilities in neat solvents and in solvent mixtures, are very important for pharmaceutical and chemical industries [17]. This is because these calculating methods could allow the optimization of several design and development processes. Thus, two of the most widely used methods for predicting solubility in co-solvent mixtures are the Yalkowsky-Roseman (YR) [18, 19] model and extended Hildebrand solubility approach (EHSA) [20-23].

This work presents a physicochemical study about the solubility prediction of SD and SMT in binary mixtures conformed by ethylene glycol + water. The study was done based on the Yalkowsky-Roseman (YR) model and extended Hildebrand solubility approach (EHSA) by using experimental solubility values and some properties relative to the fusion of this drug [24], evaluating the relevance of these models, in predicting the solubility of SD and SMR in the ethylene glycol + water cosolvent system, at different temperatures, to strengthen the data bases, related to the solubility of these drugs, providing a tool that offers reliable information, for the development of processes that involve these drugs and the solvents used.

Theoretical

Yalkowsky-Roseman model

The logarithmic solubilities of Yalkowsky-Roseman (YR) model for a solute in the different solvent mixtures including neat solvents were determined with the help of equation [18, 25, 26].

$$\ln x_{3,1+2} = f_1 \ln x_{3,1} + f_2 \ln x_{3,2} \tag{1}$$

where $x_{3,1+2}$ is the drug solubility calculated in the cosolvent mixture considered, $x_{3,1}$ is the drug solubility in the neat cosolvent, $x_{3,2}$ is the drug solubility in neat water, and f is the volume fraction of cosolvent in the mixed solvent. This last term is calculated assuming

$$f_1 = V_1(V_1 + V_2)^{-1} \tag{2}$$

where, V_1 and V_2 are the respective volumes of cosolvent and water.

The equation 1 can be written as [27]:

$$\ln x_{3,1+2} = \ln x_{3,2} + f_1\left(\ln x_{3,1} - \ln x_{3,2}\right) \tag{3}$$

which suggests a linear relationship between ln $x_{3,1+2}$ and solvent composition [27]. This exponential increase in solubility with cosolvent composition has been repeatedly observed in the literature [27].

Extended Hildebrand Solubility Approach

The extended Hildebrand solubility approach (EHSA), a modification of the Hildebrand-Scatchard equation, permits calculation of the solubility of polar and non-polar solutes in solvents ranging from non-polar hydrocarbons to highly polar solvents such as water, ethanol, and glycols [28]. The solubility parameters of solute and solvent were introduced to explain the behavior of regular and irregular solutions [29, 30]. The extended Hildebrand solubility approach has been developed to reproduce the solubility of drugs and other solids in the binary solvent systems [31-33].

Solubility on the mole fraction scale, x_3, may be represented by the equation:

$$-\log x_3 = -\log x_3^{\mathrm{id}} + \log \gamma_3 \tag{4}$$

where x_3^{id} is the ideal solubility of the crystalline solid, and γ_3 is the solute activity coefficient in mole fraction terms. Scatchard [34] and Hildebrand and Scott [35] formulated the solubility equation for regular solutions:

$$\log \frac{a_3}{x_3} = \log \gamma_3 = \frac{V_3 \emptyset_1^2}{2.30RT}(e_{11} + e_{33} - 2e_{13}) \tag{5}$$

where

$$\emptyset_1 = \frac{V_1(1-x_3)}{V_1(1-x_3)+V_3 x_3} \tag{6}$$

V_3 is the molar volume of the hypothetical supercooled liquid solute (subscript 3), ϕ_1 is the volume fraction of the solvent (subscript l), R is the molar gas constant, and T is the absolute temperature of the experiment.

The terms e_{11} and e_{22} are the cohesive energy densities of solvent and solute, and e_{12} is expressed in regular solution theory as a geometric mean of the solvent and solute cohesive energy densities and is expressed as W in this work [30, 36, 37]:

$$e_{13} = W = \sqrt{e_{11}e_{33}} \tag{7}$$

The square roots of the cohesive energy densities of solute and solvent, called solubility parameters and given the symbol , are obtained for the solvent from the energy or heat of vaporization per volume:

$$\delta_i = \sqrt{e_{ii}} = \sqrt{\frac{\Delta E^v}{V_i}} \cong \left(\frac{\Delta H^v - RT}{V_i}\right)^{1/2} \tag{8}$$

Replacing e_{ii} with , in equation 5, the expression becomes:

$$\log \gamma_3 = \frac{V_3 \emptyset_1^2}{2.30RT}(\delta_1^2 + \delta_3^2 - 2\delta_1\delta_3) \tag{9}$$

replacing the first term by , and factoring the second one:

$$\log \gamma_3 = A(\delta_1 - \delta_3)^2 \tag{10}$$

Substituting equation 10 into equation 4, one obtains the Hildebrand-Scatchard solubility equation [38]:

$$-\log x_3 = -\log x_3^{\mathrm{id}} + A(\delta_1 - \delta_3)^2 \tag{11}$$

where

$$-\log x_3^{\mathrm{id}} = -\frac{\Delta H_{fus}(T_{fus}-T)}{2.303T_{fus}} + \frac{\Delta C_P}{2.303R}\left(\frac{T_{fus}-T}{T} + \ln\frac{T}{T_{fis}}\right) \tag{12}$$

Where ΔH_{fus} is the molar enthalpy of fusion of the pure solute (at the melting point), T_{fus} is the absolute melting point, T is the absolute solution temperature, R is the constant gas (8.314 J·mol^{-1}·K^{-1}) and ΔC_p is the difference between the molar heat capacity of the crystalline form and the molar heat capacity of the hypothetical supercooled liquid form, both at the solution temperature. Since ΔC_p values are not commonly reported, they may be approximated to the entropy of fusion, ΔS_{fus} calculated as follows:

$$\Delta C_P = \Delta S_{fus} = \Delta H_{fus} T_{fus}^{-1} \tag{13}$$

replacing $\delta_1\delta_3$ by W, equation 9 becomes

$$\log \gamma_3 = A(\delta_1^2 + \delta_3^2 - 2W) \tag{14}$$

So, equation 4 is rewritten as [39, 40]

$$-\log x_3 = -\log x_3^{\mathrm{id}} + A(\delta_1^2 + \delta_3^2 - 2W) \tag{15}$$

Here, the term is equal to (where, is the Walker parameter). The factor can be calculated from experimental data by means of [41, 42]:

$$W = \frac{\delta_1^2+\delta_3^2-\frac{\log\gamma_3}{A}}{2} \tag{16}$$

The experimental values of the W parameter can be correlated by means of regression analysis by using regular polynomials as a function of δ_1 as follows [36, 43]:

$$W = C_0 + C_1\delta_1 + C_2\delta_1^2 + C_3\delta_1^3 \ldots\ldots C_n\delta_1^n \tag{17}$$

These empiric models can be used to estimate the drug solubility by means of back-calculation, resolving this property from the specific value obtained in the respective polynomial regression [38, 44].

Results and discussion

The experimental solubility data of SD and SMT in (EG + W) cosolvent mixtures were taken from Cruz *et al.* [6] and Adi *et al.* [24]. Table 1 presents basic information for the development of the YR and EHSA models.

Table 1. Some properties of the sulfadiazine and sulfamethazine.

Sulfonamide	Molar mass ($g \cdot mol^{-1}$) [45]	x_3^{id} (298.15 K) [46]	V_3 ($cm^3 \cdot mol^{-1}$) [47]	δ_3 ($MPa^{1/2}$) [46]	T_{fus} (K) [45]	ΔH_{fus} ($kJ \cdot mol^{-1}$) [45]
Sulfadiazine	250.277	30.14±0.12	150.0	28.9	532.6	44.25±0.38
Sulfamethazine	278.33	6.48±0.22	179.0	27.4	468.95	39.22±0.71

The volumetric behavior and polarity of (EG+ W) mixtures, as a function of the composition, are shown in table 2. Volume fractions and Hildebrand solubility parameters were calculated assuming additive behavior.

Table 2. Some physicochemical properties of pure solvents and (EG + W) cosolvent mixtures (298.15 K).

w_1	x_1	ρ (g/cm^3)[a]	f_1	δ_{mix} ($MPa^{1/2}$)	V_{mix} ($cm^3 \cdot mol^{-1}$)
0.00	0.000	0.9971	0.000	47.9	18.07
0.05	0.015	1.0033	0.045	47.3	18.62
0.10	0.031	1.0096	0.091	46.7	19.21
0.15	0.049	1.0160	0.137	46.1	19.84
0.20	0.068	1.0226	0.183	45.5	20.53
0.25	0.088	1.0292	0.230	44.9	21.28
0.30	0.111	1.0358	0.278	44.3	22.10
0.35	0.135	1.0425	0.326	43.6	22.99
0.40	0.162	1.0491	0.375	43.0	23.98
0.45	0.192	1.0556	0.424	42.4	25.07
0.50	0.225	1.0621	0.473	41.7	26.29

(*Continued*)

w_1	x_1	ρ (g/cm^3)[a]	f_1	δ_{mix} (MPa$^{1/2}$)	V_{mix} (cm^3·mol^{-1})
0.55	0.262	1.0683	0.523	41.1	27.66
0.60	0.303	1.0743	0.574	40.4	29.21
0.65	0.350	1.0799	0.625	39.8	30.97
0.70	0.404	1.0852	0.677	39.1	32.99
0.75	0.465	1.0900	0.729	38.4	35.34
0.80	0.537	1.0944	0.782	37.7	38.09
0.85	0.622	1.0986	0.836	37.0	41.34
0.90	0.723	1.1026	0.890	36.3	45.23
0.95	0.847	1.1067	0.945	35.6	49.97
1.00	1.000	1.1099	1.000	34.9	55.92

[a] The density was calculated by regression, from the density data published by Egorov *et al.* [48].

Tables 3 and 4 presents the solubility data of the SD and SMT calculated using the YR model, and standard deviations (SD) with respect to the experimental values.

Table 3. Calculated solubility of SD in {ethylene glycol (1) + water (2)} mixtures by using the equations 3, and standard deviations with respect to the experimental values.

f_1	**10^5 x_3 (calculated)**								
	278.15	283.15	288.15	293.15	298.15	303.15	308.15	313.15	318.15
0.00	0.161	0.201	0.286	0.380	0.481	0.649	0.869	1.140	1.220
0.05	0.185	0.224	0.333	0.395	0.591	0.672	0.943	1.398	1.850
0.09	0.225	0.300	0.415	0.564	0.687	0.913	1.238	1.833	2.239
0.14	0.280	0.351	0.514	0.626	0.769	1.056	1.241	1.750	2.588
0.18	0.318	0.412	0.540	0.748	0.828	1.214	1.336	1.910	2.832
0.23	0.413	0.498	0.630	0.837	0.973	1.358	1.547	2.138	3.043
0.28	0.486	0.589	0.723	0.976	1.140	1.566	1.856	2.437	3.316
0.33	0.631	0.759	0.918	1.228	1.478	1.925	2.293	2.931	4.412
0.37	0.781	0.984	1.222	1.573	1.808	2.437	2.854	4.013	5.653
0.42	1.029	1.188	1.396	1.956	2.248	3.115	3.770	4.816	6.559
0.47	1.212	1.410	1.694	2.333	2.695	3.735	4.331	5.803	7.546
0.52	1.560	1.677	2.139	2.860	3.493	4.707	5.941	7.506	8.813
0.57	1.897	2.090	2.964	3.561	4.514	5.858	6.893	8.648	10.431
0.63	2.587	3.085	3.703	4.904	5.732	7.561	9.287	11.340	14.447

(*Continued*)

f_1	**10^5 x_3 (calculated)**								
	278.15	283.15	288.15	293.15	298.15	303.15	308.15	313.15	318.15
0.68	3.575	4.173	5.029	6.568	7.496	10.035	11.458	14.922	17.725
0.73	4.978	5.894	6.984	8.774	10.224	12.722	15.177	18.014	21.874
0.78	7.839	9.158	9.996	12.396	13.840	16.769	19.306	22.253	26.691
0.84	10.447	12.161	14.092	16.693	19.235	22.440	25.720	29.602	34.180
0.89	14.251	16.997	20.412	22.733	26.761	29.829	32.805	38.468	43.901
0.94	22.764	25.775	28.873	32.962	37.403	41.475	46.010	51.426	57.120
1.00	33.985	37.884	41.290	47.027	53.221	57.493	63.673	69.392	75.162
Percentage dev.[a]									
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.05	11.01	13.67	7.27	19.55	0.65	18.27	11.91	-1.82	-20.56
0.09	16.10	7.75	8.13	4.34	7.28	6.79	3.68	-9.71	-20.78
0.14	19.42	17.13	9.73	17.39	19.04	13.49	26.04	14.30	-17.11
0.18	35.18	27.36	31.61	22.95	37.70	21.70	42.92	26.79	-8.25
0.23	33.58	34.87	42.56	37.86	46.30	34.27	51.10	37.43	3.65
0.28	46.48	46.38	57.37	48.57	56.13	44.15	54.45	46.57	15.73
0.33	45.98	45.97	57.49	48.85	50.97	45.47	53.67	48.49	6.01
0.37	52.98	45.25	50.66	46.88	55.11	42.84	52.10	32.38	1.06
0.42	50.93	55.56	68.26	49.61	57.15	39.24	42.14	34.95	6.60
0.47	67.14	70.01	77.52	59.24	65.51	45.03	53.11	37.31	13.68
0.52	69.88	85.84	80.37	65.43	61.69	44.10	38.41	30.44	19.66
0.57	83.20	94.46	67.43	69.58	58.79	45.33	48.30	39.42	24.56
0.63	76.69	72.32	72.91	57.61	59.13	41.66	37.15	31.23	11.07
0.68	68.71	67.11	64.73	51.02	55.27	34.63	38.84	23.36	12.06
0.73	60.36	55.64	53.89	45.49	45.65	34.29	31.24	26.71	12.67
0.78	35.19	32.19	39.89	32.90	38.03	29.17	29.50	27.49	14.83
0.84	35.08	31.78	29.49	27.71	27.76	22.70	22.32	19.41	11.80
0.89	32.30	25.20	17.01	21.72	18.47	17.66	20.99	14.77	8.78
0.94	11.01	9.98	8.60	9.27	9.66	8.16	9.12	7.49	4.76
1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[a] Calculated as 100|x3cal- x3exp|/| x3exp|

Table 4. Calculated solubility of SMT in {ethylene glycol (1) + water (2)} mixtures by using the equations 3, and standard deviations with respect to the experimental values.

f_1	$10^4 x_3$ (calculated)								
	278.15	283.15	288.15	293.15	298.15	303.15	308.15	313.15	318.15
0.00	0.114	0.132	0.174	0.222	0.281	0.367	0.433	0.555	0.661
0.05	0.143	0.165	0.217	0.274	0.346	0.449	0.528	0.673	0.796
0.09	0.181	0.208	0.271	0.340	0.426	0.550	0.646	0.817	0.961
0.14	0.228	0.263	0.338	0.422	0.527	0.675	0.791	0.994	1.161
0.18	0.290	0.333	0.424	0.525	0.653	0.831	0.972	1.211	1.407
0.23	0.368	0.422	0.532	0.655	0.810	1.025	1.195	1.480	1.707
0.28	0.469	0.536	0.670	0.819	1.008	1.267	1.474	1.812	2.076
0.33	0.599	0.683	0.845	1.026	1.256	1.569	1.822	2.223	2.530
0.37	0.766	0.873	1.069	1.288	1.570	1.948	2.256	2.733	3.089
0.42	0.984	1.119	1.356	1.622	1.967	2.424	2.801	3.368	3.781
0.47	1.266	1.438	1.724	2.047	2.470	3.024	3.485	4.159	4.637
0.52	1.635	1.852	2.197	2.590	3.110	3.781	4.346	5.148	5.699
0.57	2.116	2.392	2.808	3.286	3.925	4.739	5.434	6.387	7.021
0.63	2.746	3.098	3.598	4.179	4.966	5.954	6.809	7.943	8.669
0.68	3.574	4.024	4.623	5.329	6.300	7.499	8.555	9.902	10.728
0.73	4.666	5.242	5.957	6.814	8.012	9.470	10.774	12.373	13.307
0.78	6.109	6.848	7.696	8.736	10.218	11.989	13.605	15.499	16.546
0.84	8.022	8.974	9.972	11.231	13.065	15.218	17.223	19.463	20.622
0.89	10.566	11.794	12.959	14.479	16.752	19.368	21.862	24.504	25.767
0.94	13.961	15.549	16.889	18.720	21.540	24.718	27.824	30.931	32.277
1.00	18.504	20.564	22.078	24.274	27.774	31.631	35.508	39.146	40.533
Percentaje dev.[a]									
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.05	12.36	11.66	22.91	13.20	12.74	18.98	14.77	19.69	17.95
0.09	17.40	4.69	8.84	8.02	11.34	24.60	19.93	29.78	28.38
0.14	12.18	1.24	5.43	8.44	27.43	23.91	25.50	32.54	19.42
0.18	18.85	13.27	18.63	21.02	35.84	32.34	29.95	36.11	40.04
0.23	29.61	18.65	27.84	26.30	39.95	40.58	37.84	52.32	38.36
0.28	29.34	26.75	34.39	28.53	46.60	43.43	39.64	44.67	45.00
0.33	37.43	27.11	35.09	30.01	44.19	42.17	36.29	48.33	55.66

(*Continued*)

f_1	$10^4\, x_3$ (calculated)								
	278.15	283.15	288.15	293.15	298.15	303.15	308.15	313.15	318.15
0.37	37.27	39.30	44.95	39.84	39.63	44.81	50.09	49.10	54.52
0.42	46.86	28.13	31.12	29.70	53.71	41.57	43.03	46.15	47.57
0.47	48.82	40.15	42.25	40.14	52.88	45.01	51.88	46.66	52.15
0.52	51.25	44.57	38.75	40.66	58.41	45.39	54.68	48.69	40.82
0.57	64.73	47.66	50.01	57.02	70.25	57.51	56.57	54.80	46.89
0.63	62.07	57.77	37.33	52.50	64.72	48.24	47.30	44.97	46.17
0.68	59.80	58.85	52.27	59.96	63.26	53.24	53.26	49.75	43.74
0.73	44.53	54.75	57.65	51.89	44.45	51.24	47.68	42.26	42.17
0.78	48.37	34.04	39.23	34.39	38.04	42.25	46.32	52.83	45.54
0.84	52.71	47.51	40.83	46.51	44.27	52.47	52.92	54.94	52.28
0.89	54.28	45.75	39.26	44.00	50.37	51.64	58.98	57.35	52.41
0.94	6.69	8.78	8.08	7.83	7.92	12.85	13.00	12.92	7.93
1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[a]Calculated as $100|x_3^{cal} - x_3^{exp}|/|x_3^{exp}|$

When evaluating the individual deviations of the calculated data with respect to the experimental data, relatively large deviations are observed, with a maximum of 94.46% for the SD and 57.51% for the SMT. As a general measure of the validity of the two models, the mean percentage deviation values were calculated according to equation 18, where is the number of points of the resulting cosolvent composition.

$$MPD = \frac{100}{n}\sum_{t=1}^{n}\frac{x_3^{cal} - x_3^{Exp}}{x_3^{Exp}} \tag{18}$$

Thus, in general, the YR model presents an MPD of 31.1% for SD and 34.8% for SMT, an acceptable percentage for the pharmaceutical industry. Figure 2 shows that, in general, the deviations were greater in intermediate mixtures and are reduced in mixtures rich in either of the two solvents.

On the other hand, when plotting the calculated solubility vs. the experimental solubility (figure 3), pooled data is obtained, indicating a good predictability of the model.

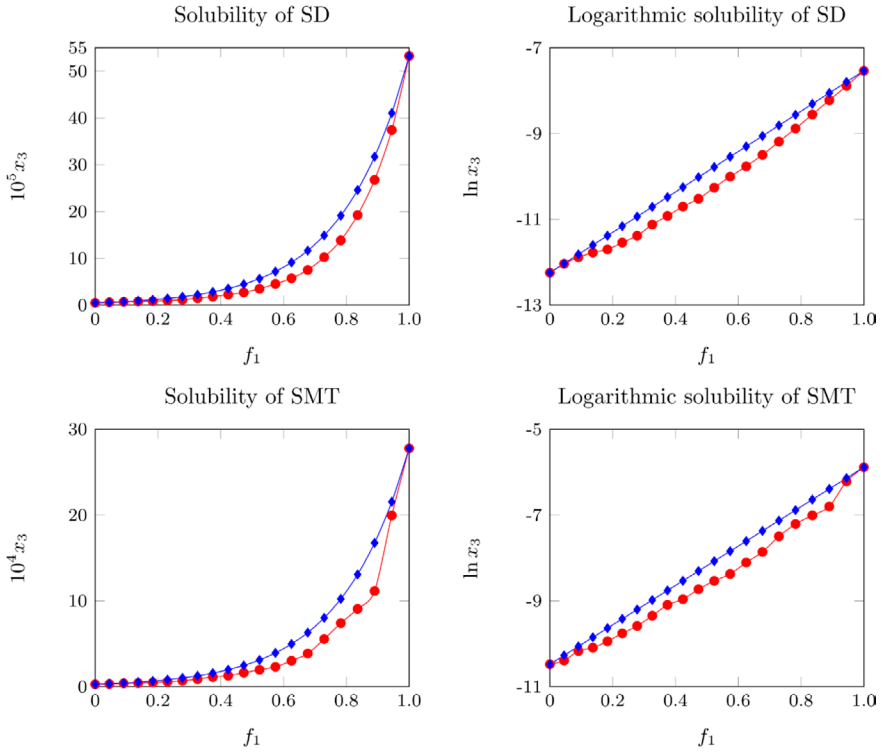

Figure 2. Experimental and calculated solubility of SD and SMT in (EG + W) mixtures at 298.15 K.

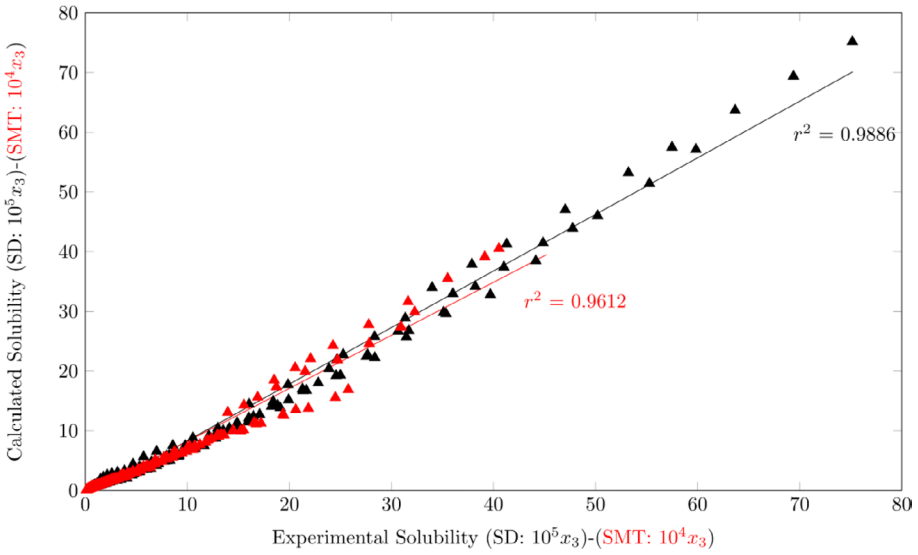

Figure 3. Calculated solubility vs. experimental solubility by YR model of SD and SMT in (EG + W) mixtures.

Figure 4 shows the experimental solubility of SD and SMT in (EG + W) mixtures, the solubility calculated using the equation for regular solutions, and the solubility calculated using the MESH as a function of the solubility parameter of solvent mixtures; the logarithm of experimental solubility and calculated solubility by EHSA are also presented. The experimental solubility is greater than the calculated solubility by using the regular solution model in every one of the mixtures evaluated. This result could be attributed to the fact that this semiempirical model does not consider specific interactions between solvent and solute, and all the involved compounds present polar groups that could interact by hydrogen bonding. In principle, SD and SMT would behave like a Lewis base in mixtures rich in water due to the pair of free electrons of its groups -SO_2-, -NH_2- and =N- in addition to the fact that water is more acidic than EG according to the acid and basicity parameters of Kamlet-Taft (α_2= 1.017±0.0236, α_1= 0.792±0.004 [49], and β_2= 0.14 β_1=0.51 [50]), and as a Lewis acid in intermediate and rich mixtures in EG due to the hydrogen of its groups -NH_2- and -NH-. Although, it is evident that the Hildebrand model of regular solutions does not allow obtaining data consistent with the experimental ones, the results obtained with the EHSA model, using the W calculated with the second order polynomial, overlap with the experimental data.

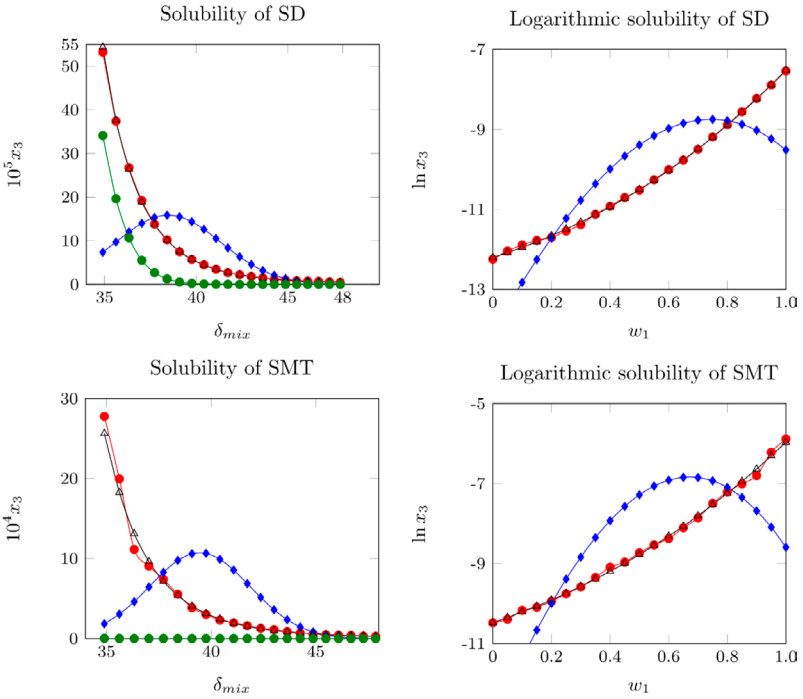

Figure 4. Experimental and calculated solubility of SD and SMT at 298.15 K (Δ: Calculated solubility by EHSA model (Polynomial 2); ●: experimental solubility; ●: Calculated solubility by EHSA model (Polynomial 1) and ●: Calculated solubility by regular solution model.

Regarding the solubility calculated using the EHSA model, to calculate the parameter (table 5), the calculated δ_{mix} value was used (table 2). On the other hand, the parameter *A*, is presented in table 5 too. Figure 5 shows that the variation of the parameter with respect to the solubility parameter of solvent mixtures, presents deviation from linear behavior.

Table 5. *A* and *W* experimental parameters for SD and SMT in (EG + W) mixtures at 298.15 K.

δ_{mix} (MPa$^{1/2}$)	SD		SMT	
	100 *A* (cm^3·J^{-1})	W (J·cm^{-3})	100 A (cm^3·J^{-1})	*W* (J·cm^{-3})
47.86	2.63	1509.4	3.80	1421.6
47.27	2.63	1483.3	3.80	1394.3
46.68	2.63	1456.7	3.80	1367.8
46.09	2.63	1430.0	3.80	1340.5
45.48	2.63	1402.9	3.80	1313.7
44.87	2.63	1376.7	3.80	1287.2
44.26	2.63	1350.6	3.80	1260.8
43.63	2.63	1325.4	3.79	1234.7
43.01	2.63	1299.8	3.79	1208.9
42.37	2.63	1274.4	3.79	1182.5
41.73	2.63	1248.9	3.79	1156.8
41.08	2.63	1224.1	3.79	1131.0
40.42	2.63	1199.5	3.79	1105.2
39.76	2.63	1174.9	3.78	1080.1
39.09	2.63	1150.6	3.78	1055.0
38.41	2.63	1126.9	3.78	1030.8
37.72	2.62	1103.3	3.77	1006.3
37.03	2.62	1080.1	3.77	981.6
36.33	2.62	1057.1	3.76	957.0
35.62	2.62	1034.3	3.74	934.8
34.90	2.62	1012.0	3.72	911.4

W values were adjusted to regular polynomials in orders from 2 to 5 (equation 17). Nevertheless, linear model was also evaluated with comparative purposes. Table 6 and table 7, summarizes the coefficients obtained in all the regular polynomials from degrees one to five for SD an SMT.

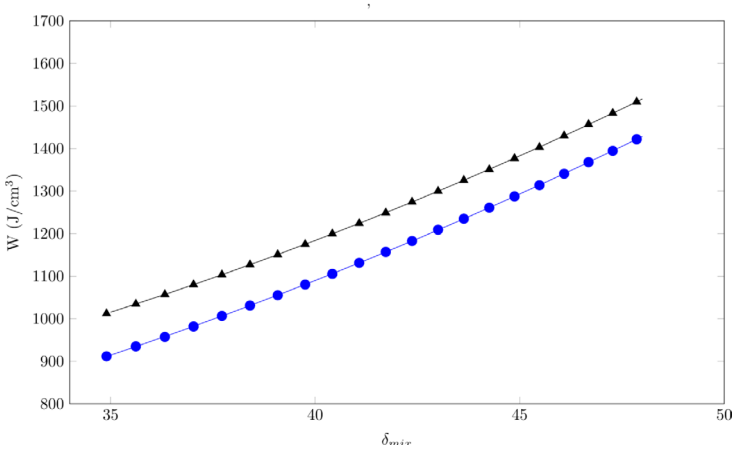

Figure 5. *W* parameter as a function of the solubility parameter of the solvent mixtures in (EG + W) mixtures (SD: ●; SMT:●).

Table 6. Coefficients and statistical parameters of regular polynomials in several orders of *W* as a function of solubility δ_{mix} free of SD (equation 17) in (EG + water) mixtures.

	Polynomial order				
Coefficient	1	2	3	4	5
C_0	-347.25±20.22	678.60±7.40	589.90±88.93	-15.45±1108.24	13471.43±13731.39
C_1	38.48±0.48	-11.47±0.36	-4.97±6.50	54.195±108.16	-1594.46±1676.56
C_2		0.602±0.004	0.44±0.16	-1.72±3.94	78.65±81.65
C_3			0.001±0.001	0.036±0.06	-1.92±1.98
C_4				-0.00025±0.00038	0.02±0.024
C_5					-0.0001±0.0001
Adj. R^2	0.997	1.000	1.000	1.000	1.000
Fit. Err	8.695	0.272	0.272	0.278	0.278

Table 7. Coefficients and statistical parameters of regular polynomials in several orders of *W* as a function of solubility δ_{mix} free of SMT (equation 17) in (EG + water) mixtures.

	Polynomial order				
Coef.	1	2	3	4	5
C_0	-482.22±18.75	468.61±10.18	665.88±116.33	3007.99±1340.08	3330.59±7132.80
C_1	39.48±0.45	-6.82±0.49	-21.27±8.50	-250.19±130.79	-289.63±2091.84
C_2		0.558±0.006	0.91±0.21	9.27±4.77	11.19±101.88
C_3			-0.003±0.002	-0.14±0.08	-0.18±2.47
C_4				0.0008±0.0004	0.001±0.030
C_5					-0.000003±0.000144
Adj. R^2	0.997	1.000	1.000	1.000	1.000
Fit. Err	8.064	0.374	0.356	0.336	0.347

Tables 8 and 9 report the calculated solubility of SD and SMT and the respective percentages of deviation. When using the values of the factor *W* calculated with the polynomial of order 1, the deviations of the calculated data with respect to the experimental data is greater than 60%, indicating that the model is not the appropriate one. However, when using the results of *W*, calculated with a polynomial greater than or equal to 2, the deviations are low, presenting a good correlation between the calculated and experimental data.

Table 8. Calculated solubility of sulfadiazine in (EG + water) mixtures by using the *W* parameters obtained from regression models in orders 1, 2, 3, 4 and 5, and standard deviations with respect to the experimental values, at 298.15 K.

δ_{mix}	x_3 (calculated)					Percentage desv.				
(MPa$^{1/2}$)	1	2	3	4	5	1	2	3	4	5
47.9	0.08	0.50	0.51	0.51	0.50	84.0	4.32	5.78	5.00	3.77
47.3	0.15	0.57	0.57	0.57	0.57	75.2	4.11	3.52	3.57	3.14
46.7	0.27	0.65	0.65	0.65	0.65	60.8	5.99	5.96	5.65	4.72
46.1	0.48	0.74	0.74	0.75	0.75	38.0	3.23	3.62	3.14	2.30
45.5	0.81	0.87	0.86	0.87	0.87	1.8	4.69	3.98	4.49	4.91
44.9	1.33	1.02	1.01	1.02	1.01	37.1	4.90	4.05	4.44	4.29
44.3	2.10	1.21	1.20	1.21	1.20	84.1	6.47	5.58	5.77	5.16
43.6	3.17	1.46	1.45	1.45	1.44	114.4	1.16	1.90	1.93	2.72
43.0	4.58	1.78	1.77	1.77	1.75	153.5	1.54	2.12	2.34	3.12
42.4	6.34	2.19	2.19	2.18	2.17	181.9	2.39	2.75	3.11	3.67
41.7	8.37	2.74	2.74	2.72	2.72	210.4	1.60	1.49	1.03	0.83
41.1	10.53	3.46	3.47	3.45	3.46	201.4	0.92	0.76	1.20	0.96
40.4	12.61	4.43	4.45	4.44	4.47	179.4	1.76	1.35	1.70	1.09
39.8	14.36	5.76	5.80	5.78	5.83	150.5	0.46	1.12	0.92	1.77
39.1	15.51	7.58	7.64	7.65	7.71	106.9	1.15	1.98	1.99	2.82
38.4	15.87	10.13	10.22	10.25	10.30	55.2	0.89	0.02	0.23	0.73
37.7	15.35	13.74	13.86	13.92	13.91	10.9	0.69	0.12	0.57	0.51
37.0	14.00	18.92	19.04	19.14	19.01	27.2	1.61	1.04	0.50	1.18
36.3	12.04	26.47	26.52	26.64	26.35	55.0	1.07	0.92	0.47	1.54
35.6	9.73	37.62	37.43	37.45	37.18	74.0	0.58	0.07	0.14	0.59
34.9	7.38	54.38	53.59	53.19	53.80	86.1	2.17	0.70	0.05	1.09
			Mean value			94.7	2.46	2.32	2.30	2.42
			Standard deviation			62.8	1.87	1.90	1.90	1.55

Table 9. Calculated solubility of sulfamethazine in EG + water mixtures by using the W parameters obtained from regression models in orders 1, 2, 3, 4 and 5, and standard deviations with respect to the experimental values, at 298.15 K.

δ_{mix} ($MPa^{1/2}$)	x_3 calculated					% Desv.				
	1	2	3	4	5	1	2	3	4	5
47.9	0.02	0.28	0.27	0.28	0.28	91.9	0.22	4.18	0.12	0.16
47.3	0.05	0.32	0.31	0.31	0.31	82.9	4.42	2.35	2.69	2.70
46.7	0.11	0.37	0.37	0.36	0.36	70.3	4.04	4.13	5.90	5.86
46.1	0.23	0.43	0.43	0.42	0.42	43.4	2.80	4.13	1.29	1.32
45.5	0.46	0.50	0.51	0.49	0.49	5.2	3.30	5.56	2.72	2.74
44.9	0.84	0.58	0.60	0.59	0.59	44.6	1.06	3.73	1.63	1.63
44.3	1.45	0.70	0.71	0.71	0.71	110.7	1.23	3.98	2.95	2.93
43.6	2.36	0.84	0.86	0.86	0.86	170.6	4.03	1.67	1.50	1.53
43.0	3.60	1.02	1.04	1.05	1.05	220.3	9.70	7.96	6.80	6.83
42.4	5.15	1.24	1.26	1.29	1.29	302.1	2.76	1.58	0.48	0.46
41.7	6.88	1.54	1.55	1.59	1.59	325.5	4.50	4.15	1.72	1.73
41.1	8.56	1.93	1.92	1.97	1.97	336.0	1.51	2.02	0.45	0.46
40.4	9.91	2.45	2.42	2.46	2.47	329.8	6.23	4.79	6.92	6.94
39.8	10.65	3.14	3.08	3.11	3.11	253.3	4.22	2.06	3.20	3.23
39.1	10.60	4.08	3.97	3.97	3.97	174.7	5.69	2.97	2.89	2.92
38.4	9.76	5.37	5.22	5.15	5.15	76.0	3.19	5.87	7.15	7.14
37.7	8.28	7.15	6.97	6.80	6.80	11.9	3.40	5.87	8.17	8.18
37.0	6.45	9.62	9.45	9.16	9.16	28.8	6.26	4.30	1.20	1.17
36.3	4.60	13.12	13.05	12.73	12.72	58.7	17.74	17.16	14.25	14.21
35.6	3.06	18.28	18.58	18.52	18.51	84.7	8.39	6.90	7.23	7.26
34.9	1.85	25.64	26.85	27.98	27.99	93.3	7.67	3.33	0.73	0.77
			Mean value			138.8	4.87	4.70	3.81	3.82
			Standard deviation			111.6	3.83	3.32	3.55	3.54

These results can be corroborated in figure 6, where the data calculated with polynomial 1 show a high dispersion, contrary to the data calculated with the polynomial of order 2, which present a correlation coefficient greater than 0.99.

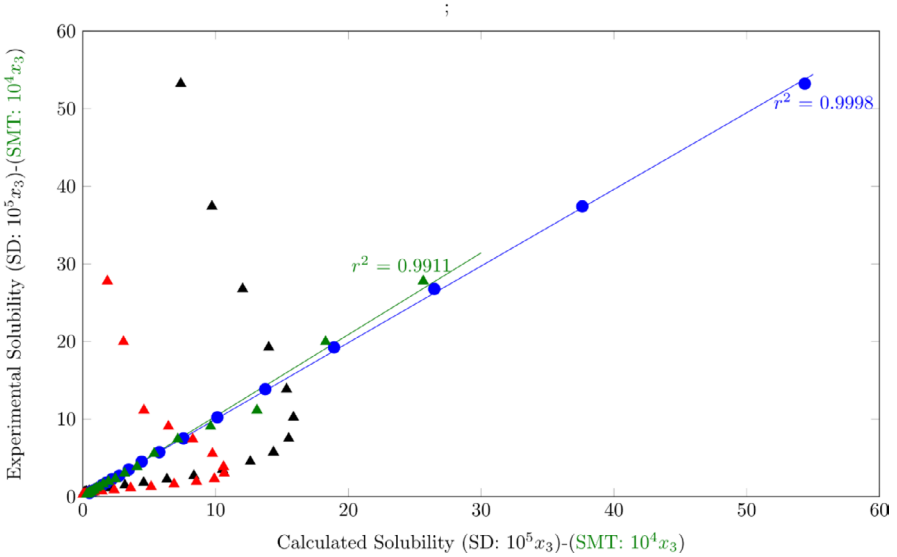

Figure 6. Calculated solubility vs experimental solubility by EHSA model of SD and SMT in (EG + W) mixtures (▲: SD polynomial 1; ▲: SMT polynomial 1; ●: SD polynomial 2; ▲: SMT polynomial 2).

Conclusions

The results obtained from the Yalkowsky-Roseman linear model do not present a good correlation with the experimental data, possibly due to the simplicity of the model, which does not consider the solute-solvent and solvent-solvent molecular interactions. However, the results of the extended Hildebrand solubility approach (EHSA), calculated with a polynomial greater than or equal to two, present interesting correlations, with deviation percentages less than 3%.

Conflict of interests

The authors declare no conflict of interest.

References

1. M.d.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), doi: 10.1016/j.molliq.2015.01.047.

2. B. Aday, P. Sola, F. Çolak, M. Kaya, Synthesis of novel sulfonamide analogs containing sulfamerazine/sulfaguanidine and their biological activities, *J. Enzym. Inhib. Med. Chem.*, **31**, 1005-1010 (2016), doi: 10.3109/14756366.2015.1079183.

3. D.R. Delgado, F. Martínez, Preferential solvation of sulfadiazine, sulfamerazine and sulfamethazine in ethanol + water solvent mixtures according to the IKBI method, *J. Mol. Liq.*, **193**, 152-159 (2014), doi: 10.1016/j.molliq.2013.12.021.

4. Regulation on Maximum Residue Limits, Salud pública, (n.d.)., URL: https://ec.europa.eu/health/veterinary-use/maximum-residue-limits/regulations_es, accessed January 29, 2021.

5. European Commission, *EEC Regulation 90/2377/EEC incorporating amending regulation 92/675/EEC*, Brussels, 1997, URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31997L0078&from=LV, accessed January 29, 2021.

6. A.M. Cruz-González, M.S. Vargas-Santana, C.P. Ortiz, N.E. Cerquera, D.R. Delgado, F. Martínez, A. Jouyban, W.E. Acree Jr., Solubility of sulfadiazine in (ethylene glycol + water) mixtures: Measurement, correlation, thermodynamics and preferential solvation, *J. Mol. Liq.*, **323**, 115058 (2021), doi: 10.1016/j.molliq.2020.115058.

7. D.R. Delgado, O. Bahamón-Hernandez, N.E. Cerquera, C.P. Ortiz, F. Martínez, E. Rahimpour, A. Jouyban, W.E. Acree, Solubility of sulfadiazine in (acetonitrile + methanol) mixtures: Determination, correlation, dissolution thermodynamics and preferential solvation, *J. Mol. Liq.*, **322**, 114979 (2021), doi: 10.1016/j.molliq.2020.114979.

8. M.M. Muñoz, F. Martinez, D.R. Delgado, A. Jouyban, W.E. Acree, Equilibrium solubility and apparent specific volume at saturation of sodium sulfadiazine in some aqueous cosolvent mixtures at 298.2 K, *Phys. Chem. Liq.*, **59**, 40-52 (2021), doi: 10.1080/00319104.2019.1675158.

9. D.M. Jiménez, Z.J. Cárdenas, D.R. Delgado, M.T. 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), doi: 10.1016/j.fluid.2015.03.046.

10. 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), doi: 10.1016/j.fluid.2014.07.013.

11. D.R. Delgado, F. Martínez, Preferential solvation of sulfadiazine, sulfamerazine and sulfamethazine in ethanol + water solvent mixtures according to the IKBI method, *J. Mol. Liq.*, **193**, 152-159 (2014), doi: 10.1016/j.molliq.2013.12.021.

12. D.R. Delgado, F. Martínez, Solution thermodynamics of sulfadiazine in some ethanol + water mixtures, *J. Mol. Liq.*, **187**, 99-105 (2013), doi: 10.1016/j.molliq.2013.06.011.

13. D.R. Delgado, F. Martínez R., Thermodynamic study of the solubility of sodium sulfadiazine in some ethanol + water cosolvent mixtures, *Vitae*, **17**, 191-198 (2010).

14. KJ. Deng, X.H. Lan, G. Sun, L.Y. Ji, X. lian Zheng, Determination of sulfonamide residues in chicken liver using high-performance liquid chromatography, *Food Anal. Methods*, **9**, 3337-3344 (2016), doi: 10.1007/s12161-016-0514-6.

15. R. Galarini, F. Diana, S. Moretti, B. Puppini, G. Saluti, L. Persic, Development and validation of a new qualitative ELISA screening for multiresidue detection of sulfonamides in food and feed, *Food Control*, **35**, 300-310 (2014), doi: 10.1016/j.foodcont.2013.07.014.

16. A. Barani, A.A. Fallah, Occurrence of tetracyclines, sulfonamides, fluoroquinolones and florfenicol in farmed rainbow trout in Iran, *Food Agr. Immunol.*, **26**, 420-429 (2015), doi: 10.1080/09540105.2014.950199.

17. R.E. Cárdenas, 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**, 822-842 (2020), doi: 10.15446/rcciquifa.v49n3.91347.

18. 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. Exact. Fis. Nat.*, **35**, 329-337 (2011).

19. J.T. Rubino, S.H. Yalkowsky, Cosolvency and deviations from log-linear solubilization, *Pharm. Res.*, **4**, 231-236 (1987), doi: 10.1023/A:1016408211963.

20. J.L. Gómez, G.A. Rodríguez, D.M. Cristancho, D.R. Delgado, A. Yurquina, F. Martínez, Extended Hildebrand Solubility Approach applied to nimodipine in PEG 400 + ethanol mixtures, *Rev. Colomb. Cienc. Quim. Farm.*, **42**, 103-121 (2013).

21. Z.J. Cárdenas, D.M. Jiménez, D.R. Delgado, M.Á. Peña, F. Martínez, Extended Hildebrand solubility approach applied to some sulphonamides in propylene glycol + water mixtures, *Phys. Chem. Liq.*, **53**, 763-775 (2015), doi: 10.1080/00319104.2015.1048247.

22. G.R. Rojas, A.F. Rivera, D.R. Delgado, Application of the Extended Hildebrand solubility approach applied to mitomycin C in ethanol+ water mixtures, *Revista Ingeniería y Región*, **13**, 149-157 (2015), doi: 10.25054/22161325.716.

23. D.M. Cristancho, D.R. Delgado, F. Martínez, Meloxicam solubility in ethanol+water mixtures according to the extended Hildebrand solubility approach, *J. Solution Chem.*, **42**, 1706-1716 (2013), doi: 10.1007/s10953-013-0058-y.

24. A. Aydi, C.P. Ortiz, D.I. Caviedes-Rubio, C. Ayadi, S. Hbaieb, D.R. Delgado, Solution thermodynamics and preferential solvation of sulfamethazine in ethylene glycol + water mixtures, *J. Taiwan Inst. Chem. Eng.*, **118**, 68-77 (2021), doi: 10.1016/j.jtice.2020.12.031.

25. J.W. Millard, F.A. Alvarez-Núñez, S.H. Yalkowsky, Solubilization by cosolvents: Establishing useful constants for the log-linear model, *Int. J. Pharm.*, **245**, 153-166 (2002), doi: 10.1016/S0378-5173(02)00334-4.

26. M. Gantiva, E.F. Vargas, M.E. Manzur, A. Yurquina, F. Martínez, Modelos de Yalkowsky-Roseman y Jouyban-Acree en la estimación de la solubilidad del ketoprofeno en algunas mezclas cosolventes propilenoglicol + agua, *Rev. Colomb. Ciencias Quim. Farm.*, **38**, 156-171 (2009).

27. S.H. Yalkowsky, J.T. Rubino, Solubilization by cosolvents I: Organic solutes in propylene glycol-water mixtures, *J. Pharm. Sci.*, **74**, 416-421 (1985), doi: 10.1002/jps.2600740410.

28. C.V.S. Subrahmanyam, M. Sreenivasa-Reddy, J. Venkata-Rao, P. Gundu-Rao, Irregular solution behaviour of paracetamol in binary solvents, *Int. J. Pharm.*, **78**, 17-24 (1992), doi: 10.1016/0378-5173(92)90350-B.

29. P.R. Sathesh Babu, C.V.S. Subrahmanyam, J. Thimmasetty, R. Manavalan, K. Valliappan, Extended Hansen's solubility approach: meloxicam in individual solvents, *Pak. J. Pharm. Sci.*, **20**, 311-316 (2007), doi: 10.1016/S0939-6411(98)00079-4.

30. J.H. Hildebrand, J.M. Prausnitz, R.L. Scott, *Regular and Related Solutions*, Van Nostrand Reinhold Co., New York, 1970.

31. A. Martin, J. Carstensen, Extended solubility approach: Solubility parameters for crystalline solid compounds, *J. Pharm. Sci.*, **70**, 170-172 (1981), doi: 10.1002/jps.2600700214.

32. D.R. Delgado, M.Á. Peña, F. Martínez, Extended Hildebrand solubility approach applied to some structurally related sulfonamides in ethanol + water mixtures, *Rev. Colomb. Quim.*, **45**(1), 34-43 (2016), doi: 10.15446/rev.colomb.quim.v45n1.57201.

33. A.R. Holguín, D.R. Delgado, F. Martínez, Indomethacin solubility in propylene glycol + water mixtures according to the Extended Hildebrand Solubility Approach, *Lat. Am. J. Pharm.*, **31**, 720-726 (2012).

34. G. Scatchard, Equilibria in non-electrolyte solutions in relation to the vapor pressures and densities of the components, *Chem. Rev.*, **8**, 321-333 (1931), doi: 10.1021/cr60030a010.

35. J.H. Hildebrand, R.L. Scott, *The Solubility of Nonelectrolytes*, 3rd ed., Dover, New York, 1964.

36. A. Martin, P.L. Wu, A. Adjei, M. Mehdizadeh, K.C. James, C. Metzler, Extended Hildebrand solubility approach: Testosterone and testosterone propionate in binary solvents, *J. Pharm. Sci.*, **71**, 1334-1340 (1982), doi: 10.1002/jps.2600711207.

37. A. Adjei, J. Newburger, A. Martin, Extended Hildebrand approach: Solubility of caffeine in dioxane-water mixtures, *J. Pharm. Sci.*, **69**, 659-661 (1980), doi: 10.1002/jps.2600690613.

38. 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), doi: 10.1080/00319104.2018.1476976.

39. M.A. Ruidiaz, D.R. Delgado, F. Martínez, Indomethacin solubility estimation in 1,4-dioxane + water mixtures by the extended hildebrand solubility approach, *Quím. Nova*, **34**, 1569-1574 (2011), doi: 10.1590/S0100-40422011000900016.

40. M.A. Ruidiaz, D.R. Delgado, C.P. Mora, A. Yurquina, F. Martínez, Estimation of the indomethacin solubility in ethanol + water mixtures by the extended Hildebrand solubility approach, *Rev. Colomb. Cienc. Quím. Farm.*, **39**, 79-95 (2010).

41. E.E. Walker, The solvent action of organic substances on polyacrylonitrile, *J. Appl. Chem.*, **2**, 470-481 (1952), doi: 10.1002/jctb.5010020808.

42. S.J. Rodríguez, D.M. Cristancho, P.C. Neita, E.F. Vargas, F. Martínez, Extended Hildebrand solubility approach in the solubility estimation of the sunscreen ethylhexyl triazone in ethyl acetate + ethanol mixtures, *Lat. Am. J. Pharm.*, **29**, 1113-1119 (2010).

43. R.G. Sotomayor, A.R. Holguín, D.M. Cristancho, D.R. Delgado, F. Martínez, Extended Hildebrand Solubility Approach applied to piroxicam in ethanol + water mixtures, *J. Mol. Liq.*, **180**, 34-38 (2013), doi: 10.1016/j.molliq.2012.12.028.

44. D.R. Delgado, M. Peña, F. Martínez, Extended Hildebrand solubility approach applied to some sulphapyrimidines in some {methanol (1) + water (2)} mixtures, *Phys. Chem. Liq.*, **56**, 176-188 (2018), doi: 10.1080/00319104.2017.1317779.

45. F. Martínez, A. Gómez, Thermodynamic study of the solubility of some sulfonamides in octanol, water, and the mutually saturated solvents, *J. Solution Chem.*, **30**, 909-923 (2001), doi: 10.1023/A:1012723731104.

46. D.R. Delgado, F. Martínez, Solubility and solution thermodynamics of some sulfonamides in 1-propanol + water mixtures, *J. Solution Chem.*, **43**, 836-852 (2014), doi: 10.1007/s10953-014-0169-0.

47. D.R. Delgado, F. Martínez, Preferential solvation of some structurally related sulfonamides in 1-propanol + water co-solvent mixtures, *Phys. Chem. Liq.*, **53**, 293-306 (2015), doi: 10.1080/00319104.2014.961191.

48. G.I. Egorov, D.M. Makarov, A.M. Kolker, Volumetric properties of the water-ethylene glycol mixtures in the temperature range 278-333.15 K at atmospheric pressure, *Russ. J. Gen. Chem.*, **80**, 1577-1585 (2010), doi: 10.1134/S1070363210080074.

49. R.W. Taft, M.J. Kamlet, The solvatochromic comparison method. 2. The .alpha.-scale of solvent hydrogen-bond donor (HBD) acidities, *J. Am. Chem. Soc.*, **98**, 2886-2894 (1976), doi: 10.1021/ja00426a036.

50. M.J. Kamlet, R.W. Taft, The Solvatochromic Comparison Method. I. The β-Scale Of Solvent Hydrogen-Bond Acceptor (HBA) Basicities, *J. Am. Chem. Soc.*, **98**, 377-383 (1976), doi: 10.1021/ja00418a009.

How to cite this article

M.S. Vargas-Santana, A.M. Cruz-González, N.E. Cerquera, A.S. Escobar-Rodriguez, R.E. Cárdenas, O. Calderón-Losada, C.P. Ortiz, D.R. Delgado, Extended Hildebrand solubility approach and Yalkowsky-Roseman model for estimating the solubility of sulfadiazine and sulfamethazine in some {ethylene glycol (1) + water (2)} mixtures at several temperatures, *Rev. Colomb. Cienc. Quim. Farm.*, **50**(3), 812-836 (2021).