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Solubility and thermodynamic function of vanillin in ten different environmentally benign solvents

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ABSTRACT

The solubility of vanillin in ten different environmentally benign solvents namely water, ethanol, ethylene glycol (EG), ethyl acetate (EA), isopropanol (IPA), propylene glycol (PG), polyethylene glycol-400 (PEG-400), Transcutol, butanol-1 and butanol-2 was measured and correlated at $T = (298–318)$ K. The resulting experimental data were correlated with the modified Apelblat and Van't Hoff models. Both the models showed good correlation of experimental solubility data with calculated ones with root mean square deviations in the range of (0.08–1.55) %. The mole fraction solubility of vanillin was observed highest in PEG-400 (4.29×10^{-1} at 298 K) followed by Transcutol, EA, butanol-2, ethanol, EG, PG, IPA, butanol-1 and water from $T = (298–318)$ K. The results of thermodynamic function in terms of dissolution enthalpy, Gibbs energy and dissolution entropy showed endothermic, spontaneous and entropy-driven dissolution of vanillin in all environmentally benign solvents.

1. Introduction

Chemically, vanillin is 3-methoxy-4-hydroxybenzaldehyde (Fig. 1) which occurs as a white to slightly yellow crystalline needles (Noubigh, Cherif, Provost, & Abderrabba, 2008; Noubigh, Mgaidi, Abderrabba, Provost, & Furst, 2007). Its molecular formula and molar mass have been reported as $C_8H_8O_3$ and 152.15 g mol^{-1}, respectively (Noubigh et al., 2008). It is obtained from the bean or pod of *Vanilla orchid* and showed strong antioxidant activity due to the presence of phenolic group (Kayaci & Uyar, 2012; Kumar, Sharma, & Mishra, 2012; Peng et al., 2010). It is commonly used flavoring agent in food, beverage and pharmaceutical industries (Hundre, Karthik, & Anandharamakrishnan, 2015; Li, Jiang, Mao, & Shen, 1998; Walton, Mayer, & Narbad, 2003). The mole fraction solubility of vanillin in water has been reported as 1.17×10^{-3} at 298 K (Noubigh et al., 2008). The solubility of organic compounds in pure solvents is an important physicochemical parameter in purification, crystallization, separation/extraction, product development and industrial optimization process (Anwer et al., 2014; Noubigh et al., 2008; Shakeel, Anwer, Shazly, & Jamil, 2014; Shakeel, Haq, Alanazi, & Alsarra, 2015). Several environmentally benign solvents (also known as green solvents) such as Transcutol, ethanol, propylene glycol (PG) and polyethylene glycol-400 (PEG-400) have been investigated for solubilization of various natural bioactive organic compounds (Anwer et al., 2014; Liu, Chen, & Ji, 2014; Shakeel et al., 2014, 2015). The temperature dependent solubility data of vanillin in water and various salt solutions have been reported in literature (Noubigh et al., 2007, 2008). However, the temperature dependent solubility data of vanillin in ethanol, butanol-1, butanol-2, ethylene glycol (EG), ethyl acetate (EA), isopropanol (IPA), PG, PEG-400 and Transcutol are not available in literature. The modified Apelblat and Van't Hoff models are the commonly used mathematical models used to correlate the experimental solubility data with calculated ones (Apelblat & Manzurola, 1999; Liu et al., 2014; Manzurola & Apelblat, 2002). Therefore, in this work, the solubilities of natural vanillin in various environmentally benign solvents such as water, ethanol, butanol-1, butanol-2, EG, EA, IPA, PG, PEG-400 and Transcutol were measured and correlated at $T = (298–318)$ K and atmospheric pressure of 0.1 MPa using an isothermal method. From solubility data, various thermodynamic functions such as molar enthalpy of dissolution ($\Delta_{sol}H^0$), molar entropy of dissolution ($\Delta_{sol}S^0$) and Gibbs free energy ($\Delta_{sol}G^0$) were also determined using Van't Hoff and Krug analysis. The solubility data of this work could be useful in purification, crystallization, separation/extraction, pre-formulation studies and formulation development of vanillin in food, chemical and pharmaceutical industries.

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2. Experimental

2.1. Materials

Vanillin, ethyl alcohol (IUPAC name: ethanol), 1-butyl alcohol (IUPAC name: butanol-1) and 2-butyl alcohol (IUPAC name: butanol-2) were procured from Sigma Aldrich (St. Louis, MO). Transcutol (IUPAC name: diethylene glycol monoethyl ether) was procured from Gattefosse (Lyon, France). EA (IUPAC name: ethyl acetate), EG (IUPAC name: ethane-1,2-diol) and IPA (IUPAC name: 2-propanol) were procured from Winlab Laboratory (Leicestershire, UK). PG (IUPAC name: propane-1,2-diol) and PEG-400 [IUPAC name: poly (oxyethylene)] were procured from Fluka Chemicals (Busch, Switzerland). Chromatographic grade acetonitrile and acetone were procured from Acros Organics (Hamilton, NJ). The water used in this work was high pure chromatographic grade water which was obtained from Milli-Q water purification system (Berlin, Germany). All these materials were of high purity and used without any further purification. The detailed information about all these materials is presented in Table 1.

2.2. HPLC analysis of vanillin

The analysis of vanillin in solubility samples was carried out by reversed phase high performance liquid chromatography (RP-HPLC) method. The analysis was carried out at 298 K with Waters HPLC system (Waters, USA) equipped with an isocratic 1515 HPLC pump, 717 autosampler, quaternary pumps, a programmable dual λ UV–visible variable-wavelength absorbance detector (Waters, 2487), column oven and an inline vacuum degasser was used. The column used in this work was Nucleodur 150 × 4.6 mm RP C_8 column having a 5 μm packing as a stationary phase. The ternary mixture of acetonitrile:water:acetone (70:20:10% v/v) was used as a mobile phase. The elution of vanillin was performed at a flow rate of 1.0 mL min^{-1} at 220 nm. The proposed RP-HPLC method was validated for linearity, accuracy, precision, sensitivity and specificity (unpublished data).

2.3. Measurement of vanillin solubility

The mole fraction solubility of vanillin in ten different environmentally benign solvents was measured from $T = (298–318)$ K at $p = 0.1$ MPa using an isothermal method of Higuchi and Connors (Higuchi & Connors, 1965). The excess amount of crystalline vanillin was added in 5 g of each environmentally benign solvent in triplicates. The concentrated suspensions were shaken continuously in a biological shaker (Julabo, PA) at 100 rpm for 72 h. The temperature of shaker was controlled precisely with thermostatic bath equipped with shaker. After 72 h, all the concentrated suspensions were taken out from the shaker and allowed to settle vanillin particles for 2 h (Anwer et al., 2014; Shakeel et al., 2015). The supernatants from each sample were centrifuged at 5000 rpm for 15 min in order to remove fine solid particles. The samples were diluted around 1000 times with respective environmentally benign solvent and subjected for analysis of vanillin content by RP-HPLC method at 220 nm as described in previous section. The proposed RP-HPLC method was observed linear in the concentration range of (0.1–100) μg g^{-1} with correlation coefficient of 0.997. The experimental mole fraction solubility (x_e) of vanillin in each environmentally benign solvent was calculated using Eq. (1) (Anwer et al., 2014; Shakeel et al., 2015):

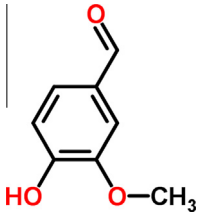

Fig. 1. Molecular structure of vanillin (molar mass: 152.15 g mol^{-1}).

$$x_e = \frac{m_1/M_1}{m_1/M_1 + m_2/M_2} \quad (1)$$

In which, m_1 and m_2 are the masses of vanillin (g) and respective environmentally benign solvent (g), respectively. M_1 and M_2 are the molar masses of vanillin (g mol^{-1}) and respective environmentally benign solvent, respectively.

3. Results and discussion

3.1. Measured solubility data of vanillin

The measured solubility data of vanillin in ten different environmentally benign solvents from $T = (298–318)$ K at atmospheric pressure of 0.1 MPa are listed in Table 2. The temperature-dependent solubility data of vanillin in water are available in literature. The solubility of vanillin in water has been reported as 1.17×10^{-3} at $T = 298$ K (Noubigh et al., 2008). In the present work, the solubility of vanillin in water was observed as 1.23×10^{-3} at $T = 298$ K. This value was very close to reported value of vanillin in water which indicated that the results of our work were in good agreement with previous literature. The graphical correlation between experimental and literature solubilities of crystalline vanillin in water is presented in Fig. 2 at $T = (298–318)$ K. The results showed good correlation between experimental and literature values of vanillin in water (Fig. 2). Overall, these results indicated good agreement of experimental data of this work with reported solubility data of vanillin in water at $T = (298–318)$ K. Generally, the values of x_e were found to be increased with the rise

Table 1
Sample table for vanillin and environmentally benign solvents used in the experiment.

Material	Molecular formula	Molar mass (g mol^{-1})	Purity (mass fraction)	Purification method	Analysis method	Source
Vanillin	$C_8H_8O_3$	152.15	0.990	None	HPLC	Sigma Aldrich
Ethanol	C_2H_5OH	46.06	0.999	None	GC	Sigma Aldrich
Propylene glycol	$C_3H_8O_2$	76.09	0.995	None	GC	Fluka Chemicals
Transcutol	$C_6H_{14}O_3$	134.17	0.999	None	GC	Gattefosse
Polyethylene glycol-400	$H(OCH_2CH_2)_nOH$	400.00	0.999	None	GC	Fluka Chemicals
Ethylene glycol	$C_2H_6O_2$	62.07	0.996	None	GC	Winlab Laboratory
Ethyl acetate	$C_4H_8O_2$	88.10	0.998	None	GC	Winlab Laboratory
Isopropyl alcohol	C_3H_8O	60.10	0.997	None	GC	Winlab Laboratory
Butanol-1	$C_2H_6O_2$	74.12	0.995	None	GC	Sigma Aldrich
Butanol-2	$C_4H_{10}O$	74.12	0.995	None	GC	Sigma Aldrich

HPLC: high performance liquid chromatography; GC: gas chromatography.

Table 2
Experimental mole fraction solubilities (x_e) of crystalline vanillin in ten different environmentally benign solvents (S) at temperatures T = (298–318) K and pressure p = 0.1 MPa[a] (values in parentheses are standard deviations).

S	x_e				
	T = 298 K	T = 303 K	T = 308 K	T = 313 K	T = 318 K
Water	1.23 (0.01) × 10^{-3}	1.54 (0.02) × 10^{-3}	1.87 (0.02) × 10^{-3}	2.19 (0.03) × 10^{-3}	2.56 (0.04) × 10^{-3}
Ethanol	7.94 (0.05) × 10^{-2}	8.33 (0.06) × 10^{-2}	8.61 (0.07) × 10^{-2}	9.03 (0.07) × 10^{-2}	9.36 (0.08) × 10^{-2}
PG	7.15 (0.04) × 10^{-2}	7.45 (0.04) × 10^{-2}	7.75 (0.05) × 10^{-2}	8.09 (0.06) × 10^{-2}	8.55 (0.07) × 10^{-2}
PEG-400	4.29 (0.01) × 10^{-1}	4.42 (0.03) × 10^{-1}	4.52 (0.02) × 10^{-1}	4.66 (0.04) × 10^{-1}	4.77 (0.06) × 10^{-1}
Transcutol	2.38 (0.02) × 10^{-1}	2.46 (0.02) × 10^{-1}	2.54 (0.03) × 10^{-1}	2.61 (0.04) × 10^{-1}	2.68 (0.04) × 10^{-1}
EG	7.54 (0.06) × 10^{-2}	7.93 (0.06) × 10^{-2}	8.34 (0.07) × 10^{-2}	8.71 (0.08) × 10^{-1}	9.09 (0.09) × 10^{-2}
IPA	6.60 (0.03) × 10^{-2}	6.91 (0.04) × 10^{-2}	7.25 (0.04) × 10^{-2}	7.59 (0.05) × 10^{-2}	7.89 (0.06) × 10^{-2}
EA	1.23 (0.01) × 10^{-1}	1.27 (0.01) × 10^{-1}	1.31 (0.02) × 10^{-1}	1.36 (0.02) × 10^{-1}	1.40 (0.03) × 10^{-1}
Butanol-1	6.47 (0.02) × 10^{-2}	6.81 (0.01) × 10^{-2}	7.15 (0.03) × 10^{-2}	7.52 (0.04) × 10^{-2}	7.86 (0.05) × 10^{-2}
Butanol-2	8.79 (0.06) × 10^{-2}	9.20 (0.07) × 10^{-2}	9.64 (0.05) × 10^{-2}	1.00 (0.04) × 10^{-1}	1.04 (0.03) × 10^{-1}

[a] The standard uncertainties u are $u(T)$ = 0.14 K, $u_r(m)$ = 0.1%, $u(p)$ = 0.003 MPa and $u_r(x_e)$ = 1.2%.

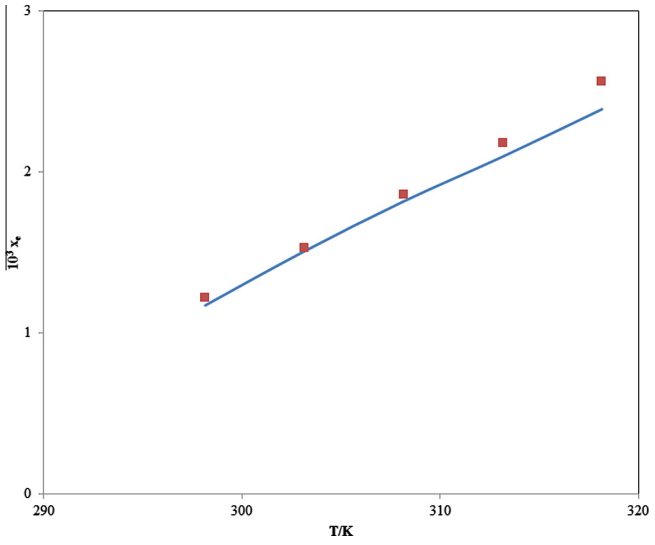

Fig. 2. Comparison of experimental mole fraction solubilities of crystalline vanillin in water with literature values at (298–318) K; symbol represents the experimental solubilities and solid line represents the literature values taken from Noubigh et al. (2008).

in temperature in all environmentally benign solvents investigated. The x_e values of crystalline vanillin were observed highest in PEG-400 (4.29×10^{-1} at T = 298 K) followed by Transcutol (2.38×10^{-1} at T = 298 K), EA (1.23×10^{-1} at T = 298 K), butanol-2 (8.79×10^{-2} at T = 298 K), ethanol (7.94×10^{-2} at T = 298 K), EG (7.54×10^{-2} at T = 298 K), PG (7.15×10^{-2} at T = 298 K), IPA (6.60×10^{-2} at T = 298 K), butanol-1 (6.47×10^{-2} at T = 298 K) and water (1.23×10^{-3} at T = 298 K) from T = (298–318) K (Table 2). The x_e values of crystalline vanillin in PEG-400, Transcutol and EA were significantly higher than water and other environmentally benign solvents. However, the x_e values of vanillin in butanol-2, ethanol, EG, PG, IPA and butanol-1 were not significantly different at each temperature investigated. Nevertheless, the x_e values of vanillin in butanol-2, ethanol, EG, PG, IPA and butanol-1 were significantly higher than water at each temperature investigated. The higher x_e values of vanillin in organic solvents were probably due to lower polarity of organic solvents as compared to water. Overall, the solubility of vanillin was good in all environmentally benign solvents investigated. Based on these results, crystalline vanillin has been considered as freely soluble in PEG-400, Transcutol, EA, butanol-2, ethanol, EG, PG, IPA and butanol-1 and soluble in water according to the United States Pharmacopoeia (USP) classification of solubility.

3.2. Correlation of experimental solubilities with Van't Hoff model

Van't Hoff model was applied to correlate experimental solubilities of vanillin with calculated ones (Liu et al., 2014). According to this model, the mole fraction solubility of crystalline vanillin can be calculated using Eq. (2):

$$\ln x^{idl} = a + \frac{b}{T} \tag{2}$$

In which, x^{idl} is the mole fraction solubility of vanillin calculated by Van't Hoff model. The parameters a and b are the Van't Hoff model parameters which were calculated by plotting ln x_e as a function of $1/T$. For the correlation of x_e with x^{idl}, the root mean square deviations ($RMSD$) were calculated with the help of Eq. (3) (Shakeel et al., 2015).

$$RMSD = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\frac{x^{idl} - x_e}{x_e}\right)^2\right]^{\frac{1}{2}} \tag{3}$$

In which, N represents the number of temperature points. The correlation between x_e and x^{idl} in ten different environmentally benign solvents from T = (298–318) K is presented in Fig. S1.

The values of a, b, correlation coefficients (R^2) and $RMSD$ in all environmentally benign solvents are listed in Table S1. The $RMSD$ values in ten different environmentally benign solvents were observed in the range of (0.08–1.55) % (Table S1). The highest value of $RMSD$ was observed in water (1.55%). However, the lowest one was observed in butanol-1 (0.08%). The R^2 values for crystalline vanillin in ten different environmentally benign solvents were observed as 0.9920–0.9990. These data indicated good correlation of experimental solubilities of crystalline vanillin with Van't Hoff model.

3.3. Correlation of experimental solubilities with the modified Apelblat model

The modified Apelblat model was also used to correlate experimental solubilities of vanillin with calculated ones (Apelblat & Manzurola, 1999; Manzurola & Apelblat, 2002). The solubility of crystalline vanillin can be calculated using Eq. (4) for this model:

$$\ln x^{Apl} = A + \frac{B}{T} + C\ln(T) \tag{4}$$

In which, x^{Apl} is the calculated solubility of vanillin and T is the absolute temperature (K). The coefficients A, B and C are the modified Apelblat parameters which were calculated by multivariate

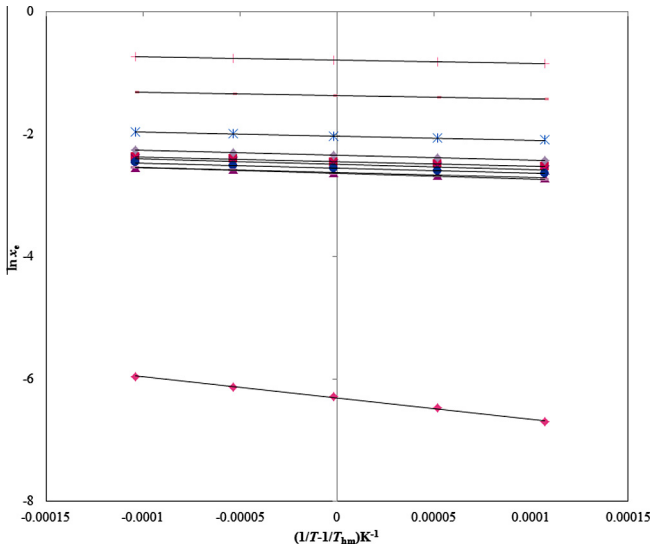

Fig. 3. Van't Hoff plots for experimental solubilities of crystalline vanillin in ten different environmentally benign solvents at mean harmonic temperature of 307.98 K; ◆ water, ■ ethanol, ▲ IPA, × EG, ✳ EA, ● PG, + PEG-400, ▬ Transcutol, ▬ butanol-1 and ◆ butanol-2.

non-linear regression analysis of experimental solubilities of vanillin listed in Table 2 (Shakeel et al., 2015). In order to correlate x_e with x^{Apl}, the *RMSD* values were calculated again using Eq. (3).

The values of the modified Apelblat parameters *A, B,* and *C*, R^2 and *RMSD* in ten different environmentally benign solvents are presented in Table S2. The *RMSD* values in ten different environmentally benign solvents were observed in the range of (0.13–0.57) % (Table S2). The R^2 values in ten different environmentally benign solvents were observed as 0.9970–0.9999. These data indicated again good correlation of experimental solubilities of crystalline vanillin with the modified Apelblat model. The correlation between x_e and x^{Apl} in ten different environmentally benign solvents from T = (298–318) K is presented in Fig. S2.

3.4. Thermodynamic function of vanillin dissolution

The dissolution enthalpy ($\Delta_{sol}H^0$) for crystalline vanillin in ten different environmentally benign solvents was determined by reported method of Van't Hoff analysis (Holguín, Rodríguez, Cristancho, Delgado, & Martínez et al., 2012; Ruidiaz, Delgado, Martínez, & Marcus, 2010). According to this method, the $\Delta_{sol}H^0$ values can be calculated at mean harmonic temperature (T_{hm}) using Eq. (5):

$$\left(\frac{\partial \ln x}{\partial\left(\frac{1}{T}-\frac{1}{T_{hm}}\right)}\right)_p = -\frac{\Delta_{sol}H^0}{R} \quad (5)$$

In which, R represents the universal gas constant. The T_{hm} was 307.98 K in this work. The Van't Hoff plots were constructed between ln x_e and $1/T - 1/T_{hm}$ using Eq. (5). These plots were found to be linear with R^2 values in the range of 0.992–0.999 as shown in Fig. 3.

The $\Delta_{sol}H^0$ values of crystalline vanillin in ten different environmentally benign solvents were determined from the slope of Fig. 3. The Gibbs free energy ($\Delta_{sol}G^0$) for the dissolution of vanillin in ten different environmentally benign solvents was calculated at T_{hm} by Krug analysis using Eq. (6) (Krug, Hunter, & Grieger, 1976):

$$\Delta_{sol}G^0 = -RT_{hm} \times intercept \quad (6)$$

In which, the intercept for each environmentally benign solvent was determined from Fig. 3.

Finally, the dissolution entropy ($\Delta_{sol}S^0$) for crystalline vanillin in ten different environmentally benign solvents was determined using Eq. (7):

$$\Delta_{sol}S^0 = \frac{\Delta_{sol}H^0 - \Delta_{sol}G^0}{T_{hm}} \quad (7)$$

The results of thermodynamic function in terms of $\Delta_{sol}H^0$, $\Delta_{sol}G^0$ and $\Delta_{sol}S^0$ for the dissolution of vanillin in ten different environmentally benign solvents are listed in Table 3.

The $\Delta_{sol}H^0$ values for vanillin dissolution were observed as positive values in all environmentally benign solvents investigated, indicating an endothermic dissolution behavior of vanillin in all environmentally benign solvents. The $\Delta_{sol}H^0$ value for vanillin dissolution in water, butanol-1, butanol-2, ethanol, EG, EA, IPA, PG, PEG-400 and Transcutol was observed as 28.73 kJ mol^{-1}, 6.85 kJ mol^{-1}, 7.69 kJ mol^{-1}, 6.45 kJ mol^{-1}, 7.36 kJ mol^{-1}, 5.23 kJ mol^{-1}, 7.11 kJ mol^{-1}, 6.92 kJ mol^{-1}, 4.14 kJ mol^{-1}and 4.65 kJ mol^{-1}, respectively. The $\Delta_{sol}G^0$ values for vanillin dissolution were also observed as positive values in all environmentally benign solvents, indicating spontaneous dissolution of vanillin in all environmentally benign solvents investigated. The $\Delta_{sol}G^0$ value for vanillin dissolution in water, butanol-1, butanol-2, ethanol, EG, EA, IPA, PG, PEG-400 and Transcutol was observed as 16.15 kJ mol^{-1}, 5.99 kJ mol^{-1}, 6.75 kJ mol^{-1}, 6.26 kJ mol^{-1}, 6.37 kJ mol^{-1}, 5.20 kJ mol^{-1}, 6.72 kJ mol^{-1}, 6.53 kJ mol^{-1}, 2.02 kJ mol^{-1}and 3.51 kJ mol^{-1}, respectively. The $\Delta_{sol}G^0$ and $\Delta_{sol}H^0$ values for vanillin dissolution were significantly lower in PEG-400, Transcutol and EA as compared to water. However, the $\Delta_{sol}G^0$ and $\Delta_{sol}H^0$ values for vanillin dissolution in ethanol, PG, EG, butanol-1, butanol-2 and IPA were not changed significantly. The data of $\Delta_{sol}G^0$ and $\Delta_{sol}H^0$ were in good agreement with solubility data of crystalline vanillin. The $\Delta_{sol}S^0$ values for vanillin dissolution were also observed as positive values in all environmentally benign solvents, indicating an entropy-driven dissolution of vanillin in all environmentally benign solvents. The lower values of $\Delta_{sol}H^0$ in PEG-400, EA and Transcutol indicated that relatively low energy is required for the solubilization of vanillin in PEG-400, EA and Transcutol as compared to water. The positive values of $\Delta_{sol}H^0$ for vanillin dissolution were possible due to the stronger interactions between vanillin molecules and the environmentally benign solvent molecules as compared to those between the solvent–solvent and vanillin–vanillin molecules as reported in literature (Shakeel et al., 2014, 2015).

Table 3
Thermodynamic parameters along with R^2 values for dissolution of crystalline vanillin in ten different environmentally benign solvents at mean harmonic temperature of 307.98 K (values in parentheses are standard deviations).

Parameters	Water	Ethanol	PG	PEG-400	Transcutol	EG	IPA	EA	Butanol-1	Butanol-2
$\Delta_{sol}H^0$/kJ mol^{-1}	28.73 (0.24)	6.45 (0.08)	6.92 (0.10)	4.14 (0.06)	4.65 (0.07)	7.36 (0.11)	7.11 (0.10)	5.23 (0.05)	6.85 (0.06)	7.69 (0.12)
$\Delta_{sol}G^0$/kJ mol^{-1}	16.15 (0.22)	6.26 (0.07)	6.53 (0.09)	2.02 (0.02)	3.51 (0.04)	6.37 (0.10)	6.72 (0.11)	5.20 (0.08)	5.99 (0.07)	6.75 (0.08)
$\Delta_{sol}S^0$/J mol^{-1} K^{-1}	40.82 (0.38)	0.60 (0.00)	1.26 (0.00)	6.88 (0.07)	3.69 (0.02)	3.23 (0.01)	1.22 (0.00)	0.11 (0.00)	2.78 (0.04)	3.03 (0.02)
R^2	0.996 (0.01)	0.997 (0.02)	0.992 (0.00)	0.999 (0.01)	0.999 (0.02)	0.999 (0.01)	0.999 (0.00)	0.997 (0.01)	0.999 (0.00)	0.999 (0.02)

4. Conclusion

The solubilities of crystalline vanillin in ten different environmentally benign solvents such as water, ethanol, butanol-1, butanol-2, EG, EA, IPA, PG, PEG-400 and Transcutol were measured at $T = (298–318)$ K using an isothermal method. The mole fraction solubility of vanillin was observed highest in PEG-400 followed by Transcutol, EA, butanol-2, ethanol, EG, PG, IPA, butanol-1 and water at $T = (298–318)$ K. The experimental solubility data of vanillin were correlated well with the modified Apelblat and Van't Hoff models in all environmentally benign at $T = (298–318)$ K. Thermodynamic function of vanillin dissolution was measured by Van't Hoff and Krug analysis. The results of thermodynamic function indicated endothermic, spontaneous and entropy-driven dissolution of crystalline vanillin in all environmentally benign solvents investigated. Based on solubility data of this work, crystalline vanillin has been considered as freely soluble in PEG-400, Transcutol, EA, butanol-2, ethanol, EG, PG, IPA and butanol-1 and soluble in water according to USP classification of solubility. The solubility data of this work could be useful in purification, crystallization, separation/extraction, preformulation studies and formulation development of vanillin.

5. Conflict of interest

The authors report no conflict of interest related with this manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foodchem.2015.01.102.

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