SEBHA UNIVERSITY JOURNAL OF PURE & APPLIED SCIENCES VOL.25 NO. 1 2026
DOI: 10.51984/w352jc43

مجلة جامعة سبها للعلوم البحتة والتطبيقية
Sebha University Journal of Pure & Applied Sciences

Journal homepage: www.sebhau.edu.ly/journal/jopas

Thermodynamic Behavior of Commercial Paracetamol Suspension under Aqueous Dilution

Aisha AL-Abbasi*, Mohammed Ahwidi, and Raja Ziriq

Chemistry Department, Faculty of Science, Sebha University, Libya.

Keywords:
Paracetamol.
Suspension.
Density.
Viscosity.
Surface Tension.
Redlich–Kister model.
Non-Ideal Mixtures.

ABSTRACT

This study examines the thermophysical and excess thermodynamic behavior of paracetamol Suspension upon dilution with water to form binary mixtures (paracetamol-water) at room temperature over a concentration range of 1 mg/mL – 10 mg/mL. Experimental measurements of density, viscosity and surface tension were used to calculate derived parameters including molar volume (Vm), excess molar volume (VE), excess viscosity (η^E), and excess surface tension (γ^E). The results showed that density decreased from 1.0152 g/mL to 0.998 g/mL with decreasing paracetamol concentration; additionally, the viscosity decreased from 1.1746 to 0.8903 mPa·s upon the dilution process. Surface tension initially increased, peaking at 75.64 mN/m at 5 mg/mL, before decreasing at lower concentrations. The minimum excess molar volume was −0.177 cm^3/mol, indicating volume contraction and strong molecular interactions. Maximum excess viscosity and surface tension were observed at mole fractions around 0.12, with $\eta^E = 0.284$ mPa·s and $\gamma^E = -7.52$ mN/m. The Redlich–Kister polynomial model provided an excellent fit for all excess properties with R^2 values above 0.98. These findings highlight the significant non-ideality and strong solute–solvent interactions in the system, offering valuable insight for pharmaceutical formulation and solubility optimization.

السلوك الديناميكي الحراري لمعلق الباراسيتامول التجاري تحت التخفيف المائي

عائشة العباسي*, محمد هويدي، و رجاء زريق

قسم الكيمياء، كلية العلوم، جامعة سبها، ليبيا.

الكلمات المفتاحية:
باراسيتامول.
معلق.
الكثافة.
اللزوجة.
التوتر السطحي.
نموذج ريدليتش-كيستر.
المخاليط غير المثالية.

الملخص

تتناول هذه الدراسة السلوك الثرموفيزيائي والدوال الثرموديناميكية الفائضة لمعلّق الباراسيتامول عند تخفيفه بالماء لتكوين مخاليط ثنائية (باراسيتامول–ماء) في درجة حرارة الغرفة، ضمن نطاق تركيز يتراوح بين 1 إلى 10 ملغم/مل. تم إجراء قياسات تجريبية للكثافة واللزوجة والتوتر السطحي، واستخدامها لحساب عدد من المعاملات المشتقة مثل الحجم المولي (Vm)، الحجم المولي الفائض (VE)، اللزوجة الفائضة (η^E)، والتوتر السطحي الفائض (γ^E). أظهرت النتائج أن الكثافة انخفضت من 1.0152 جم/مل إلى 0.998 جم/مل مع انخفاض تركيز الباراسيتامول؛ كما انخفضت اللزوجة من 1.1746 إلى 0.8903 مللي باسكال·ثانية خلال عملية التخفيف. أما التوتر السطحي فقد ارتفع في البداية، وبلغ ذروته عند 75.64 مللي نيوتن/م عند تركيز 5 ملغم/مل، قبل أن ينخفض مجددًا عند التراكيز الأقل. سُجّل الحد الأدنى للحجم المولي الفائض بقيمة −0.177 سم³/مول، مما يشير إلى حدوث انكماش حجمي وتفاعلات جزيئية قوية. كما لوحظت القيم القصوى للزوجة الفائضة والتوتر السطحي الفائض عند الكسور المولية القريبة من 0.12، حيث $\eta^E = 0.284$ مللي باسكال·ثانية و$\gamma^E = -7.52$ مللي نيوتن/م. وقد أظهر نموذج بولينوم ريدليخ–كيستر توافقًا ممتازًا مع جميع الخصائص الفائضة، حيث تجاوزت قيم معامل التحديد R^2 0.98. تسلط هذه النتائج الضوء على السلوك غير المثالي الكبير وقوة التفاعلات بين المذاب والمذيب في النظام، مما يوفر رؤى قيّمة لتطوير المستحضرات الصيدلانية وتحسين الذوبانية.

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*Corresponding author.
E-mail addresses:ais.alabbasi@sebhau.edu.ly, (M Ahwidi) moh.masaoud@sebhau.edu.ly, (R. Ziriq) raja.krifiet@sebhau.edu.ly
Article History : Received 07 August 25 - Received in revised form 21 November 25 - Accepted 25 January 26

1. Introduction

Paracetamol (also known as acetaminophen) is a widely used analgesic mediator that has been utilized internationally for long time, due to its efficacy, safety, and minimal gastrointestinal side effects related to anti-inflammatory drugs (NSAIDs) [1, 2]. It is an essential drug in both home and medical settings because of its medical use, which has made it a first-line treatment for mild to moderate fever and pain in both adults and children [1, 3, 4]. The medication comes in a number of oral dosage forms. These consist of liquid forms like elixirs, emulsions, and suspensions as well as solid forms like tablets, caplets, and capsules, as well as gel capsules[1] . The suspension form is primarily designed for children, because it is easier to administer and children are more likely to comply [5]. Paracetamol suspension is biphasic systems in which a active substance is dispersed as fine solid throughout a liquid, because the paracetamol does not dissolve completely and remains suspended [4, 6, 7]. Paracetamol's solubility and rate of dissolution are related to its bioavailability [8, 9]. In order to improve its oral bioavailability and absorption, paracetamol is diluted in water, primarily in suspension formulations [10, 11]. After being absorbed, paracetamol is first-pass metabolised in the liver, where it is primarily conjugated with glucuronic acid and sulphate to form water-soluble metabolites that are eliminated through urine (up to 85% in 24 hours, according to Savides et al., 1984 [11]). In order to achieve effective concentrations quickly in children, it is crucial that the diluted form maximises contact with absorptive surfaces [1, 3, 5, 12].

Therefore, improving and optimising paracetamol's kinetic performance requires an understanding of its physical interactions in solvent systems, especially water. The drug's solubility is affected by a number of variables, including temperature, concentration, and molecular interactions. Numerous studies have been conducted on the thermodynamic properties and solubility of paracetamol in different solvents [13-20]. Paracetamol solubility declines in sugar-water systems, with sorbitol having the biggest impact [15]. The solubility process has positive free energy values and is not spontaneous. Activated carbon efficiently eliminates paracetamol from aqueous solutions; adsorption rises with temperature and falls in basic solutions [14]. At high temperatures, the process is favourable and spontaneous. These investigations offer important new information about the thermodynamic and thermophysical characteristics of paracetamol in various solvent systems. Through solubility tests at various temperatures, the thermodynamic functions of Gibbs energy, enthalpy, and entropy for the solubility of acetaminophen in propylene glycol + water solvent mixtures were assessed. At every temperature examined, the solubility was greater in 100% propylene glycol [20].

Important insights into the nature of solute–solvent interactions can be gained in this context by examining dilution behaviour and thermophysical characteristics like density, viscosity, and surface tension. Additionally, calculating excess thermodynamic properties (such as excess molar volume, viscosity, and surface tension) provides more detailed information about the strength of molecular interactions and the behaviour that deviates from ideal solution. Drug formulation, improving solubility, and comprehending the mixing behaviour in multi-component pharmaceutical systems all depend on these parameters. To the best of our knowledge, this is the first study to link the dilution process of paracetamol suspension with experimentally measured excess properties. The current study attempts to explore the thermodynamic and physicochemical properties of paracetamol in aqueous solutions, with a particular focus on its dilution behaviour in suspension formulations, in response to the ongoing interest in understanding the chemistry of paracetamol [21-25]. The results directly affect how well paediatric paracetamol formulations dissolve and are delivered.

2. Experimental Section

2.1 Materials

Adol® a commercial paracetamol 250 mg/5 ml oral suspension (Table 1), was used without additional care. Propylene glycol (163.9 mg/5ml), sorbitol (682.0 mg/5ml), and sucrose (2.5g/5ml) are also present in Paracetamol Suspension. additionally includes tartrazine and carmoisine (as flavouring), propyl parahydroxybenzoate, and less than 1 mmol sodium/ml. As a solvent, distilled water was employed.

Table 1: Paracetamol 250mg/5ml Oral Suspension ingredients

Component	Amount	Notes	(% w/w)
Paracetamol	250 mg	Active ingredient	4.0%
Sucrose	2.5 g (2500 mg)	Sweetener	40.0%
Propylene glycol	163.9 mg	stabilizer	2.62%
Sorbitol	682.0 mg	Sweetener	10.91%
Sodium	<1 mmol ≈ <23 mg	Negligible	
Colorants	trace	Tartrazine, Carmoisine	42.47%
Water	balance to 5 mL	Solvent base	

2.2 Mixture Preparation

The commercial paracetamol suspension and distilled water were used in a methodical dilution process to create a number of paracetamol suspension solutions with different concentrations (based on Table 2). Ten mixtures were made by adjusting the amounts of water (VH_2O) and paracetamol suspension (V_{para}), while maintaining a constant total volume of 30 mL for each mixture. The lowest concentration (0 mg/mL) was pure water with no paracetamol added (Mixture 10), while the highest concentration mixture (10 mg/mL) was 30 mL of paracetamol suspension without any water (Mixture 1). Gradually reducing the volume of paracetamol suspension and increasing the volume of water produced intermediate concentrations between 9 and 1 mg/mL. For example, Mixture 3 contained 24 mL of paracetamol and 6 mL of water, resulting in an 8 mg/mL solution. For experimental analysis, this dilution method guaranteed precise and repeatable preparation of paracetamol solutions over a broad concentration range.

Table 2: Dilution process of paracetamol suspension

Mixture No	Para conc. mg/mL	Para volume V_{para}	Water volume V_{H2O}
1	10	30	0
2	9	27	3
3	8	24	6
4	7	21	9
5	6	18	12
6	5	15	15
7	4	12	18
8	3	9	21
9	1	3	27
10	0	0	30

2.3 Experimental Methods

Using common laboratory procedures, a number of measurements were made in order to look into the thermophysical behaviour of aqueous paracetamol solutions. A 25 cm³ calibrated pycnometer with a 1 mm diameter capillary was used to measure the densities of the pure solvent and paracetamol solutions (ranging from 1 mg/mL to 10 mg/mL). A single-pan digital balance with an accuracy of ±0.0001 g was used to obtain mass readings. An Ostwald viscometer was used to measure viscosity, and the Stallagmometer method (also known as the drop weight method), which works well with diluted aqueous systems, was used to assess surface tension. Density (d_{mix}), viscosity (η_{mix}), and surface tension (γ_{mix}) were all measured at room temperature (298.15 K). The thermodynamic quantities molar volume (V_M), excess molar volume (V^E), excess molar viscosity (η^E), and excess molar tension (γ^E) were computed from these measurements. The accuracy and dependability of the data, which showed distinct concentration-dependent trends in all measured properties, were validated by the consistency of results across replicates.

2.4 Data Analysis and Calculations

The following thermophysical and thermodynamic parameters were calculated from the experimental data using the respective formulas:

2.4.1 Molar Volume (V_m) and Excess Molar Volume (V^E)

The molar volume and the excess molar volume were calculated by equations 1 & 2, respectively.

$$V_m = M / \rho \qquad (1)$$

$$V^E = V_m - (X_1 \cdot V_{m_1} + X_2 \cdot V_{m_2}) \qquad (2)$$

Where V_m and V^E are the molar volume (cm³/mol) and the excess molar volume (cm³/mol), respectively, M is the molar mass of paracetamol (151.16 g/mol), X_1 and X_2 are the mole fractions of solvent and solute, respectively, and ρ is the density of the solution (g/cm³).

2.4.2 Viscosity (η) and Excess Molar Viscosity (η^E)

The viscosity was calculated by equation 3. On the other hand, **excess molar viscosity** was calculated by equation 4.

$$\eta_1 / \eta_2 = (\rho_1 \times t_1) / (\rho_2 \times t_2) \qquad (3)$$

$$\eta^E = \eta_{mix} - (X_{para} \cdot \eta_{para} + X_{water} \cdot \eta_{water}) \qquad (4)$$

Where η is the viscosity (mPa·s), and t is the flow time (s). The subscripts 1 and 2 denote the sample and the reference fluid (typically water), respectively. Viscosity of pure water (η_{water}) = **0.8903 mPa·s**, and the viscosity of pure paracetamol solution at X = 0.12 is 1.1746 **mPa·s**; we will assume this approximates η_{para}.

2.4.3 Surface Tension (γ) and Excess Molar Surface Tension (γ^E)

The surface tension and excess molar surface tension were calculated by the following equations:

$$\gamma_1 / \gamma_2 = (\rho_1 \times n_2) / (\rho_2 \times n_1) \qquad (5)$$

$$\gamma^E = \gamma_{mix} - (X_{para} \cdot \gamma_{para} + X_{water} \cdot \gamma_{water}) \qquad (6)$$

Where γ is the surface tension (mN/m), the subscripts 1 and 2 denote the sample and the reference fluid (typically water), respectively.With the assumptions: Surface tension of pure water (γ_{water}) = 71.78 mN/m, and surface tension of pure paracetamol (approximate) from the highest mole fraction = 64.255 mN/m**.**

2.4.4 Redlich–Kister Polynomial Model

In order to account for the non-ideal behaviour caused by molecular interactions between the components, the Redlich–Kister polynomial model is frequently used to correlate excess thermodynamic properties such as excess enthalpy, excess volume, and excess viscosity in binary mixtures. The model expresses the excess property Y^E as a function of the mole fraction x of one component, usually in the form of equation 9:

$$Y^E = x_1 \, x_2 \sum_{i=0}^{n} A_i \, (x_1 - x_2)^i \qquad (7)$$

where Y^E is the excess thermodynamic property, x_1 and x_2 are the mole fractions of components 1 and 2, respectively, and A_i are adjustable fitting parameters found through regression analysis. The Redlich–Kister model is valued for its adaptability and capacity to fit experimental data over a wide composition range, which makes it particularly helpful in forecasting excess properties for binary liquids.

3. Results and Discussion

The experimental results for aqueous paracetamol solutions at 298.15 K are shown in Table 3. Paracetamol concentrations in ppm and mg/mL, mole fractions (X_{para}), solution density (d_{mix}), molar volume (V_M), dynamic viscosity (η), and surface tension (γ) are all included in the dataset. To comprehend the physicochemical behaviour of paracetamol in aqueous media, these parameters were computed.

This study offers a thorough assessment of the concentration-dependent behaviour of paracetamol in aqueous solution, by examining a number of important thermophysical and thermodynamic parameters,

Table 3: Thermophysical properties of paracetamol aqueous solutions at 298.15 K

Mixture No	**Conc. mg/mL**	**X_{para} *10^{-2}**	**ρ (g/cm³)**	**V_m (cm³/mol)**	**η_{mix} (mPa·s)**	**γ_{mix} (mN/m)**	**V^E (cm³/mol)**	ηE **(mPa·s)**	γ^E **(mN/m)**
1	10	0	1.0152	17.71	1.1746	64.255	-0.177	0.2502	–6.6220
2	9	0.120	1.0144	17.726	1.1482	67.123	-0.163	0.2272	–3.8443
3	8	0.108	1.0135	17.744	1.1166	69.979	-0.148	0.1990	–1.0786
4	7	0.096	1.0134	17.748	1.0706	72.888	-0.134	0.1564	+1.7401
5	6	0.084	1.0121	17.773	1.0454	74.250	-0.12	0.1346	+3.0118
6	5	0.072	1.0112	17.791	1.0343	75.639	-0.106	0.1269	+4.3105
7	4	0.060	1.0092	17.828	1.0103	74.908	-0.092	0.1064	+3.4892
8	3	0.048	1.0064	17.879	0.9855	74.121	-0.078	0.0850	+2.6119
9	1	0.036	1.002	17.962	0.9241	72.644	-0.05	0.0304	+0.9543
10	0	0.012	0.998	18.036	0.8903	71.780	**0**	**0**	**0**

Where: ppm= para concentration in ppm, mg/mL= para concentration in mg/ml, X_{para}= mole fraction of para, d_{mix}= para density, V_M= para molar volume, V^E= para excess molar volume, γ_{mix} = para surface tension and η_{mix}= para viscosity,

3.1 Density and Molar Volume

The findings demonstrate distinct alterations in the thermodynamic and physical characteristics of the paracetamol–water mixtures as the paracetamol concentration dropped (dilution).

The solution density (Figure 1) clearly shows a decreasing trend from 1.0152 g/cm³ to 0.998 g/cm³ as the paracetamol concentration drops from 10 to 1 mg/mL. The overall mass per unit volume decreases as a result of the paracetamol molecules being incorporated into the aqueous medium.

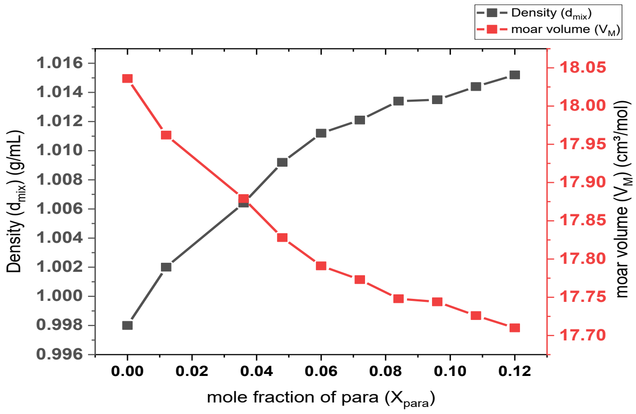

Figure 1: Density and Molar Volume of paracetamol in aqueous solution

The molar volume (Vm), on the other hand, exhibits an increasing trend, rising from 17.710 cm³/mol at 10 mg/mL to 18.036 cm³/mol at 1 mg/mL. This inverse relationship suggests that solute–solvent interactions have improved molecular packing, resulting in a more compact structure and lower free volume. Strong intermolecular interactions in solution are supported by this trend, which also points to less-than-ideal mixing behaviour.

3.2 Viscosity and Surface Tension

As more water is added, the viscosity decreases significantly from 1.1746 to 0.8903 mPa·s, suggesting stronger intermolecular forces and possibly hydrogen bonding, and that paracetamol molecules move more efficiently (Figure 2). This suggests stronger intermolecular interactions, possibly via hydrogen bonding between the hydroxyl/amide groups of paracetamol and water molecules, which leads to an increase in solution resistance to flow in concentrated solutions. This is consistent with non-Newtonian behaviour frequently seen in pharmaceutical solutes at high concentrations.

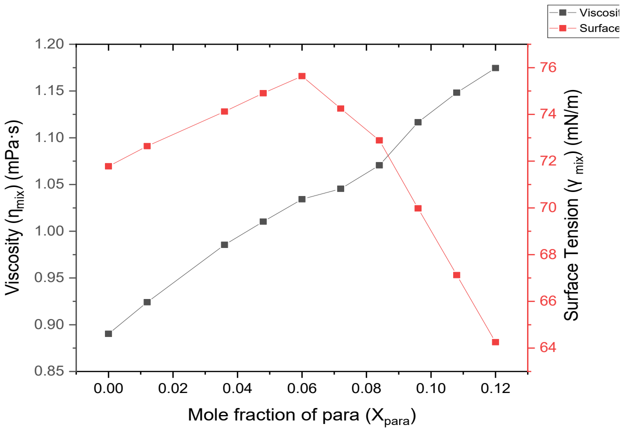

Figure 2: Viscosity and surface tension of paracetamol in aqueous solution

Additionally, surface tension dropped from 75.64 to 71.78 mN/m, indicating that cohesive forces are stronger at higher concentrations. Competing effects could be the cause of this biphasic behaviour:

- When used in small amounts, paracetamol increases surface tension, which fortifies the cohesive forces at the air–water interface.
- At greater concentrations, paracetamol may start to break down the structure of the water or build up at the interface, which would lower surface tension and cohesive forces.

Overall, the trends in d_{mix}, V_M, η_{mix}, and γ_{mix} show that strong solute–solvent interactions are the main cause of paracetamol–water mixtures' deviation from ideal behaviour. Higher concentrations of these interactions result in more complex surface activity, higher viscosity, and more compact molecular arrangements. Since they affect solubility, stability, bioavailability, and drug delivery properties, these findings are extremely pertinent to the pharmaceutical industry, especially in formulation science.

3.3 Excess Molar Properties

Figure 3 and 4 show the computed excess properties of paracetamol-water mixtures based on the experimental data. All concentrations showed negative V^E values, indicating that strong solute–solvent interactions predominate between the solute and solvent rather than within the pure components themselves, causing volume contraction upon mixing. These interactions, which could involve dipole-dipole forces or hydrogen bonds, show that paracetamol molecules interact favourably with water molecules, lowering the volume of the entire solution below optimal levels.

Strong intermolecular interactions at higher concentrations are suggested by the excess viscosity, which is highest at $X_{para} = 0.12$. Furthermore, excess surface tension decreases as a result of solute–solvent interactions at higher concentrations ($X_{para} > 0.096$).

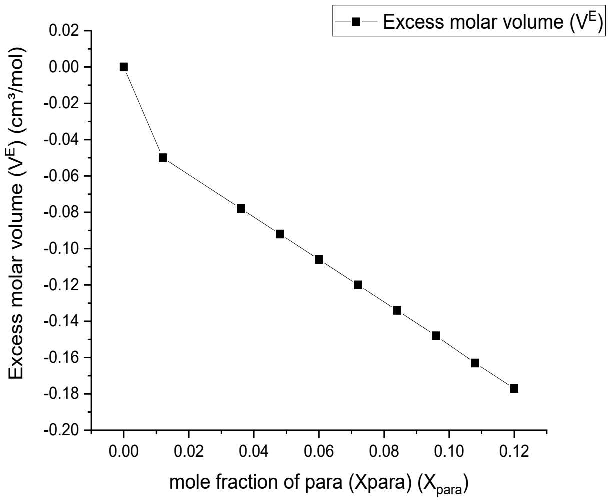

Figure 3: Excess molar volume of paracetamol suspension

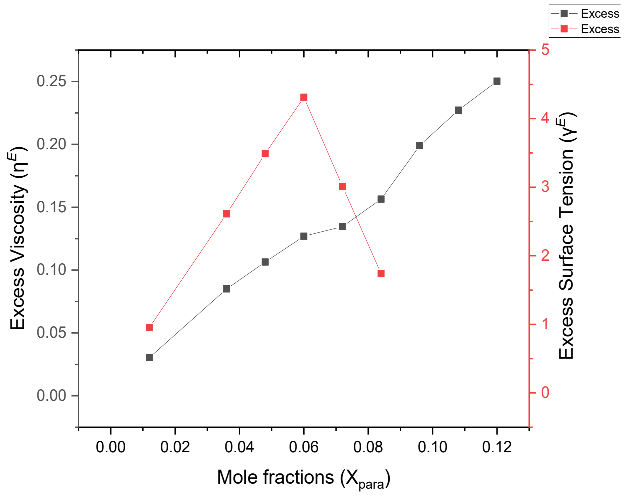

Figure 4: Excess molar **viscosity** and **surface tension** of paracetamol suspension

3.4 Redlich–Kister polynomial Model

The Redlich–Kister polynomial model, which is frequently used to characterise excess thermodynamic properties in binary mixtures, was successfully used to fit the experimental data for excess molar volume (V^E), excess viscosity (η^E), and excess surface tension (γ^E) (Table 4).

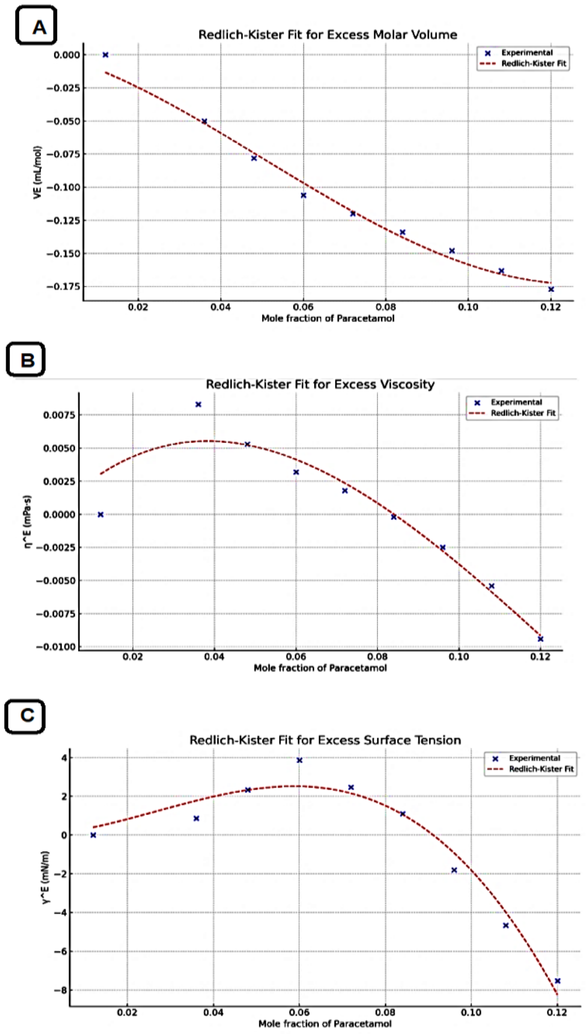

Figure 5: Redlich–Kister plots of excess molar volume, **viscosity** and surface tension

The visual agreement between Redlich-Kister fits and experimental values is good for each property plot (Figure 5). The thermodynamic behaviour and molecular interactions of the water-paracetamol binary system can be inferred from these findings.

Table 4: Redlich–Kister coefficients and their corresponding fitted equations for the excess properties

Property	A_0	A_1	A_2	Fitted Equation
(V^E)	20.143	-52.779	31.749	$VE = x_1 \cdot x_2 \cdot (20.14 - 52.78 \cdot (x_1 - x_2) + 31.75 \cdot (x_1 - x_2)^2)$
(η^E)	0.678	-3.028	2.660	$\eta^E = x_1 \cdot x_2 \cdot (0.678 - 3.028 \cdot (x_1 - x_2) + 2.660 \cdot (x_1 - x_2)^2)$
(γ^E)	-4382.27	9672.29	-5274.74	$\gamma^E = x_1 \cdot x_2 \cdot (-4382.27 + 9672.29 \cdot (x_1 - x_2) - 5274.74 \cdot (x_1 - x_2)^2)$

3.5 Physicochemical Impact of Paracetamol Suspension Components Upon Aqueous Dilutio

The commercial paracetamol suspension 250 mg/5 mL is a multicomponent system comprising active paracetamol, sucrose, sorbitol, propylene glycol, and minor additives such as tartrazine, carmoisine, and sodium. Significant alterations in the suspension's physicochemical characteristics, including density, surface tension, viscosity, and excess thermodynamic properties, occur upon dilution with distilled water (Table 5).

Because of the high levels of sorbitol and sucrose, the native formulation has a significantly higher density. These poly-hydroxy compounds' large molar masses and hydrogen-bonding ability contribute to the density of the solution. The density gradually drops with dilution because the less dense water breaks up the suspension's structured matrix. Propylene glycol's and sorbitol's amphiphilia, to a lesser degree, control surface tension. These substances have a tendency to adsorb at the interface between air and liquid, which lowers surface tension by decreasing cohesive forces [15, 26, 27]. Moreover, because the concentration of surface-active species decreases with dilution, the surface tension increases relative to that of pure water. Both sucrose and sorbitol have a significant impact on viscosity because they are known to cause high solution viscosity through molecular entanglement and extensive hydrogen bonding. Propylene glycol's moderate internal friction also makes it a mild contributor to viscosity. As the cohesive structure of the sugar matrix is broken down and the solution gets closer to Newtonian behaviour, the viscosity drastically drops upon dilution.

Table 5: Effect of paracetamol suspension component on the thermodynamic properties

Property	Main Contributors	Behavior on Dilution
Density	Sucrose > Sorbitol > PG	Decreases (less dense)
Surface Tension	PG > Sorbitol	Increases (loss of surfactants)
Viscosity	Sucrose > Sorbitol > PG	Strongly decreases
Excess Volume	PG + Water	Negative (volume)
Excess Viscosity	PG + Sucrose/Water	Positive (network formation)
Excess Enthalpy	All components	Exothermic mixing

Excess properties shed light on molecular interactions from a thermodynamic standpoint. Strong intermolecular attractions, especially hydrogen bonds between water, polyols, and glycol, cause volume contraction when the system's excess volume (V^E) is negative upon dilution. On the other hand, temporary structuring brought on by less-than-ideal mixing may cause the excess viscosity (η^E) to show positive deviations.

3.6 Effect of Dilution on Paracetamol Bioavailability in the Stomach

Paracetamol–water mixtures observed thermophysical and excess characteristics provide valuable information about how dilution may impact the drug's behaviour in the stomach environment and, in turn, its bioavailability. Our findings showed that as dilution increased, density (from 1.0152 to 0.998 g/cm³), viscosity (from 1.1746 to 0.8903 mPa·s), and surface tension (from 75.64 to 71.78 mN/m) all significantly decreased. This suggests that as paracetamol molecules become more solvated, molecular crowding decreases and solute–solute interactions weaken. Strong solute–solvent interactions and compact molecular arrangements in more concentrated mixtures are suggested by the steady increase in molar volume and the negative excess molar volume (VE), which at higher mole fractions reaches a minimum of −0.177 cm³/mol.

The drug's in vivo performance is directly impacted by these physicochemical behaviours, especially in the stomach where dilution naturally happens due to gastric fluids or co-ingestion with water. Because only dissolved drugs can be absorbed through the gastrointestinal tract, enhanced solute–solvent interaction and molecular dispersion at moderate dilution levels favour increased dissolution. At higher concentrations, the positive excess viscosity values ($\eta^E = 0.2502$ mPa·s at $X_{para} = 0.12$) further support the notion that paracetamol functions as a structure-making solute, thereby enhancing the dissolution kinetics. Our findings also show that the magnitude of excess properties decreases at very low concentrations, suggesting near-ideal mixing behaviour. This implies that paracetamol's physicochemical uniqueness may be diminished by excessive dilution.

This implies that paracetamol's physicochemical uniqueness in solution may be diminished by excessive dilution, which could also lessen the local concentration gradient required for efficient passive absorption. Additionally, enhanced cohesive interactions at the air–solution interface are indicated by the decreased surface tension at high concentrations, which may affect how quickly drug molecules partition across biological membranes.

4. Conclusion

Significant deviations from optimal mixing are found in the thermophysical and thermodynamic analysis of paracetamol–water mixtures at 298.15 K, which are caused by solute–solvent interactions. As the concentration of paracetamol drops, the density drops from 1.0152 to 0.998 g/mL and the viscosity drops from 1.1746 to 0.8903 mPa·s, confirming tighter molecular packing and stronger hydrogen bonding. Volume contraction upon mixing is reflected by a markedly negative excess molar volume (V^E), with a minimum of −0.177 cm³/mol. Furthermore, there were non-linear trends in the viscosity and surface tension, with intermediate concentrations showing the highest values of $\eta^E = 0.284$ mPa·s and $\gamma^E = -7.52$ mN/m. These actions show that in aqueous solutions, paracetamol functions as a solute that creates structure. The Redlich–Kister polynomial model successfully captured these excess properties, with fitting parameters providing predictive utility for other compositions. Overall, this study demonstrates that paracetamol significantly alters the physicochemical characteristics of aqueous systems, which is essential for developing effective drug delivery formulations and enhancing bioavailability.

5. Acknowledgment The authors express their gratitude to the Chemistry Department of Sebha University's Faculty of Science for providing analytical support and laboratory facilities.

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