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Solubility of 2,4-diamino-6-(4-pyridyl)-1,3,5-triazine in tetrahydrofuran and alcohols between 288.15 K and 318.15 K

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Abstract. 2,4-diamino-6-(4-pyridyl)-1,3,5-triazine (DAPT) was synthesized and analyzed by nuclear magnetic resonance and Fourier transform infrared spectroscopy, thermogravimetric and elemental analysis techniques as well as by high-resolution transmission electron microscopy. DAPT solubility (in tetrahydrofuran, methanol, ethanol, n-propanol, and isopropanol) in the 288.15-318.15 K range was measured using the static analytical technique. We also performed quantum chemical calculations using Gaussian 09 and determined influence of solvent polarity and solute-solvent interactions on DAPT solubility. Experimental results were treated by modified Apelblat and Buchowski-Ksiazaczak (λh) equations as well as by the Wilson and nonrandom two-liquid (NRTL) models. All four models showed excellent agreement. This study provides valuable data for the purification of DAPT at the preferential crystallization procedure.

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Keywords. Solubility; 2,4-diamino-6-(4-pyridyl)-1,3,5-triazine; Quantum chemical calculations; Thermodynamic correlation

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1. Introduction

1,3,5-triazine and its derivatives are heterocyclic compounds attracting a lot of scientific attention because of their biological activity, low toxicity and stability [1-5]. Because of their strong herbicidal and bactericidal properties combined with low animal toxicity, triazine derivatives are often included into commercial wound-dressing remedies. Triazine derivatives are also widely used in pharmaceutical products, such as anti-HIV drugs [2] and antitumor agents [3] because triazine derivatives act as ligands capable to form complexes of biological significance [6]. Pyridyl-substituted diamino triazines are such compounds capable to form other multi-dimensional structures through H-bond-based stacking of two amino-groups and multiple nitrogen atoms [7].

2,4-diamino-6-(4-pyridyl)-1,3,5-triazine (DAPT, $C_8H_8N_6$, CAS Reg No. 18020-61-6), containing a pyridyl ring and two amino-groups, is a potential ligand for catalytic reactions. It is also useful for the fabrication of thin-film molecular devices because DAPT forms complexes with other compounds [7]. Properties of the products involving DAPT strongly depend on the purity of the DAPT used. One of the most well-known and important industrial methods of DAPT separation and purification is its crystallization from a solution, which is based on compound solubility in a solvent [8]. DAPT solubility in solvents was not extensively analyzed; yet, like many other organic compounds, it depends on various parameters such as the rule of "like dissolves the like", solvent polarity, intermolecular forces between solute and solvent,

etc [9,10]. Recent developments of theoretical simulations currently allow researchers to model and analyze compound structures and their properties (including the influence of intermolecular forces on the compound solubility) using computer software [11-13].

This paper reports solubility data for DAPT in different solvents (like tetrahydrofuran, and alcohols like methanol, ethanol, n-propanol, isopropanol) obtained for the 288.15-318.15 K range and at ambient pressure using gravimetry. DAPT demonstrated very different solubility in different solvents, which was determined by quantum chemical calculations. To get a comprehensive picture of the solubility of DAPT, various models were adapted, which include Apelblat [14] and the Buchowski-Ksiazaczak (λh) equations [15] as well as the Wilson [16] and nonrandom two-liquid (NRTL) [17] models.

2. Experimental section

2.1 Materials

All materials were of commercial grades and were used as such. The chemicals, source, purity and the analytical methods used are summarized in Table 1.

2.2 Apparatus

The measurement of solubility was carried out in an apparatus, the details of which are described in the literature [18]. The experiments were carried out in a cell fitted with a jacket and a magnetic stirrer having a particular volume. DCY-3006 thermostat (manufactured by Shanghai Laboratory Instrument Works) capable of ± 0.05 K

temperature control was used in a circulating water bath. Inner chamber temperature was measured using a calibrated thermometer with \pm 0.05 K accuracy. AR124CN analytical balance (OHAUS) with \pm 0.1 mg precision was also used. Fouriertransform infrared (FT-IR) spectroscopy was performed using Nicolet 6700 instrument. For this purpose, samples were ground with KBr and then pressed until clear pellets were obtained. ¹H NMR and ¹³C NMR were performed by Bruker 400 spectrometer. The sample composition was determined using Vario EL Cube (Elementar, Germany). Thermogravimetric analysis (TGA) was carried by a Mettler TGA/DSC-1 instrument in the 303.13-823.15 K temperature range at 10 K/min heating rate under flowing N₂ atmosphere. High-resolution transmission electron microscopy (HRTEM) data was collected by a FEI Tecnai G2 F20 operated at 200 kV. 2.3 Synthesis and Characterization of DAPT

DAPT was synthesized by using a modified literature method [19]. A mixture containing 1.0411 g of 3-cyanopyridine (10 mmol), 0.8408 g of dicyandiamide (10 mmol), and 0.5 g of KOH (8.9 mmol) dissolved in 50 mL of 2-methoxy-ethanol was heated for 2 h under refluxing condition. After the solution cooled naturally to ambient temperature, formed precipitate was filtered. The solid was washed with hot water after filtration to yield the pure product as a white powder (1.731 g, 9.2 mmol, 92% yield. Scheme 1 gives the detailed synthetic procedure of DAPT. The ¹H and ¹³C NMR spectra of DAPT are shown in Fig. 1. Anal. Calcd. (%) for C₈H₈N₆: C, 51.06; H, 4.28; N, 44.66. Found (%): C, 50.96; H, 4.31; N, 44.23. ¹H NMR (DMSO- d_6) ppm, δ :

9.36 (1H, H-3'), 8.70 (1H, H-5'), 8.48 (1H, H-1'), 7.52 (1H, H-6'), 6.89 (4H, NH₂). ¹³C NMR (DMSO-*d*₆) ppm, δ: 169.25 (C-6), 167.74(C-2 and C-4), 152.13(C-3'), 149.43(C-5'), 135.43(C-1'), 132.92(C-2'), 123.90(C-6') (For numbering, see structure formula in Scheme 1). FTIR (KBr, cm⁻¹) v: 3466-3341, 3204, 1644, 1594, 1548, 1453, 1395, 807.

HRTEM helped us to analyze the shapes of the formed crystals and to analyze the DAPT microstructure. DAPT was found to have small pin-like structures of 5 µm with thickness varying from mono to few layers.

TGA and DSC were performed in 303.15-823.15 K temperature range at 10 K/min heating rate under constant N₂ flow equal to 50 mL/min (see Figure 3). The moisture adsorbed on the surface of the sample due to exposure in the ambient atmospheric condition was the reason behind the initial mass loss of the sample. From 525.15 K to 578.32 K temperature range, the sample was observed to loss 80% of the initial weight with almost complete decomposition at 823.15 K. Melting point of DAPT was characterized as 521.48 K with an uncertainty of \pm 0.78 K. The fusion enthalpy of DAPT was 96.50 kJ·mol⁻¹ with the relative uncertainty of \pm 0.82 kJ·mol⁻¹.

2.4 Solubility Measurement

Solubility measurement for DAPT in different solvents including tetrahydrofuran, methanol, ethanol, n-propanol, and isopropanol were carried out using a static equilibrium technique. For this purpose, excess DAPT was added in the pure solvent with stirring of the solution constantly for a minimum of 4 h under a constant

temperature. The stirring was left alone to settle down and obtain a clear solution. The clear supernatant was transferred into a preliminary-weighed 5.0 mL vial using a preheated on-off injector coupled with a 0.2 µm PTFE filter, after which the vial was immediately covered. After measuring the weight of the vial the sample was evaporated under vacuum drying oven at 353.15 K which is well below the decomposition temperature of DAPT (464 K) and it was continued till a constant weight was reached. Each experiment was carried out in triplicate to verify the result. The mean values of the solubility in a mole fraction were calculated from three different samples at each temperature. The solubility of DAPT in each solvent was determined using the equation shown below:

$$x = \frac{m_1/M_1}{m_1/M_1 + m_2/M_2} \tag{1},$$

where, x is the mole fraction of the solute, m_1 , m_2 represent the mass of the solute, solvent, and M_1 , M_2 are the molecular weight of the solute, solvent, respectively.

2.5 Density Functional Theory Calculations of Interaction Energy

Gaussian 09 method [20] was used to carry out the calculation based on Density functional theory (DFT) for the identification of interaction profiles of DAPT with various solvents. It was well known from earlier reports that solubility data could be well explained by DFT based calculations [11-13]. Frequency analysis and Geometry optimizations were performed at B3LYP/6-311G (d, p) levels. Zero-point corrections to energies were included in the frequency analysis along with the thermochemical information at NTP. Default values in Gaussian were adopted based on the

convergence criteria. The total energies of the isolated DAPT and solvent molecules were subtracted from the energies of their (1:1) complex to obtain the gas-phase (solute + solvent) interaction energies. The interaction energy can be defined as [12]:

$$E_{\text{inter}} = -(E_{0-1} - E_0 - E_1) \tag{2}$$

where E_1 is the total initial energy of DAPT, E_0 is initial solvent energy and E_{0-1} is the energy of the DAPT-solvent complex.

3. Results and discussion

3.1 Solubility Determination in the Selected Solvents

Table 2 and Figure 4 present DAPT solubility data in various solvents studied at different temperatures. DAPT solubility in all solvents increased as temperature increased. Maximum DAPT solubility was in THF. In alcohol, the DAPT solubility was slowly increased with increasing temperature. The solvents had the following order for solubility of DAPT: tetrahydrofuran > methanol > ethanol > n-propanol > isopropanol. In general, solvent polarity plays the most defining factor playing a role in the material solubility [21,22]. The polarity of the solvents used in this work can be expressed as following [23]: methanol > ethanol > isopropanol > tetrahydrofuran > n-propanol. This order does not agree with the DAPT solubility in these solvents. Thus, in the case of DAPT, solvent polarity was not the dominant factor for its solubility degree. It is indeed the intermolecular interactions between solvent molecules and DAPT that determine DAPT solubility. The calculated values of intermolecular interaction energies, described at the B3LYP/6-311G (d, p) level, are presented in

Table 3. It is evident from Table 3 that THF-DAPT interaction is stronger (22.9 kJ/mol) in comparison to the other solvents. This can be explained on the basis of interaction of DAPT via NH (from NH₂ group) with the oxygen atom of furan ring can provide a lone pair of electrons to hold together by a strong N–H · · · O bond (Figure 5). In the case of alcohols, the hydroxyl group formed a weak bond of O–H · · · N (pyridine or triazine) type, having interaction energies of 17.4, 16.8, 16.6 and 15.0 kJ/mol for methanol, ethanol, n-propanol and isopropanol, respectively. The larger the energy value of E_{inter} , the stronger interactions occurred between DAPT and the solvent molecules. So the THF can dissolve the largest amount of solute. All these results together suggested that the polarities of the solvents and the energy of intermolecular interactions could indeed play a key role in affecting the solubility behavior of DAPT.

3.2 Solubility Correlation

We used modified Apelblat equations to establish how DAPT solubility depends on temperature [14]:

$$\ln x = A + \frac{B}{T} + C \ln T \tag{3}$$

where, A, B and C are the model parameters of the modified Apelblat equation; x is a mole of DAPT dissolved and T is the absolute temperature. Table 4 gives the parameters of the model. The relative and root-mean-square relative deviations (*RD* and *Rmsrd*) for the solvents used in this work were calculated as shown below:

$$RD = \frac{x_i^{\exp} - x_i^{cal}}{x_i^{\exp}}$$
(4)

$$Rmsrd = \left[\frac{1}{N}\sum_{i=1}^{N} \left(\frac{x_i^{\exp} - x_i^{\operatorname{cal}}}{x_i^{\exp}}\right)^2\right]^{1/2}$$
(5)

where, *N* is the total number of experimental data points, x_i^{exp} and x_i^{cal} stand for the values obtained from experiment and calculation, respectively. Table 2 lists the calculated results, which were then fitted using Equation 3.

The Buchowski-Ksiazaczak λh equation [15] was also used in this work to process our the solubility data because it describes the solid-liquid equilibria (SLE) very well [24-26]:

$$\ln\left[1 + \frac{\lambda(1-x_1)}{x_1}\right] = \lambda h(\frac{1}{T} - \frac{1}{T_m})$$
(6),

where, $T_{\rm m}$ is the melting point of the DAPT, and λ and h are model parameters obtained from the fitting experimental data.

The optimized parameters λ and *h* for DAPT in five solvents along with the *Rmsrd* values are described in Table 5. When the λh equation was used to regress the experimental data, the average *Rmsrd* was 2.09% with the maximum being no more than 7%.

In order to better understand and describe the solubility data, activity coefficient obtained using Wilson [16] and NRTL [17] models were used to correlate the solid-liquid equilibria [8, 27-29]:

$$\ln\frac{1}{x_1\gamma_1} = \frac{\Delta_{fus}H}{RT_m} \left(\frac{T_m}{T} - 1\right) \tag{7}$$

where, $\Delta_{\text{fus}}H$ is fusion enthalpy; T_{m} is melting temperature; R is the gas constant; and x_1 and γ_1 are mole fraction and activity coefficient of a solute, respectively.

The binary cross-interaction parameters in the Wilson equation ($\Delta \lambda_{12}$ and $\Delta \lambda_{21}$) and NRTL equation (Δg_{12} and Δg_{21}) were presumed to be linearly dependent on temperature:

$$k_{ij} = \alpha_{ij} + \beta_{ij}T \tag{8},$$

where *k* denotes one of the above-mentioned interaction parameters. In order to fit α and β obtained from the experiments, the equation was applied:

$$\min f = \sum_{i=1}^{N_p} (\ln \gamma_i^{\exp} - \ln \gamma_i^{cal})^2$$
(9)

Eqn. 7 was used to calculate the experimental activity coefficients. Now we used the Levenberg-Marquardt method to minimize Eqn. 9. For each model, the correlation results were derived by comparison of the root-mean-square relative deviation and the optimized values of the parameters are shown in Table 4 and the calculated solubilities with relative deviation are listed in Table 2. Accurate experimental results could be replicated by the optimized parameters from all the models as evident from Table 2 and Table 4. When comparing the *Rmsrd* values among different models, the modified Apelblat equation, the λ h equation, the Wilson and the NRTL models showed the following values of $\Sigma Rmsrd$: 5.67, 10.43, 6.01 and 6.07, respectively. These values indicate that the modified Apelblat equation provided better-fitting performance than other models. Thus, it is more accurate to describe processed in the system studied in this work.

4. Conclusions

DAPT was synthesized and different instrumental techniques like IR, NMR, TGA, HRTEM were used to characterize the synthesized product. Five different solvents were used to study the DAPT solubility employing a static analytical technique in the 288.15-318.15 K range. THF showed maximum solubility for DAPT whereas isopropanol resulting in minimum value. DAPT solubility in the solvents studied in this work increased as temperature increased. Quantum mechanical calculations proved that the solubility of DAPT is dependent on the strength of solute-solvent bonding. The modified Apelblat and λh equations as well as Wilson and NRTL models were used to assess the validity of our solubility data. The Apelblat equation described our data more accurately than the λh equation with an average relative error <0.03. From the obtained results, we can conclude that the solvent dependent solubility data of DAPT are important in the purification of pyridyldiaminotriazines.

Acknowledgments

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References

[1] N.J. Vogelzang, J.E. Herndon, C. Cirrincione, D.C. Harmon, K.H. Antman, J.M. Corson, Y. Suzuki, M.L. Citron, M.R. Green. Dihydro-5-azacytidine in malignant mesothelioma: A Phase II trial demonstrating activity accompanied by cardiac toxicity. Cancer, 79 (1997) 2237-2242.

[2] Z. Brzozowski, F. Saczewski, M. Gdaniec. Synthesis, structural characterization and antitumor activity of novel 2, 4-diamino-1, 3, 5-triazine derivatives. Eur J. Med. Chem. 35 (2000) 1053-1064.

[3] C.B. Yoo, P.A. Jones. Epigenetic therapy of cancer: past, present and future. Nat. Rev. Drug Discov. 5 (2006) 37-50.

[4] K.E. Maly, E. Gagnon, T. Maris, J.D. Wuest. Engineering hydrogen-bonded molecular crystals built from derivatives of hexaphenylbenzene and related compounds. J. Am. Chem. Soc. 129 (2007) 4306-4322.

[5] P. Li, H.D. Arman, H. Wang, L. Weng, K. Alfooty, R.F. Angawi, B. Chen. Solvent dependent structures of melamine: porous or nonporous? Cryst. Growth Des. 15 (2015) 1871-1875.

[6] J.Y. Li, M.J. Xie, J. Jiang, Q.W. Chang, Q.S. Ye, W.P. Liu, J.L. Chen, P. Ning. Synthesis and crystal structure of two polydimensional molecular architectures from cobalt (II), copper (II) complexes of 2, 4-diamino-6-pyridyl-1, 3, 5-triazine. Asian J. Chem. 26 (2014) 419-422.

[7] A. Duong, M.A. Dubois, T. Maris, V. Metivaud, J.H. Yi, A. Nanci, A. Rochefort, J.D. Wuest. Engineering homologous molecular organization in 2D and 3D. Cocrystallization of pyridyl-substituted diaminotriazines with alkanecarboxylic acids. J. Phys. Chem. C 115 (2011) 12908-12919.

[8] J.M. Prausnitz, R.N. Lichtenthaler, E.G. Azevedo. Molecular Thermodynamics of Fluid-Phase Equilibria, 3rd ed., Prentice Hall, New York, 1999.

[9] W.L. Smith. Selective solubility: "Like Dissolves Like". J. Chem. Educ. 54 (1977) 228-229.

[10] J.Q. Liu, H. Chen, S.F. An, T.T. Li. Solubility measurement and correlation of 2-phenyl-1H-indole in fourteen mono organic solvents from 289.05K to 338.55K. J. Mol. Liq. 302 (2020) 112491.

[11] H. Zhang, Q. Yin, Z. Liu, J. Gong, Y. Bao, M. Zhang, H. Hao, B. Hou, C. Xie. Measurement and correlation of solubility of dodecanedioic acid in different pure solvents from T = (288.15 to 323.15) K. J. Chem. Thermodyn. 68 (2014) 270-274.

[12] X. Shao, H. Ge, Z. Li, C. Ren, J. Wang. Solubility of methylphosphonic acid in selected organic solvents. Fluid Phase Equilib. 390 (2015) 7-13.

[13] C.Yu, Z. Huang, Z. Zeng, W. Xue. Thermodynamic models for correlation of solubility of hexaquocobalt(II) bis(p-toluenesulfonate) in liquid mixtures of water and ethanol from 288.15 to 333.15 K. J. Solution Chem. 45 (2016) 395-409.

[14] Apelblat, A.; Manzurola, E. Solubilities of o-acetylsalicylic, 4-aminosalicylic, 3,
5-dinitrosalicylic, and p-toluic acid, and magnesium-DL-aspartate in water fromT=(278 to 348) K. J. Chem. Thermodyn. 31 (1999) 85-91.

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

[16] G.M. Wilson. Vapor-liquid equilibrium. XI. A new expression for the excess free energy of mixing. J. Am. Chem. Soc. 86 (1964) 127-130.

[17] H. Renon, J.M. Prausnitz. Local compositions in thermodynamic excess functions for liquid mixtures. AIChE J. 14 (1968) 135-144.

[18] M.Y. Li, D. Constantinescu, L.S. Wang, A. Mohs, J. Gmehling. Solubilities of NaCl, KCl, LiCl, and LiBr in methanol, ethanol, acetone, and mixed solvents and correlation using the LIQUAC model. Ind. Eng. Chem. Res. 49 (2010) 4981-4988.

[19] A. Diaz-Ortiz, J. Elguero, C. Foces-Foces, A. de la Hoz, A. Moreno, M. del Carmen Mateo, A. Sanchez-Migallon, G. Valiente. Green synthesis and self-association of 2, 4-diamino-1, 3, 5-triazine derivatives. New J. Chem. 28 (2004) 952-958.

[20] M.J. Frisch, G.W. Trucks, H.B. Schlegel, *et al. Gaussian 09*, revision A.01; Gaussian, Inc., Wallingford CT, 2009.

[21] S. Imran, A. Hossain, K.Mahali, P.S. Guin, A. Datta, S. Roya. Solubility and peculiar thermodynamical behaviour of 2-aminobenzoic acid in aqueous binary solvent mixtures at 288.15 to 308.15 K. J. Mol. Liq. 302 (2020) 112566.

[22] K. Mahali, P.S. Guin, S. Roy, B.K. Dolui.Solubility and solute–solvent interaction phenomenon of succinic acid in aqueous ethanol mixtures. J. Mol. Liq. 229 (2017) 172–177.

[23] B.E. Poling, J.M. Prausnitz, J.P. O'Connell, The Properties of Gases and Liquids, 5th ed., McGrawHill, New York, 2001.

[24] X. Ma, Q. Zhao, Q. Liu, Y. Xing, R. Fan, R. Tian. Synthesis and solubility of 5,5-dimethyl-2-(phenyl(phenylamino)methyl)-1,3,2-dioxaphosphinane 2-oxide in selected solvents between 278.15 K and 347.15 K. J. Chem. Eng. Data 62 (2017) 4196-4204.

[25] Y. Wang, Y. Chen, P. Zhu, Y. Bao, C. Xie, J. Gong, X. Jiang, B. Hou, W. Chen. Measurement and correlation of the solubility of 2,6-dihydroxybenzoic acid in alcohols and binary solvents. J. Chem. Eng. Data 62 (2017) 3009-3014.

[26] K.H. Kim, H.K. Oh, B. Heo, N.A. Kim, D.G. Lim, S.H. Jeong. Solubility evaluation and thermodynamic modeling of β -lapachone in water and ten organic solvents at different temperatures. Fluid Phase Equilib. 472 (2018) 1-8.

[27] Y.J. Li, K. Wu, Y. Li, Y. Zhang, J.J. Liu, X.Z. Wang. Solubility in different solvents, crystal polymorph and morphology, and optimization of crystallization process of AIBN. J. Chem. Eng. Data 63 (2018) 27-38.

[28] P. Zhang, R. Zhao, C. Zhang, T. Lia, B. Ren. Solubility determination and correlation of cyromazine in sixteen pure solvents and mixing properties of solutions. Fluid Phase Equilib. 475 (2018) 77-88.

[29] H. Shekaari, M.T. Zafarani-Moattar, M. Mokhtarpour. Experimental determination and correlation of acetaminophen solubility in aqueous solutions of choline chloride based deep eutectic solvents at various temperatures. Fluid Phase Equilib. 462 (2018) 100-110.

Source	Purity (mass	Analysis
	fraction)	method
Synthesized in this work	≥0.993	HPLC ^a
Shanghai Aladdin Chemical Reagent Co.	≥0.99	HPLC
Shanghai Aladdin Chemical Reagent Co.	≥0.98	HPLC
Shanghai Aladdin Chemical Reagent Co.	≥0.98	GC^{b}
Shanghai Aladdin Chemical Reagent Co.	≥0.995	GC
Shanghai Aladdin Chemical Reagent Co.	≥0.995	GC
Shanghai Aladdin Chemical Reagent Co.	≥0.995	GC
Shanghai Aladdin Chemical Reagent Co.	≥0.995	GC
Shanghai Aladdin Chemical Reagent Co.	≥0.995	GC
	Source Synthesized in this work Shanghai Aladdin Chemical Reagent Co. Shanghai Aladdin Chemical Reagent Co.	SourcePurity (mass fraction)Synthesized in this work ≥ 0.993 Shanghai Aladdin Chemical Reagent Co. ≥ 0.99 Shanghai Aladdin Chemical Reagent Co. ≥ 0.98 Shanghai Aladdin Chemical Reagent Co. ≥ 0.98 Shanghai Aladdin Chemical Reagent Co. ≥ 0.98 Shanghai Aladdin Chemical Reagent Co. ≥ 0.995

Table 1. Purity of the chemicals used in the study

^{*a*}High-performance liquid chromatography. ^{*b*}Gas-liquid chromatography.

<i>T</i> /K	$10^{2}x$	Apelblat equation		λh equ	λh equation		NRTL		Wilson	
		$10^2 x^c$	$10^2 RD$	$10^2 x^c$	$10^2 RD$	$10^2 x^c$	$10^2 RD$	$10^2 x^c$	$10^2 RD$	
Tetrahyd	lrofuran									
288.15	0.3081	0.3073	-0.26	0.3110	0.96	0.3121	1.29	0.3122	1.34	
293.15	0.3339	0.3342	0.09	0.3352	0.39	0.3348	0.28	0.3349	0.31	
298.15	0.3622	0.3605	-0.48	0.3596	-0.72	0.3584	-1.06	0.3584	-1.04	
303.15	0.3897	0.3857	-1.02	0.3841	-1.43	0.3827	-1.80	0.3827	-1.79	
308.15	0.4071	0.4098	0.65	0.4087	0.39	0.4078	0.16	0.4078	0.18	
313.15	0.4329	0.4323	-0.15	0.4331	0.05	0.4336	0.15	0.4337	0.18	
318.15	0.4552	0.4530	-0.48	0.4574	0.48	0.4601	1.07	0.4603	1.12	
Methano	01									
288.15	0.1377	0.1360	-1.25	0.1337	-2.91	0.1364	-0.93	0.1360	-1.21	
293.15	0.1494	0.1527	2.23	0.1523	1.96	0.1528	2.26	0.1529	2.34	
298.15	0.1698	0.1713	0.90	0.1724	1.52	0.1711	0.77	0.1715	1.02	
303.15	0.1977	0.1919	-2.92	0.1938	-1.97	0.1916	-3.08	0.1921	-2.82	
308.15	0.2143	0.2147	0.19	0.2165	1.02	0.2146	0.12	0.2149	0.28	
313.15	0.2369	0.2399	1.26	0.2404	1.46	0.2401	1.35	0.2400	1.32	
318.15	0.2687	0.2677	-0.39	0.2653	-1.28	0.2684	-0.11	0.2677	-0.37	
Ethanol										
288.15	0.07339	0.07288	-0.69	0.07075	-3.60	0.07276	-0.86	0.07270	-0.93	
293.15	0.08134	0.08271	1.68	0.08203	0.85	0.08249	1.41	0.08257	1.51	
298.15	0.09246	0.09401	1.68	0.09452	2.22	0.09377	1.42	0.09388	1.54	
303.15	0.1097	0.1070	-2.43	0.1082	-1.34	0.1068	-2.63	0.1069	-2.59	
308.15	0.1218	0.1220	0.18	0.1232	1.13	0.1218	0.02	0.1218	0.01	
313.15	0.1372	0.1393	1.52	0.1394	1.60	0.1390	1.34	0.1390	1.31	
318.15	0.1593	0.1591	-0.10	0.1568	-1.54	0.1587	-0.37	0.1588	-0.33	
n-Propar	nol									
288.15	0.06406	0.06387	-0.30	0.05992	-6.47	0.06418	0.18	0.06397	-0.14	

Table 2. Experimental and theoretically predicated (using the methods listed below) mole fraction solubility (x) of DAPT in different solvents at 0.1 MPa.^a

293.15	0.07201	0.07197	-0.05	0.07103	-1.36	0.07216	0.21	0.07237	0.51
298.15	0.08302	0.08202	-1.21	0.08358	0.67	0.08225	-0.93	0.08247	-0.66
303.15	0.09417	0.09444	0.29	0.09763	3.68	0.09484	0.71	0.09477	0.64
308.15	0.1106	0.1098	-0.72	0.1132	2.38	0.1104	-0.21	0.1100	-0.57
313.15	0.1285	0.1288	0.24	0.1304	1.50	0.1295	0.74	0.1290	0.40
318.15	0.1534	0.1524	-0.67	0.1492	-2.74	0.1527	-0.43	0.1533	-0.10
Isopropa	nol								
288.15	0.04258	0.04225	-0.77	0.04024	-5.49	0.04239	-0.45	0.04213	-1.07
293.15	0.05056	0.05165	2.16	0.05081	0.50	0.05178	2.42	0.05187	2.59
298.15	0.06412	0.06315	-1.51	0.06350	-0.97	0.06334	-1.22	0.06350	-0.97
303.15	0.07871	0.07723	-1.88	0.07853	-0.23	0.07752	-1.52	0.07741	-1.66
308.15	0.09251	0.09445	2.09	0.09612	3.90	0.09485	2.53	0.09420	1.83
313.15	0.1157	0.1155	-0.18	0.1164	0.63	0.1160	0.24	0.1150	-0.63
318.15	0.1418	0.1412	-0.43	0.1396	-1.55	0.1417	-0.10	0.1419	0.04

^aStandard uncertainties u are $u(T) = \pm 0.05$ K, $u_r(p) = 0.05$, $u_r(x) = 0.03$.

Solution

solvents	Interaction energy $(kJ \cdot mol^{-1})$
Tetrahydrofuran	22.9
Methanol	17.4
Ethanol	16.8
n-Propanol	16.6
Isopropanol	15.0

Table 3. Calculated interaction energy between DAPT and solvents

		Apelbla	t equation	λh Equation			
solvent	A	В	С	Rmsrd/%	λ	h	Rmsrd/%
Tetrahydrofuran	128.25	-7042.7	-19.351	0.54	6.2133	279.03	0.76
Methanol	-58.409	-589.66	8.7865	1.59	7.5222	334.48	1.83
Ethanol	-138.71	3914.1	20.818	1.43	4.6595	570.87	1.95
n-Propanol	-355.33	13445	53.203	0.62	7.1562	425.65	3.23
Isopropanol	-159	3707.4	24.431	1.49	25.144	163.87	2.66
Overall				5.67			10.43

Table 4. DAPT parameters and *Rmsrd* obtained by applying modified Apelblat and λh equations for the solvents

25.

	Wilson	NRTL								
Solvent	α_{12}	β_{12}	α ₂₁	β_{21}	Rmsrd%	α_{12}	β_{12}	α ₂₁	β_{21}	Rmsrd%
THF	16.294	1.0503	-61436	179.78	1.04	-86599	188.47	-99.251	27.796	1.02
Methanol	80.829	13.736	-86627	188.91	1.61	-65809	139.59	-10554	31.452	1.61
Ethanol	9566.6	-17.253	-84783	185.11	1.42	-63760	131.1	-16114	56.322	1.41
n-Propanol	26839	-77.548	-87137	202.91	0.48	-34328	58.649	-16813	42.412	0.56
Isopropanol	111320	-323.45	-67415	135.92	1.46	-45916	83.761	-13921	40.892	1.49
overall					6.01					6.07

Table 5. Regression parameters and Rmsrd for DAPT obtained using Wilson and NRTL models for the solventsWilsonNRTL

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Scheme 1. Synthetic route of DAPT.



Figure 1. ¹H NMR and ¹³C NMR spectra of DAPT.



Figure 2. HRTEM micrographs of DAPT.



Figure 3. TGA/DSC curves for DAPT recorded under N_2 flow at 10 K/min heating rate.



Figure 4. Experimental solubility of DAPT in different solvents: ●, tetrahydrofuran;
▲, methanol; ▼, ethanol; ◆, n-propanol; ◄, isopropanol.



Figure 5. Interactions between DAPT and tetrahydrofuran (a), methanol (b), ethanol (c), n-propanol (d), and isopropanol (e).

Sili

Graphical Abstract



Author Statement

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Declaration of interests

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

The authors declare the following financial interests/personal relationships which

may be considered as potential competing interests:

Highlights

► The solubilities of 2,4-diamino-6-(4-pyridyl)-1,3,5-triazine in five different solvents have been obtained.

► The interaction energies between solute and solvents were calculated by Density functional theory (DFT).

► The experimental solubility data of 2,4-diamino-6-(4-pyridyl)-1,3,5-triazine were correlated by four thermodynamic models.

Solution