Science Discovery Chemistry
2026, Vol. 1, No. 2, pp. 73–90
https://doi.org/10.11648/j.sdc.20260102.12

Research Article

Examination of Excess Thermodynamic Properties Catalysed by Aromatic Hydrocarbons for the Binary Liquid Systems at 298.15K

Dhirendra Kumar Sharma*, Chandrapal Prajapati, Gauri Khanwalkar, Sandeep Sahu

Department of Chemistry, Bundelkhand University, Jhansi, India

Abstract

In this study, the thermo-acoustical and physicochemical behavior of a binary liquid mixture was investigated over the entire concentration range at 298.15K. Utilizing experimentally measured data of density (ρ) viscosity (η) and ultrasonic velocity (u), primary physical properties were computed, including the intermolecular free length (L_f), surface tension (S), acoustic impedance (Z), and relaxation time (τ). To gain deeper insights into the structural arrangements and the nature of molecular interactions within the mixture, the corresponding excess parameters excess surface tension (S^E), excess acoustical impedance (Z^E), excessrelaxation time (τ^E) and excess intermolecular free length (L_f^E) were derived. The variations of these excess properties as a function of mixture composition were analyzed and fitted using the Redlich–Kister polynomial equation. The trends observed in these excess parameters offer direct evidence regarding the strength and nature of the molecular packing and hetero-molecular interactions present within the system. These results contribute valuable empirical profiles required for validating fluid theories and optimizing chemical processing models. The sign and magnitude of the calculated excess values reveal the existence of weak interactions between the component molecules, providing vital thermodynamic data for industrial and process engineering applications. The variation of physical properties such as surface tension (S), intermolecular free length (L_f), relaxation time (τ) and acoustic impedance (Z) with mixture composition confirms the presence of molecular interactions among the constituent components. Furthermore, the positive deviations observed across all corresponding excess parameters (S^E), (Z^E), (L_f^E) and (τ^E) indicate weak-to-moderate interactions within these systems, dominated primarily by π–π and solute-solvent interaction

Keywords

Density, Surface Tension, Molecular Interaction, Speed of Sound, Viscosity, Relaxation Time, Aromatic Hydrocarbon

1. Introduction

Hydrocarbons primarily act as substrates in catalytic processes, but specific hydrocarbon-derived intermediates (like carbonium ions) or carbon-based materials can act as catalysts. Key uses include catalytic cracking of heavy hydrocarbons into fuel (gasoline, diesel), aromatization to produce aromatics, and hydrocarbon hydrogenation/oxidation reactions. Investigating molecular interactions within liquid blends relies on an array of analytical techniques, including NMR, Raman,

---

*Correspondence: Dhirendra Kumar Sharma (dhirendra.dr@rediffmail.com)

Received: 8 May 2026; **Accepted:** 18 May 2026; **Published:** 15 June 2026

IR, and UV spectroscopy, alongside dielectric measurements. Among these, ultrasonic testing has emerged as an increasingly powerful and non-destructive tool for probing the physicochemical properties of fluid systems. Consequently, extensive research has utilized ultrasonic velocities to evaluate structural arrangements and molecular forces in both pure compounds and non-reactive organic mixtures [1-7]. These studies typically investigate the thermodynamic behavior of standard chemical families such as alcohols, esters, alkanes, and halo alkanes to gather essential data across various thermodynamic variables. Crucially, exploring excess thermodynamic properties, defined as the difference between experimentally measured values and those calculated for an ideal mixture, reveals the specific nature and strength of these intermolecular interactions [8]. When two distinct solvents are blended, specific interactions such as hydrogen bonding, dipole–dipole forces, and charge-transfer complexation can occur. These excess quantities are essential not only for the fundamental study of solution dynamics but also for chemical engineering applications, serving as critical benchmarks for validating theoretical solutionmodels and optimizing mass transfer, separation, and fluid transport processes [9-11]. Ultimately, systematically analyzing the physicochemical characteristics of binary and ternary mixtures over a wide range of compositions and temperatures is essential to establishing the precise relationship between a liquid system's internal structural configuration and its macroscopic physical properties [12]. Deviations from ideal-solution behavior in binary liquid media frequently arise from differences in the molecular architecture and chemical characteristics of the constituent solvents, alongside external variables such as composition and temperature. Because these microscopic molecular interactions dictate macroscopic chemical behavior, the experimental determination of fundamental physical properties namely density (ρ), viscosity (η), refractive index, and ultrasonic velocity (u) is widely employed to elucidate prevailing intermolecular forces. These primary attributes facilitate the calculation of derived excess thermodynamic functions, including excess free volume, internal pressure, and isentropic compressibility, from which valuable insights into solvent packing and heteromolecular dynamics can be deduced. Precise thermo physical data of binary systems remain indispensable for advancing the fundamental theory of fluid mixing and for solving chemical engineering challenges in process and equipment design. Excess thermodynamic properties effectively quantify the degree of system non-ideality resulting from specific hetero-molecular forces. Within these media, a diverse array of simultaneous interactions may occur, encompassing universal dispersion forces, charge-transfer complexation, hydrogen bonding, and dipole–dipole or dipole–induced-dipole interactions. Generally, dispersion forces and the structural de-association of self-linked pure components impart positive contributions to excess functions. Conversely, specific interactions like hydrogen bonding and dipole forces typically exert a negative influence. The net balance of these opposing effects is governed by the chemical nature of the components and the mixture composition. Consequently, a systematic transition from positive to increasingly negative excess values denotes a structural contraction and a closerintermolecular approach, which simultaneously reduces both the compressibility and molar volume of the system. To probe these complex fluid mechanisms, the measurementof viscosity and ultrasonic velocity represents one of the most reliable diagnostic tools available, complementing traditional spectroscopic techniques. In particular, the scientific and engineering communities have devoted considerable attention to evaluating internal pressure and free volume through various acoustic and thermodynamic approaches, as they provide foundational insights into structural clustering and dipolar forces. Building upon these concepts, the present study investigates the intermolecular phenomena of binary liquid media by reporting the experimental density (ρ), speed of sound (u), and viscosity (η) over the entire composition spectrum at 298.15 K for systems composed of isopropyl benzene (cumene) mixed with various aromatic hydrocarbons. From these primary data, the acoustic impedance (Z), surface tension (S), and corresponding excess thermodynamic functions were derived. Given that these derived parameters are highly sensitive to local molecular forces, their compositional dependencies serve as to clarify the nature and magnitude of the interactions between the constituent chemical species. A highly reliable probe.

2. Martial and Methods

2.1. Chemical

Table 1 lists the compounds this study used the following sources of those chemicals. Since all of the compounds were highly pure, no further purification steps were needed. Key physical measurements of viscosity (η), density (ρ) and speed of sound (u) were made to verify each chemical's purity. To confirm the reliability of these reagents prior to mixture preparation, baseline physical properties specifically density (ρ), viscosity (η), ultrasonic velocity (u), and refractive index (n) were experimentally evaluated. The reliability of the experimental density (ρ) [15-18, 23, 24, 26-29], viscosity (η) [16, 21, 22, 26-28, 30, 32, 36] and ultrasonic velocity (u) [16, 19, 20, 23, 25, 31, 33-36], was assessed by comparing the experimental data of pure components with the corresponding literature values at studied temperature 298.15 K are reported in Table 2. Excellent agreement between these contrasts, as illustrated in Table 2, attests to the chemicals' dependability and appropriateness for the experimental work.

Table 1. *Specifications of the chemical compounds utilized, including their CAS registry numbers and mass fraction purities.*

Component	Formula	CAS Reg. No.	Supplier	Mass Fraction Purity (%)	Water Content	Method Purity analysis method
Cumene	C_9H_{12}	80-15-9	CDH, (P) Ltd. New Delhi, India	99.0%	0.1%	Double distillation
Mesitylene	C_9H_{12}	108-67-8	CDH, (P) Ltd. New Delhi, India	99.0%	0.01%	Double distillation
Ethyl benzene	C_8H_{10}	100-41-4	CDH, (P) Ltd. New Delhi, India	99.0%	0.1%	Double distillation
Toluene	C_7H_8	108-88-3	CDH, (P) Ltd. New Delhi, India	99.0%	0.1%	Double distillation
n-Propyl benzene	C_9H_{12}	103-65-1	CDH, (P) Ltd. New Delhi, India	99.0%	0.01%	Double distillation
t-Butyl benzene	$C_{10}H_{14}$	98-06-6	CDH, (P) Ltd. New Delhi, India	99.0%	0.1%	Double distillation
Biphenyl	$C_{12}H_{10}$	92-52-4	CDH, (P) Ltd. New Delhi, India	99.0%	0.05%	Double distillation

2.1.1. Measurements

In this work, six binary liquid systems were investigated: isopropyl benzene (cumene) + ethyl benzene, isopropyl benzene (cumene) + toluene, isopropyl benzene (cumene) + mesitylene, isopropyl benzene (cumene) + n-propyl benzene, isopropyl benzene (cumene) + tert-butyl benzene, and isopropyl benzene (cumene) + biphenyl. After being kept above pellets of sodium hydroxide for a few days, every chemical underwent fractional distillation twice using the procedure outlined in the literature. [13]. The purification process outlined by Zhao et al. [14]. Prior to the measurements, all chemicals were stored over sodium hydroxide pellets for several days and subsequently purified by double fractional distillation following standard literature procedures. To prevent moisture adsorption, the purified compounds were stored in dark bottles over freshly activated molecular sieves. Binary mixtures covering the complete mole fraction spectrum were prepared gravimetrically by mixing precisely calculated masses of the pure components. To minimize evaporation losses during sample preparation, the component liquids were injected into sealed glass vials using gas-tight syringes equipped with 24-gauge needles. All weighing operations were performed on a digital electronic balance (Citizen Scale (I) Pvt. Ltd., Mumbai, India) with a precision of ± 0.1 mg. The uncertainty in the total mole fraction was estimated to be within ± 0.0005. For each binary system, the prepared composition mixtures were tested on the same day for density (ρ), viscosity (η), and ultrasonic velocity (u) to minimize any composition or environmental degradation.

2.1.2. Density

In the present study, the density profiles of the pure components and their corresponding binary systems were evaluated utilizing a 25cm 3 relative density (R.D.) bottle. Calibration of the relative density (R.D.) bottle was executed at 298.15 K using triply distilled water characterized by a specific conductance below 1×10^6 ohm $^{-1}$, alongside purified methyl alcohol, referencing validated literature densities. Sample introduction was performed gravimetrically using a syringe equipped with a bubble-free needle assembly. Thermal equilibrium of the sample matrix was achieved by immersing the pycnometer in a specialized water bath equipped with a high-precision thermostat (MSI Goyal Scientific, Meerut, India) capable of maintaining the temperature within 0.01 K. The temperature was continuously monitored via a pre-calibrated thermometer under strict equilibrium conditions. The maximum experimental uncertainty associated with the reported density values was established to be of $\pm 1 \times 10^{-5}$ g.cm^{-3}

2.1.3. Sound Velocity

In the current study, an interferometric technique was employed to determine the ultrasonic velocity of the liquid systems. While methods like Mc Skimin's [37] single-crystal pulse-echo interferometer or Carstensen [38] phase- variation technique are widely known for assessing sound velocity variations in highly absorbing media, a high- precision single-crystal variable-path fixed-frequency interferometer (Model F-80, Mittal Enterprises, New Delhi) was utilized in this work. Measurements were performed at a fixed frequency of 3 MHz. To maintain strict thermal stability, the interferometer cell was surrounded by a jacket connected to a microprocessor-controlled circulating water bath

(MSI Goyal Scientific, Meerut, India) maintained at 298.15 K within ±0.01 K. The instrument was calibrated at 298.15 K using triple-distilled water, methyl alcohol, and benzene, benchmarking against established literature values. The measurement mechanism relies on the precise determination of the acoustic wavelength generated by a quartz crystal within the measuring cell. The experimental values obtained for pure isopropyl benzene (cumene), ethyl benzene, toluene, mesitylene, n-propyl benzene, tert-butyl benzene, and biphenyl were in excellent agreement with those reported in the literature. The experimental uncertainty in the ultrasonic velocity determinations was found to be within ± 1 $m.s^{-1}$. The ultrasonic velocity (u) was calculated using the following formula:

$$U = \lambda.f \quad (1)$$

2.1.4. Viscosity

The dynamic viscosities of the pure liquids and their binary mixtures were measured using a suspended Ubbelohde-type Ostwald viscometer with a capacity of approximately 15 ml. The viscometer featured a capillary tube with aninternal diameter of 0.5mm and a length of roughly 90 mm to facilitate the free gravity flow of the liquids between the upper and lower bulb reservoirs under atmospheric pressure. The assembly was calibrated at 298.15 K using triply distilled water, methanol, and benzene, following procedures well-documented in the literature. Efflux times were recorded using an electronic stopwatch (Racer) featuring a time resolution of ±0.01s, and at least four independent flow time measurements were averaged for each sample. To eliminate volatile evaporation losses during testing, glass stoppers were securely positioned at the viscometer apertures. The maximum experimental uncertainty in the viscosity determinations was within ± 0.008m Pa.s. The measured viscosities for pure isopropyl benzene (cumene), ethyl benzene, toluene, mesitylene, n-propyl benzene, tert-butyl benzene, and biphenyl exhibited excellent agreement with validated literature values.

Table 2. Experimental and literature values of density (ρ), speed of sound (u), and viscosity (η) for pure liquids at 298.15K under atmospheric pressure.

Compound	ρ ($g.cm^{-3}$)		u ($m.s^{-1}$)		η (m Pa s)	
	Observed	Literature	Observed	Literature	Observed	Literature
Cumene	0.8532	0.8581 [26]	1326	1325 [31]	0.7337	0.7337 [26]
		0.5574 [27]		1308 [35]		0.7390 [27]
Mesitylene	0.8616	0.8612 [23]	1338	1336 [23]	0.6449	0.6486 [32]
		0.8611 [24]		1336 [25]		0.6600 [36]
Ethylbenzene	0.8674	0.8620 [16]	1324	1312 [16]	0.6345	0.6280 [16]
		0.8626 [17]		1318 [36]		0.6373 [16]
Toluene	0.8576	0.8624 [15]	1306	1307 [19]	0.5527	0.5525 [21]
		0.8622 [18]		1309 [20]		0.5531 [22]
n-Propylbenzene	0.8624	0.8577 [28]	1315	1320 [33]	0.7931	0.7995 [30]
		0.8577 [29]		1320 [34]		0.7827 [28]
t-butylbenzene	0.8624	0.8624 [24]	1316	1315 [23]	0.7449	NA
		0.8622 [23]		1315 [25]		NA
Biphenyl	0.7920	NA	1118	NA	0.6108	NA

NA: Datanotavailable

2.2. Redlich-Kister Equation

The Redlich–Kister (RK) polynomial equation [39] is a widely accepted algebraic expression utilized for correlating the excess properties of binary chemical mixtures. It correlates the excess property (Y^E) as a function of the component mole fractions (x_1 and x_2), and is mathematically expressed as follows:

$$Y = x_1 x_2 \sum_{j=1}^{p} Aj - 1(x1 - x2)\ j^{-1} \quad (2)$$

Where Y is (L_f^E, τ^E, S^E, Z^E,) and $x_1$and x_2 are pure components 1 and 2's mole fractions, respectively. a_{j-1} is the polynomial coefficient, and p is the polynomial degree.

To assess the accuracy and reliability of the mathematical correlation, the goodness of fit of the regression polynomial was evaluated using standard statistical indicators, most notably the standard deviation (σ).

3. Theoretical Aspect

Utilizing the measured primary data of density (ρ), ultrasonic velocity (u), and dynamic viscosity (η) for the pure liquids and their corresponding binary systems, standard algebraic expressions were implemented to derive the relevant viscometric and thermo acoustic functions. Specifically, parameters such as isentropic compressibility (β_{ad}), intermolecular free length (L_f), acoustic impedance (Z), free volume (V_f), and relaxation time (τ) were evaluated using the following relationships:

3.1. Intermolecular Free Length(L_f)

To gain insight into the structural configuration of the liquid media, the intermolecular free length (L_f) defined as the clear distance separating the surfaces of adjacent molecules was evaluated. This parameter acts as a sensitive probe for elucidating the nature and magnitude of hetero-molecular interactions, reflecting the geometric constraints and local force fields within the binary blend. In agreement with the literature [40, 41], the structural variation of L_f exhibits an inverse relationship with molecular clustering, such that an expansion of the intermolecular free length induces an increase in the adiabatic compressibility (β_{ad}).

$$L_f = K\ \beta_{ad}^{1/2} \tag{3}$$

Where K denotes the empirical Jacobson constant, which varies as a function of temperature (T) according to the relation: $(93.875 + 0.375 \times T) \times 10^{-8}$ and β_{ad} is the adiabatic compressibility.

3.2. Adiabatic Compressibility(β_{ad})

The recorded ultrasonic velocity (u) and density (ρ) were used to compute the medium's adiabatic compressibility (β_{ad}) using the following relation [42, 43]:

$$\beta_{ad} = u^{-2}\rho^{-1} \tag{4}$$

3.3. Acoustic Impedance(Z)

As a result of sound pressure, sound moves through various materials. Because a solid's molecules or atoms are elastically connected to one another, the extra pressure causes waves to travel through the solid. According to [44, 45], a material's acoustic impedance (Z) is calculated by multiplying its density (ρ) by its ultrasonic velocity (u).

$$Z = U \times \rho \tag{5}$$

3.4. Surface Tension(S)

The Aurebach connection [46] is the first relationship we examined, and its equation is as follows:

$$S = 6.4 \times 10\text{-}3.\ \rho.\ u3/2 \tag{6}$$

The surface tension of the system under investigation at 298.15 K was calculated using equation (6) using measured density, ρ, and ultrasonic speed, u, of liquid mixtures and pure liquids.

3.5. Relaxation Time(τ)

To evaluate the dynamic traits of the fluid medium, investigators analyzed its relaxation time (τ), which represents the specific period needed for a disrupted system to recover its structural balance. This kinetic feature is deeply tied to the viscoelastic behaviors taking place inside the liquid matrix, making it a reliable indicator for assessing stress-relaxation capabilities. In binary solution architectures, the relaxation time outlines the definite timeframe required for component molecules to transition from a previous stable state into a newly prompted equilibrium under standard conditions [47, 48].

$$\boldsymbol{\tau} = 4/3\ \beta_{ad} \times \eta \tag{7}$$

In liquid mixtures, the extra functions show a greater sensitivity to interactions between molecules. The difference between the experimental thermodynamic and acoustic parameters mixture (A_{EXP}) and those corresponding to an ideal mixture (A_{IDEAL}) was computed using the measured thermodynamic parameters so as to see into the liquid combinations' impracticality. The following formula has been used to compute the excess intermolecular free length (L_f), excess surface tension (S^E), excess acoustical impedance (Z^E) and excess relaxation time (τ^E):

$$A^E = A_{EXP.} - A_{IDEAL} \tag{8}$$

Table 3 presents the relevant data for various binary mixtures maintained at 298.15 K, specifically focusing on combinations of isopropyl benzene (cumene) with ethyl benzene, toluene, mesitylene, n-propyl benzene, tert-butyl benzene, and biphenyl.

4. Results and Discussion

Table 3 compiles the experimental data for density (ρ), viscosity (η), and ultrasonic velocity (u) concerning binary mixtures of isopropyl benzene (cumene) with ethyl benzene, mesitylene, n-propyl benzene, tert-butylbenzene, and biphenyl at 298.15 K. Furthermore, this table presents various derived thermodynamic and acoustic parameters calculated from the primary measurements, including the surface tension (S), acoustical impedance (Z), relaxation time (τ), and intermolecular free length (L_f).

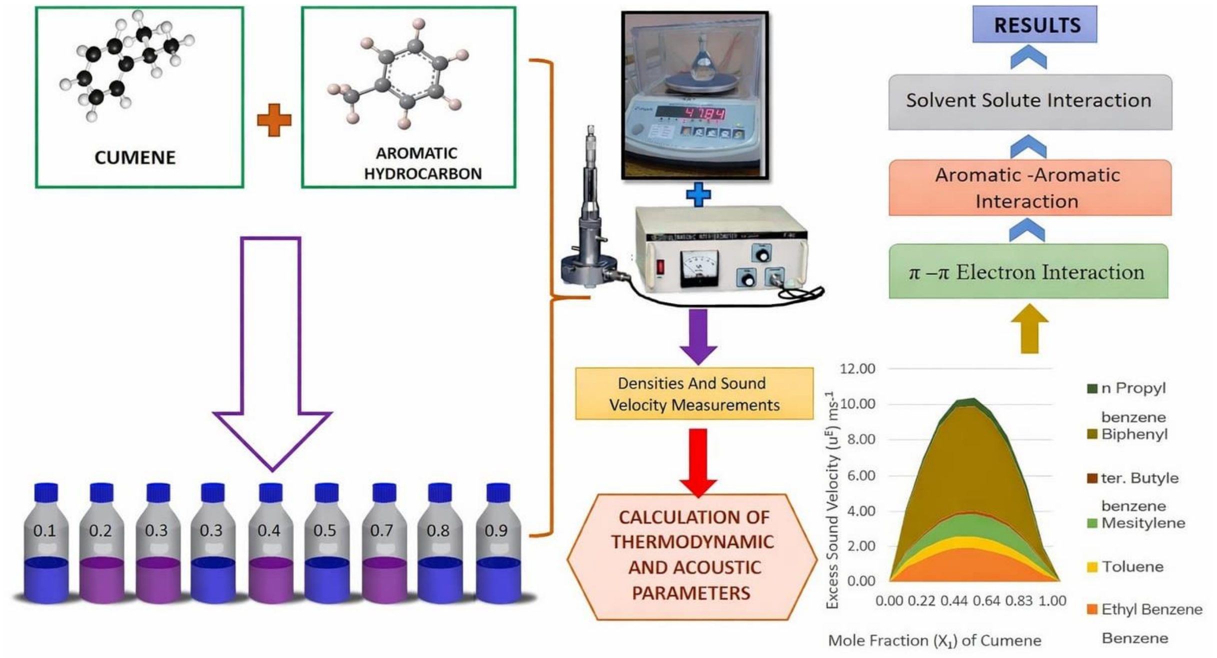

Figure 1. *Interactions between Isopropyl Benzene (Cumene) with Aromatic Hydrocarbons at 298.15K.*

Table 3. *Measured physical properties [density (ρ), viscosity (η), and ultrasonic velocity (u)] along with calculated thermodynamic and acoustic parameters [intermolecular free length (L_f), surface tension (S), acoustical impedance (Z), and relaxation time (τ)] for binary mixtures of isopropyl benzene with various aromatic hydrocarbons at 298.15 K.*

Mole fraction Cumene (x_1)	**Density (ρ) g.cm^{-3}**	**Viscosity (η) mPa.s**	**Speed of Sound (u) ms^{-1}**	**Intermolecular free length (L_f × 10^4) /m**	**Relaxation time (τ) × 10^5s**	**Surface tension (S) × 10^{-3} / N.m^{-1}**	**Acoustic impedance (Z) × 10^{-2} g.cm..s^{-1}**
isopropyl benzene + ethyl benzene							
0.0000	0.8630	0.6345	1308	2.1109	0.5730	0.26128	11.2880
0.1193	0.8612	0.6472	1310	2.1077	0.5854	0.26165	11.3042
0.2209	0.8600	0.6633	1314	2.1064	0.5977	0.26221	11.3109
0.3312	0.8596	0.6715	1316	2.1042	0.6079	0.26264	11.3123
0.4397	0.8592	0.3882	1317	2.1022	0.6189	0.26297	11.3243
0.5319	0.8588	0.6931	1318	2.1003	0.6248	0.26317	11.3276
0.6395	0.858	0.7042	1320	2.0947	0.6311	0.26328	11.3315
0.7301	0.8572	0.7124	1321	2.0909	0.6369	0.26331	11.3328
0.8315	0.8564	0.7198	1322	2.0864	0.6424	0.26343	11.3334
0.9313	0.8554	0.7249	1324	2.0818	0.6483	0.26355	11.3288
1.0000	0.8532	0.7337	1326	2.0776	0.6521	0.26366	11.3134
isopropyl benzene + toluene							
0.0000	0.8672	0.5527	1312	2.0879	0.5083	0.26375	11.3777

Mole fraction Cumene (x_1)	Density (ρ) g.cm^{-3}	Viscosity (η) mPa.s	Speed of Sound (u) ms^{-1}	Intermolecular free length (L_f × 10^4) /m	Relaxation time (τ) × 10^{5}s	Surface tension (S) × 10^{-3} / N.m^{-1}	Acoustic impedance (Z) × 10^{-2} g.cm..s^{-1}
0.1193	0.8628	0.5801	1314	2.0873	0.5267	0.26375	11.3749
0.2209	0.8612	0.6046	1315	2.0866	0.5435	0.26374	11.3702
0.3312	0.8600	0.6293	1316	2.0859	0.5616	0.26374	113657
0.4397	0.8592	0.6457	1318	2.0854	0.5789	0.26374	11.3671
0.5319	0.8584	0.6706	1319	2.0851	0.5949	0.26373	11.3573
0.6395	0.8576	0.6869	1320	2.0838	0.6084	0.26371	11.3447
0.7301	0.8568	0.7032	1321	2.0826	0.6176	0.26371	11.3355
0.8315	0.8556	0.7191	1322	2.0811	0.6302	0.26368	11.3281
0.9313	0.8544	0.7266	1324	2.0792	0.6436	0.26368	11.3208
1.0000	0.8532	0.7337	1326	2.0776	0.6521	0.26366	11.3134
isopropyl benzene + meistylene							
0.0000	0.8616	0.6449	1338	2.0206	0.5229	0.26205	11.5282
0.1193	0.8612	0.6216	1336	2.0288	0.5395	0.26224	11.5116
0.2209	0.8608	0.6384	1335	2.0352	0.5558	0.26242	11.4976
0.3312	0.8604	0.6551	1334	2.0421	0.5723	0.26260	114823
0.4397	0.86	0.6718	1333	2.0490	0.5889	0.26278	11.4724
0.5319	0.8596	0.6885	1332	2.0541	0.6051	0.26294	11.4558
0.6395	0.8592	0.6967	1331	2.0596	0.6138	0.26311	11.4445
0.7301	0.8588	0.7048	1330	2.0650	0.6227	0.26325	11.4141
0.8315	0.8584	0.7130	1329	2.0703	0.6345	0.26340	11.3703
0.9313	0.8576	0.7293	1328	2.0752	0.6474	0.26355	11.3485
1.0000	0.8532	0.7337	1326	2.0776	0.6521	0.26366	11.3134
isopropyl benzene + n-propyl benzene							
0.0000	0.8624	0.7931	1315	2.0899	0.7091	0.26375	11.3406
0.1193	0.8620	0.7896	1316	2.0890	0.7057	0.26374	11.3439
0.2209	0.8618	0.7884	1317	2.0882	0.7043	0.26373	11.3499
0.3312	0.8614	0.7724	1318	2.0870	0.6987	0.26372	11.3592
0.4397	0.8604	0.7664	1319	2.0864	0.6945	0.26371	11.3573
0.5319	0.8596	0.7626	1320	2.0857	0.6864	0.26371	11.3553
0.6395	0.8588	0.7558	1321	2.0839	0.6788	0.26370	11.3480
0.7301	0.8584	0.7524	1322	2.0824	0.6722	0.26369	11.3434
0.8315	0.8576	0.74630	1324	2.0806	0.6663	0.26368	11.3361
0.9313	0.8560	0.7422	1325	2.0787	0.6600	0.26367	11.3314
1.0000	0.8532	0.7337	1326	2.0776	0.6521	0.26366	11.3134
isopropyl benzene + t-butyl benzene							
0.0000	0.8624	0.7449	1316	2.0868	0.6649	0.26229	11.3492
0.1193	0.8620	0.7445	1317	2.0858	0.6650	0.26245	11.3525

Mole fraction Cumene (x_1)	Density (ρ) g.cm^{-3}	Viscosity (η) mPa.s	Speed of Sound (u) ms^{-1}	Intermolecular free length (L_f × 10^4) /m	Relaxation time (τ) × 10^{5}s	Surface tension (S) × 10^{-3} / N.m^{-1}	Acoustic impedance (Z) × 10^{-2} g.cm..s^{-1}
0.2209	0.8612	0.7440	1318	2.0852	0.6646	0.26260	11.3506
0.3312	0.8604	0.7436	1319	2.0852	0.6634	0.26275	11.3487
0.4397	0.8596	0.7420	1320	2.0846	0.6628	0.26290	11.3467
0.5319	0.8586	0.7398	1321	2.0833	0.6609	0.26302	11.3421
0.6395	0.8572	0.7389	1322	2.0821	0.6581	0.26318	11.3401
0.7301	0.8564	0.7373	1323	2.0810	0.6564	0.26330	11.3355
0.8315	0.8556	0.7364	1324	2.0799	0.6552	0.26344	11.3281
0.9313	0.8548	0.7351	1325	2.0785	0.6537	0.26357	11.3208
1.0000	0.8532	0.7337	1326	2.0776	0.6521	0.26366	11.3134
isopropyl benzene + Biphenyl							
0.0000	0.7920	0.6108	1118	3.1484	0.8135	0.24088	8.8546
0.1193	0.7956	0.6215	1144	3.0214	0.8174	0.24360	9.1519
0.2209	0.8036	0.6357	1174	2.9130	0.8043	0.24593	9.4047
0.3312	0.8084	0.6510	1186	2.7958	0.7922	0.24846	9.6852
0.4397	0.8144	0.6710	1198	2.6802	0.7694	0.25093	9.9528
0.5319	0.8248	0.6932	1212	2.5809	0.7654	0.25303	10.1780
0.6395	0.8276	0.7308	1242	2.4652	0.7708	0.25548	10.4378
0.7301	0.8324	0.7161	1274	2.3677	0.7254	0.25753	10.6598
0.8315	0.8436	0.7215	1286	2.2591	0.6973	0.25983	10.9071
0.9313	0.8484	0.7295	1300	2.1518	0.6715	0.26210	11.1494
1.0000	0.8532	0.7337	1326	2.0776	0.6521	0.26366	11.3134

Table 4. *Over flowing thermodynamic parameters (L_f^E, τ^E, S^E, and Z^E) for a binary mixture composed of isopropyl benzene (1) + aromatic hydrocarbons (2) at 298.15K.*

Mole fraction 1,3-Dioxolane (x_1)	Excess intermolecular free length (L_f^E) × 10^2/m	Excess relaxation time (τ^E) s	Excess Surface tension (S^E) × 10^5 / N.m^{-1}	Excess Acoustic impedance (Z^E) × 10^{-2} g.cm..s^{-1}
isopropyl benzene + ethyl benzene				
0.0000	0.0000	0.00000	0.0000	0.0000
0.1193	0.16	0.43676	0.2379	0.8754
0.2209	0.32	0.72839	0.4209	1.4266
0.3312	0.46	0.90782	0.5309	2.0071
0.4397	0.55	0.96210	0.5605	2.4819
0.5319	0.58	0.92590	0.5330	2.7511
0.6395	0.57	0.80293	0.4496	2.8413
0.7301	0.51	0.64369	0.3445	2.6765
0.8315	0.37	0.41820	0.1976	2.1711
0.9313	0.17	0.16072	0.0318	1.2824

Mole fraction 1,3-Dioxolane (x_1)	**Excess intermolecular free length (L_f^E) × 10^2/m**	**Excess relaxation time (τ^E) s**	**Excess Surface tension (S^E) × 10^5 / N.m^{-1}**	**Excess Acoustic impedance (Z^E) × 10^{-2} g.cm..s^{-1}**
1.0000	0.0000	0.00000	0.0000	0.0000
	isopropyl benzene + toluene			
0.0000	0.0000	0.00000	0.0000	0.0000
0.1193	0.06	0.21918	0.0828	0.5663
0.2209	0.12	0.43716	0.1441	0.9464
0.3312	0.18	0.61139	0.1942	1.1641
0.4397	0.23	0.71314	0.2246	1.2107
0.5319	0.26	0.74060	0.2339	1.1429
0.6395	0.25	0.69868	0.2237	0.9657
0.7301	0.23	0.59731	0.1958	0.7553
0.8315	0.18	0.40745	0.1420	0.4772
0.9313	0.08	0.13696	0.0641	0.1829
1.0000	0.0000	0.00000	0.0000	0.0000
	isopropyl benzene + meistylene			
0.0000	0.0000	0.00000	0.0000	0.0000
0.1193	0.12	0.25255	0.0661	0.8414
0.2209	0.21	0.51377	0.1385	1.7902
0.3312	0.27	0.72991	0.2084	2.8454
0.4397	0.31	0.86512	0.2608	3.7452
0.5319	0.32	0.91295	0.2867	4.2780
0.6395	0.31	0.88310	0.2888	4.4877
0.7301	0.27	0.78031	0.2618	4.2077
0.8315	0.21	0.57424	0.1946	3.2736
0.9313	0.12	0.27069	0.0844	1.5877
1.0000	0.0000	0.00000	0.0000	0.0000
	isopropyl benzene + n-propyl benzene			
0.0000	0.0000	0.00000	0.0000	0.0000
0.1193	0.08	0.40892	0.0667	0.9631
0.2209	0.14	0.61699	0.1384	1.7335
0.3312	0.18	0.76785	0.2041	2.3545
0.4397	0.20	0.84005	0.2507	2.7297
0.5319	0.20	0.84200	0.2720	2.8523
0.6395	0.19	0.77527	0.2709	2.7525
0.7301	0.16	0.66144	0.2444	2.4543
0.8315	0.12	0.47154	0.1829	1.8752
0.9313	0.06	0.22019	0.0851	1.0395
1.0000	0.0000	0.00000	0.0000	0.0000
	isopropyl benzene + t-butyl benzene			

Mole fraction 1,3-Dioxolane (x_1)	**Excess intermolecular free length (L_f^E) × 10^2/m**	**Excess relaxation time (τ^E) s**	**Excess Surface tension (S^E) × 10^5 / N.m^{-1}**	**Excess Acoustic impedance (Z^E) × 10^{-2} g.cm..s^{-1}**
0.0000	0.0000	0.00000	0.0000	0.0000
0.1193	0.16	0.17860	0.0445	0.5832
0.2209	0.26	0.26612	0.1614	0.9137
0.3312	0.32	0.29988	0.3483	1.1795
0.4397	0.38	0.28547	0.5453	1.3356
0.5319	0.41	0.24716	0.6867	1.3780
0.6395	0.34	0.18489	0.7796	1.3133
0.7301	0.27	0.12781	0.7648	1.1562
0.8315	0.19	0.07008	0.6107	0.8607
0.9313	0.11	0.03086	0.2803	0.4383
1.0000	0.0000	0.00000	0.0000	0.0000
	isopropyl benzene + Biphenyl			
0.0000	0.0000	0.00000	0.0000	0.0000
0.1193	0.15	0.16024	0.1241	0.5812
0.2209	0.24	0.25412	0.2346	1.0269
0.3312	0.32	0.33524	0.3094	1.3341
0.4397	0.36	0.38741	0.3401	1.4698
0.5319	0.37	0.40528	0.3352	1.4649
0.6395	0.35	0.38973	0.2960	1.3308
0.7301	0.30	0.34176	0.2371	1.1194
0.8315	0.20	0.24529	0.1456	0.7859
0.9313	0.07	0.10119	0.0313	0.3676
1.0000	0.0000	0.00000	0.0000	0.0000

Table 4 summaries the derived excess parameters at 298.15 K: excess intermolecular free length (L_f^E), excess surface tension (S^E), excess acoustical impedance (Z^E) and excess relaxation time (τ^E).

4.1. Derived Parameters

The experimental values of ultrasonic velocity (u), density (ρ) and viscosity (η) for mixtures of isopropyl benzene (cumene) with aromatic hydrocarbons at 298.15 K are presented in Table 3. The intermolecular free length (L_f) relaxation time (τ), surface tension (S) and acoustic impedance (Z) calculated from these data are also presented in Table 3.

4.2. Intermolecular Free Length (Lf)

By treating molecules as incompressible hard spheres of uniform radius, the intermolecular free length (L_f) can be directly correlated with spatial packing efficiency. Figure 3 illustrates the dependency of L_f on the mole fraction of isopropyl benzene (cumene) across various binary systems. These mixtures include cumene paired individually with ethyl benzene, toluene, mesitylene, n-propyl benzene, tert-butyl benzene, and biphenyl.

The calculated data are compiled in Table 3. Within binary liquid mixtures, the strength of intermolecular attraction between components is reflected by the system's intermolecular free length (L_f). As evidenced by Table 3 and Figure 3, L_f decreases monotonically with both increasing temperature and rising concentrations of isopropyl benzene (cumene). Across all six binary systems, this decrease in intermolecular free length exhibits a nearly linear trend. Conversely, thermal expansion causes a slight elevation in L_f values at higher temperatures due to increased molecular spacing. According to the model proposed by Eyring and Kincaid [49], an expansion in free length upon mixing corresponds to a subsequent decrease in ultrasonic velocity a behavior consistently observed in all investigated mixtures. Furthermore, the L_f values derived via Equation (3) for the binary combinations of cumene with various aromatic hydrocarbons follow a distinct descending sequence:

ethyl benzene > toluene >mesitylene> n-propyl benzene >tert-butyl benzene > biphenyl.

This increase in L_f with an increased number of -CH_3 group linked to the benzene ring is due to the rising strength of contact. Dispersion forces and π-π interaction are two examples of the diverse kinds of forces that exist between molecules in various systems. All systems have dispersion forces, and in a system where there are multiple types of interactions between the components, the deviation of sound velocity would be the net consequence of contributions from each type of contact.

The strengthening of attractive intermolecular forces within the binary liquid mixtures is further supported by the observed decline in intermolecular free length (L_f) as the mole fraction of isopropyl benzene (cumene) increases (Table 3). This reduction in L_f signifies a rising magnitude of attractive molecular interactions within the liquid matrix. Correspondingly, the relaxation time (τ) values show a concurrent increase with rising cumene concentration, providing additional evidence of these structural dynamics. This behavior demonstrates that specific chemical intermolecular connections dominate over weaker dispersive forces in these blended systems. Generally, the thermodynamic behavior of binary liquid mixtures is governed by a competition between physical forces (such as dispersion) and chemical forces (such as dipole-dipole interactions). According to Jacobson's free length theory, dominant dispersive effects would typically expand the intermolecular free length. Consequently, the distinct contraction of L_f detailed in Table 3 unequivocally confirms the presence of strong, specific interactions between the solvent and co-solvent molecules.

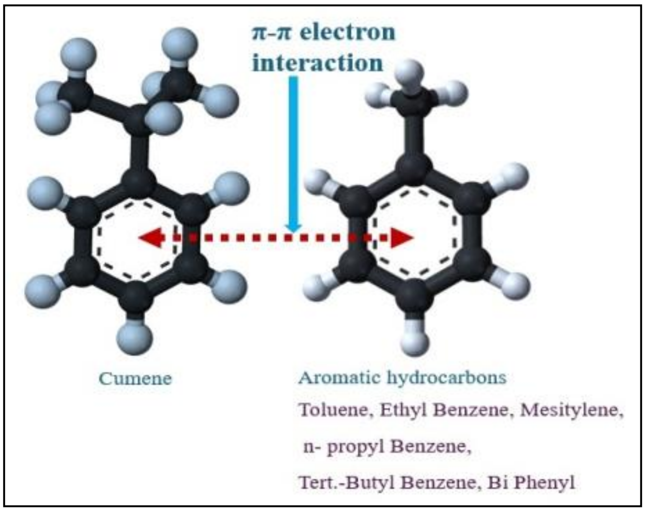

Figure 2. *Interactions between isopropyl benzene (cumene) and aromatic hydrocarbons.*

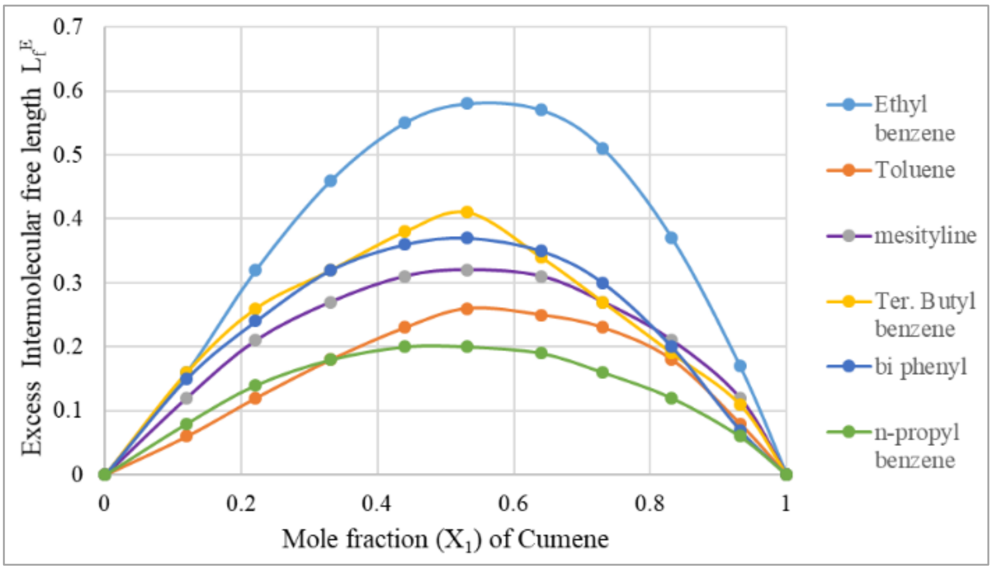

Figure 3. *Excess intermolecular free length (L_f^E) as a function of isopropyl benzene (cumene) mole fraction (X_1) for various binary liquid mixtures containing aromatic hydrocarbons at 298.15 K.*

4.4. Relaxation Time (τ)

Figure 4 shows the excess relaxation time values (τ^E) for the cumene with aromatic hydrocarbon binary systems. At 298.15 K, it is clear that all six mixes show notable positive (τ^E) values over the whole composition range. As seen in Figure 4, the divergence in using the ultrasonic speed and mole fraction of cumene for the six systems shows a non-linear reduction in velocity without any minimum. No complex formation between the components is shown by the lack of a maximum or minimum at any intermediate concentration of cumene with ethyl benzene, toluene, mesitylene, n-propyl benzene, tert-butyl benzene, and biphenyl. These findings align with the overall patterns of relaxation time fluctuations in binary liquids. Moreover, it is anticipated that structural variations among the species in solution may affect additional physical properties. When the mole fraction rises, the relaxation period (τ), which is about 10^5seconds, increases because structural relaxation process [50] and in such a situation, it is suggested that, the molecule gets rearranged due to co-operative process [51]. Relaxation time increases with isopropyl benzene (cumene) content, which is the amount of time needed for a system to recover to equilibrium following a disturbance [52, 53]. The main reasons for variations in relaxation time are temperature and concentration-induced changes in solution viscosity. Regarding the binary systems of isopropyl benzene (cumene) + aromatic hydrocarbons, Figure 3 shows how the excess relaxation time varies using the mole percentage of isopropyl benzene (cumene). Table 4 provides the corresponding values. The creation of transient π–cation complexes slows down molecular motion in the isopropyl benzene (cumene) + aromatic hydrocarbons system, causing the relaxation period to initially increase up to 0.2 mole percentage (Figure 4). But around 0.2 mol fraction, the structure becomes saturated and the bulky isopropyl benzene (cumene) starts to dominate steric effects, which causes the molecular network to loosen and mobility to increase. As a result, the relaxation time decreases, suggesting a quicker structural reorganisation. Since many binary combinations of liquids only show one relaxation time, several studies have employed empirical mixing principles to describe the growth of relaxation time with increasing concentration, and the mixture relaxation time often varies smoothly with composition. We start by bringing out certain issues that are typical of these methods. When is the best time to relax Figure 4 displays the experimental relaxation times of isopropyl benzene (cumene) and their binary mixes at 298.15 K. Because of the π-π interaction, which limits molecular rotations, the solvent molecules have long relaxation durations. On the other hand, because isopropyl benzene (cumene) is non-associated, the solute molecules have shorter relaxation durations than the solvent. Because the solute molecules oppose the solvent, mixture relaxation durations lengthen as the concentration of isopropyl benzene (cumene).

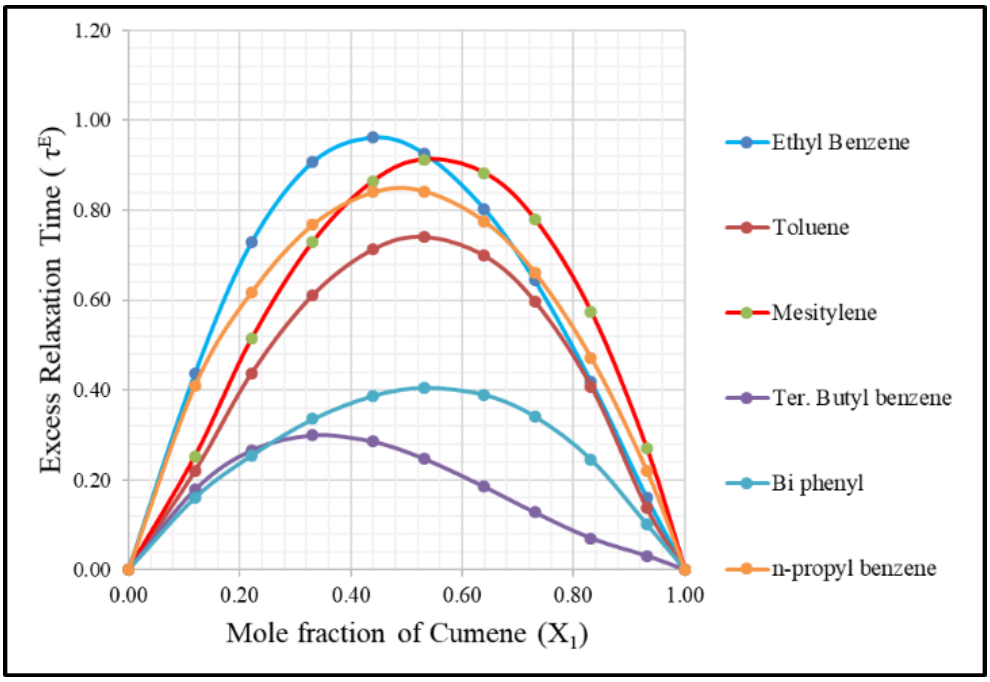

Figure 4. *Excess relaxation time (τ^E) as a function of isopropyl benzene (cumene) mole fraction (X_1) for various binary liquid mixtures containing aromatic hydrocarbons at 298.15 K.*

4.5. Acoustic Impedance (Z)

Table 3 compiles the calculated acoustic impedance (Z) values for all six investigated binary systems. Acoustic impedance is fundamentally defined as the ratio of an instantaneous excess pressure within a medium to the respective instantaneous particle velocity. As acoustic waves propagate through a material, localized pressure fluctuations manifest, a phenomenon governed primarily by the inertial and elastic properties of the medium [54]. As detailed in Table 3, acoustic impedance (Z), decreases continuously with rising concentrations of isopropyl benzene (cumene) across all liquid mixtures. This downward trend signifies a reduction in structural packing density, a corresponding expansion of the system's free volume, and the prevalence of weak intermolecular interactions between components. Ultimately, the apparent drop in acoustic impedance serves as clear evidence of increased free volume or weakened specific contacts within the liquid matrix.

Specific acoustic impedance is fundamentally dictated by the molecular packing characteristics of a given system [55]. Crucial insights regarding intermolecular dynamics can be extracted from both the sign and magnitude of the excess acoustic impedance (Z^E). Generally, positive Z^E values imply the presence of weak interactions or structural disruption within the liquid matrix [56].

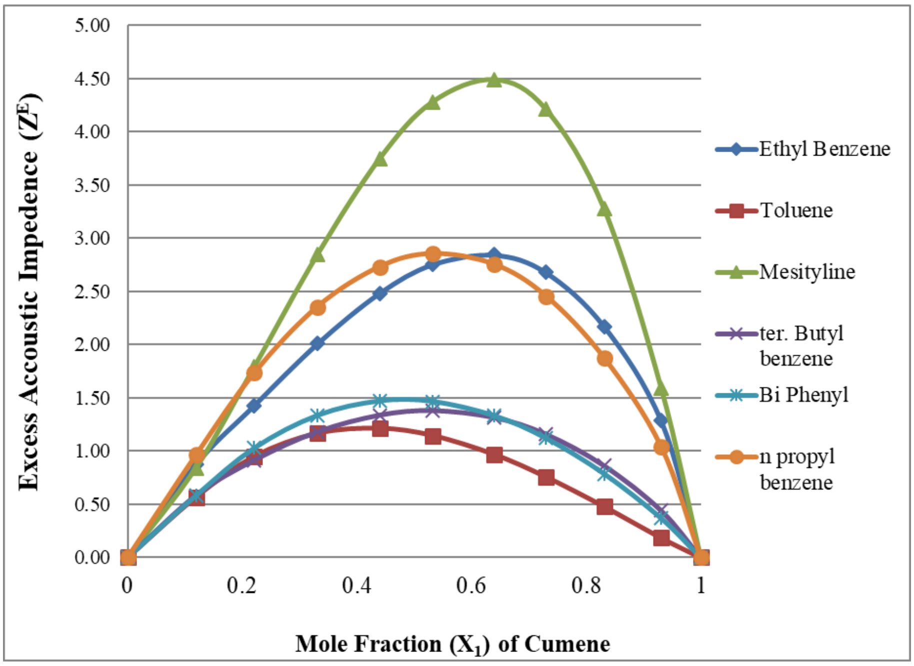

Figure 5. *Excess acoustic impedance (Z^E) as a function of isopropyl benzene (cumene) mole fraction (X_1) for various binary liquid mixtures containing aromatic hydrocarbons at 298.15 K.*

Figure 5 and Table 3 detail the dependency of excess acoustic impedance on the mole fraction of isopropyl benzene (cumene) across the six binary liquid systems. This upward, positive trend reflects a pronounced structure-breaking effect, which can be attributed to heightened mixture compressibility, weak π–π connections, and localized weak solute–solvent interactions. To the best of our knowledge, the excess acoustic impedance data for these specific mixtures have not been previously reported in the literature. As illustrated in Figure 5, all investigated systems exhibit a consistent trend, peaking or reaching a defining threshold around a cumene mole fraction of approximately 0.2 to 0.4. This behavior strongly implies that the addition of cumene disrupts the local structural order of the aromatic hydrocarbons, a phenomenon driven by weak dipole interactions that lack the energy required to promote molecular alignment [57-59].

4.6. Surface Tension (S)

Table 3 documents the surface tension (S) values across the full composition range of mole fractions (X_1) for the binary mixtures at 298.15 K. This dataset encompasses both the pure components including isopropyl benzene (cumene), ethyl benzene, toluene, mesitylene, n-propyl benzene, tert-butyl benzene, and biphenyl and their respective binary combinations. Across all investigated mixtures, the surface tension (S) exhibits a continuous, linear decrease as the mole fraction of isopropyl benzene (cumene) increases.

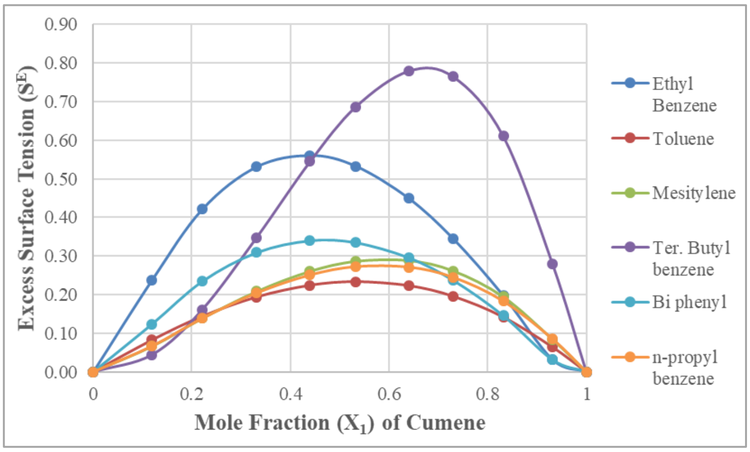

Figure 6. *Excess surface tension (S^E) as a function of isopropyl benzene (cumene) mole fraction (X_1) for various binary liquid mixtures containing aromatic hydrocarbons at 298.15 K.*

Among the crucial components influencing heat and mass transmission is surface tension, which was a crucial physical and chemical characteristic [60]. The experimental device's reliability is demonstrated by the small difference between the measured value and the reference value. Table 3 displayed the computed surface tension data, while Table 4 displayed the excess surface tension data. Based on the computed surface tension (S) values, Figure 6 was created. Figure 6 shows that I: As x_1 grows, S also increases because of a rise in isopropyl benzene (cumene) volume, which enhances π-π bonding and raises surface tension. Eq. (6) [46] computed the isopropyl benzene (cumene) according to the data, which was displayed with in Table 3. Based on excess surface tension (S^E) Table 4, Figure 6 was created. The isopropyl benzene (cumene) first rises and then falls, and a lower surface deviation indicates that the two components' surface tension values were closer together. II: The isopropyl benzene (cumene) was entirely positive, which was precisely because more active components would remain in the body region due to a shift in the repulsive or attractive force between various molecules, producing a favorable value of surface tension deviation. Using a variety of empirical, semi-empirical, and statistical theories, success full there have been attempts in recent years to theoretically predict the surface tensions and deviations in surface tension of liquid mixtures. Here, we extend this by presenting six distinct surface tension prediction models and links that have been eliminated from the existing research. Figure 6 makes it evident that at 298.15K, the throughout the whole composition range, excess surface tension (S^E) values are positive. Notably, the volumetric and compressibility behavior [61], which were strongly linked to the solute/solvent structures, have a greater impact on the surface behavior of the current system than does the solute/solvent effect.

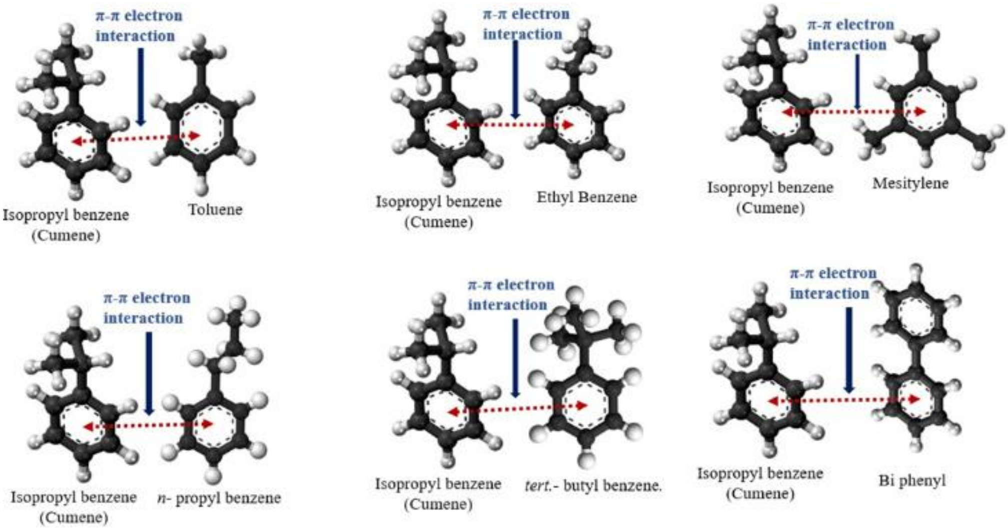

Figure 7. *Schematic representation of the structural and molecular interactions between isopropyl benzene (cumene) and various aromatic hydrocarbons.*

Across the entire range of mole fractions, the calculated excess parameters specifically excess intermolecular free length (L_f^E), excess relaxation time (τ^E), excess surface tension (S^E), and excess acoustic impedance (Z^E) exhibit entirely positive values for all six binary mixtures. This consistent trend is observed across the systems of isopropyl benzene (cumene) blended individually with ethyl benzene, toluene, mesitylene, n-propyl benzene, tert-butyl benzene, and biphenyl.

The magnitude of the excess parameters specifically excess intermolecular free length (L_f^E), excess relaxation time (τ^E), excess surface tension (S^E), and excess acoustic impedance (Z^E) follows a decreasing sequence of: ethyl benzene > toluene >mesitylene> n-propyl benzene >tert-butyl benzene > biphenyl. This exact order directly reflects the relative strength of the intermolecular interactions across the studied systems. Throughout the entire composition range, these positive, favorable excess values are consistently maintained for all six binary mixtures of isopropyl benzene (cumene) with the respective aromatic hydrocarbons. Ultimately, the parallel trends observed across (L_f^E),(τ^E), (S^E) and (Z^E) confirm that the intensity of molecular interactions [62] systematically diminishes according to the aforementioned structural ranking.

5. Conclusion

The density, viscosity, ultrasonic velocity, and other properties that depend on concentration in combinations of binary liquids of isopropyl benzene (cumene) + ethyl benzene, isopropyl benzene (cumene) + toluene, isopropyl benzene (cumene) + mesitylene, isopropyl benzene (cumene) + n-propyl benzene, isopropyl benzene (cumene) + tert-butyl benzene, and isopropyl benzene (cumene) + biphenyl have all been measured at a constant temperature 298.15K and frequency 3 MHz.To understand how molecules interact that result in the process of complex formation amongst the molecules of the solvent and the solute through π–π interactions. The nonlinear differences in the related parameters, including surface tension, acoustic impedance, relaxation duration, and intermolecular free length, were analysed in light of the binary system's characteristics. The observation of positive correlations between the excess values of these acoustic parameters and both temperature and concentration indicated the presence of interactions between the distinct molecules. The current study lays the groundwork for future research on aromatic-aromatic systems. To gain a deeper understanding of solute–solvent interactions, this could be expanded upon in future research approach to ternary mixtures and a larger range of temperatures and frequencies. Spectroscopic studies and complementary computer modelling would also aid in verifying the experimental results. Furthermore, as aromatic liquids are being used more and more in chemical synthesis, energy storage, solvent design, and separation procedures, these researches are beneficial.

Abbreviations

ρ	Density of the Mixture ($g.cm^{-3}$)
u	Sound Speed of the Mixture ($m.s^{-1}$)
u^E	Excess Sound Velocity ($m.s^{-1}$)
η	Viscosity (m.Pas)
M	Molar Mass
T	Temperature
P	Pressure
V	Volume
η^E	Excess Viscosity (m.Pas)
T	Temperature (Kelvin)
(τ)	Relaxation Time
(τ^E)	Excess Relaxation Time
(L_f)	Intermolecular Free Length
(L_f^E)	Excess Intermolecular Free Length
(β_{ad})	Adiabatic Compressibility (Pa^{-1})
(S)	Surface Tension ($N.m^{-1}$)
(S^E)	Excess Surface Tension ($N.m^{-1}$)
(Z)	Acoustic Impedance ($g.cm.s^{-1}$)
(Z^E)	Excess Acoustic Impedance ($g.cm.s^{-1}$)
Y^E	Thermodynamic Excess Function
X_1	Mole Fraction of Isopropyl Benzene (Cumene)

Acknowledgments

The authors gratefully acknowledge to Uttar Pradesh Council of Science and Technology, Lucknow (No. CST/CHEM/D-648 dated 01/08/2024) for financial support (Project ID: 3409).

Author Contributions

Dhirendra Kumar Sharma: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization

Chandrapal Prajapati: Visualization, Validation, Supervision, Investigation, Formal analysis, Conceptualization

Gauri Khanwalkar: Formal analysis, Data curation, Conceptualization

Sandeep Sahu: Software, Resources, Formal analysis, Conceptualization

Data Availability Statement

The data that has been used is confidential.

Conflicts of Interest

According to the authors, no known competing financial interests or personal ties could have influenced any of the work reported in this study.

References

[1] A. Pineiro, P. Brocos, A. Amigo, M. Pintos, and R. Bravo, Refractive index of binary mixtures of tetra hydro furan with 1-alkanols at 25 ℃ and temperature dependence of n and ρ for the pure liquids, J. Solution Chemistry, 2002, 31, pp. 369–380. https://doi.org/10.1023/A:1015807331250

[2] A. J. Treszczanowicz, T. Treszczanowicz, T. Kasprzycka-Guttman, and T. S. Pawloeski, Excess molar volumes for binary mixtures of 1-alkanoland 1-alkene. I. The system1-alkanol+1-octene at 25 ℃, J. Solution Chemistry, 2002, 31, pp. 455–466. https://doi.org/10.1023/A:1020265528680

[3] A. J. Treszczanowicz, and T. Treszczanowicz, Thermodynamic excess properties of the 1-alkylamine + alkane systems in terms of an associated mixture model with equation of state contribution, Journal of Physics Chemistry, 2003, 217, pp. 689–706. https://doi.org/10.1524/zpch.217.6.689.20447

[4] C. M. Kinart, W. J. Kinart, D. ChecinskaMajak, and A. Cwiklinska, Volumetric behaviour of binary liquid mixtures of 2-methoxy ethanol with n-butylamine, sec-butylamine and tertbutylamine, Journal of Molecular Liquid, 2004, 109, pp. 19–22. https://doi.org/10.1016/j.molliq.2003.07.002

[5] J. Wisniak, R. Infante, R. D. Peralta, and L. F. Ramos, Excess molar volume of 2,2'-oxybis [propane] with benzene, toluene, cyclo hexane, and methyl ethanoate at298.15, Journal of Physics Chemistry Liquid, 2001,39, pp. 625–636. https://doi.org/10.1080/00319100108030682

[6] P. P. Singh, R. Malik, S. Maken, W. E. AcreeJr, and A. I. Zvaigzni, Thermo chemical investigations of associated solutions: 12. Mole fraction versus volume fraction based association constants for predicting excess molar enthalpies of acetone–bromo form–alkane mixtures, ThermochimicaActa, 1990,165, pp. 113–127. https://doi.org/10.1016/0040-6031(90)80211-G

[7] P. P. Singh, R. Malik, S. Maken, and W. E. Acree Jr., Thermodynamic properties of ternary non electrolyte solutions. Part 3. —Excess molar volumes of 2-propanone–tri bromo methane–alkane mixtures, Journal of Chemical Society, Faraday Transactions, 1990, 86, pp. 2853–2857. http://doi.org/10.1039/FT9908602853

[8] A. K. Nain, Densities and volumetric properties of binary mixtures of formamide with 1-butanol, 2-butanol, 1,3-butanediol and 1,4-butanediol at temperatures between 293.15 and 318.15 K, Journal of Solution Chemistry,2007, 36(4), pp. 497–516, https://doi.org/10.1007/s10953-007-9122-9

[9] A. Pal, and A. Kumar, Excess molar volumes and viscosities for binary mixtures of alkoxypropanols with 1-alkanols at 298.15 K, Journal of Molecular Liquids,2006, 123(2-3), pp. 146151, https://doi.org/10.1016/j.molliq.2005.05.009

[10] M. V. Rathnam, S. Mohite, and M. S. S. Kumar, Density, excess volume, and viscosity of vinyl acetate or benzyl acetate with (o-, m-, p-) xylenes and ethylbenzene at T = (303.15 and 313.15) K, Journal of Solution Chemistry, 2010, 39(11), pp. 1735–1748, https://doi.org/10.1007/s10953-010-9610-1

[11] V. A. Rana, H. Chaube, and D. H. Gadani, Dielectric permittivity, density, viscosity and refractive index of binary mixtures of anisole with methanol and 1-propanol at different temperatures, Journal of Molecular Liquids,2011, 264(3), pp. 191–196, https://doi.org/10.1016/j.molliq.2011.09.009,

[12] S. Nallani, and V. Jaana, Thermodynamic and transport properties of binary liquid mixtures of n-methylacetamide with alkyl (methyl, ethyl, n-propyl and n-butyl) acetates at 308.15 K, Rasayan Journal of Chemistry, 2008, 1(3), pp. 602–608, https://rasayanjournal.co.in/vol-1/issue-3/28.pdf

[13] D. D. Perrin, and W. L. F. Armarego, purification of Laboratory Chemicals 3rdEdn. (Pergamon, UK) 1988, https://www.scirp.org/reference/referencespapers?referenceid=1287461

[14] Y. Zhao, J. wang, X. Xuan, and J. Lu, Effect of Temperature on Excess Molar Volumes and Viscosities for Propylene Carbonate + N, N-Dimethylformamide Mixtures, Journal of Chemical Engineering Data, 2000, 45(3), pp. 440-444, https://pubs.acs.org/doi/10.1021/je9902746

[15] E. Hanan, M. El-sayed, and A. Abdul-Fattah, Asfour. Density and viscosity of the regular quinary system: Benzene (1) + Toluene (2) + Ethyl benzene (3) + Heptane (4) + Cyclooctane (5) and its quaternary sub-systems at 293.15 and 298.15K, Journal of Solution Chemistry, 2013, 42, pp. 136-150, https://link.springer.com/article/10.1007/s10953-012-9950-0

[16] V. K. Rattan, S. Singh, and B. P. S. Sethi, Viscosity, density and Ultrasonic velocities of binary mixtures of Ethylbenzene with ethanol, 1-propanol and 1-butanol at (298.15 and 308.15) K, Journal of Chemical Engineering Data, 2004, 49(4), pp. 1074-1077, https://pubs.acs.org/doi/10.1021/je049912x

[17] J. A. Riddick, W. B. Bunger, and T. K. Sakano, Organic solvents: Physical properties and Methods of Purification, 4th ed.: Willey Interscience. New York, 1986, https://www.osti.gov/biblio/6190969

[18] Thermodynamic Research Center, Texas A & M University, College Station, T RC Thermodynamic Tables Hydrocarbons, Suppl. No. 92, 1988, https://books.google.co.in/books/about/TRC_Thermodynamic_Tables.html?id=vClCAQAAIAAJ&redir_esc=y

[19] A. K. Nain, and D. Chand, Correlation between molecular interactions and excess thermodynamic parameters of binary mixtures. J. Pure Appl. Ultrason, 2021, 43, pp. 8-16, https://docs.google.com/gview?url=http://www.ultrasonicsindia.org/USI-43(1-2)2021.pdf&embedded=true

[20] M. I. Aralaguppi, T. M. Aminabhavi, S. B. Harogoppad, and R. H. balindgi, Journal of Chemical Engineering Data, 1992, 37(3), pp. 29-303, https://pubs.acs.org/doi/pdf/10.1021/je00007a006

[21] B. K. Sarkar, A. Choudhury, and B. Sinha, Excess molar volume, excess viscosities and ultrasonic speed of sound of binary mixtures of 1,2-Dimethoxyethane with some aromatic liquids at 298.15K. Journal of Solution Chemistry, 2012, 41, pp. 53-74, https://link.springer.com/article/10.1007/s10953-011-9780-5

[22] A. K. Nain, Ultrasonic and viscometric studies of molecular interactions in binary mixtures of tetrahydrofuran with some aromatic hydrocarbons at temperatures from 288.15 to 318.145K, Physics and Chemistry of Liquids,2007,45(4), pp. 371-388, https://doi.org/10.1080/00319100701230405

[23] J. M. Resa, C. Gonzalez, S. Prieto, E. Diez, and M. Iglesias, Mixing properties of propyl acetate + aromatic hydrocarbons at 298.15K. Korean Journal of Chemical Engineering, 2006, 23(1), pp. 93-101, https://link.springer.com/article/10.1007/BF02705698

[24] TRC thermodynamic tables, Thermodynamic Research Center, Texas A & M University, College Station, TX 1994, https://link.springer.com/chapter/10.1007/978-3-642-74140-1_6

[25] J. M. Resa, C. Gonzalez, de L. Ortiz, and J. Lanz, Densities, excess molar volume and refractive indices of ethyl acetate and aromatic hydrocarbon binary mixtures, Journal of Chemical Thermodynamics, 2002, 34(7), pp. 995-1004, https://www.sciencedirect.com/journal/the-journal-of-chemical-thermodynamics/vol/34/issue/7

[26] D. K. Sharma, C. P. Prajapati, and S. Kumar, Density, Ultrasonic Velocity, Viscosity and their Excess Parameters of Some Binary Liquid Mixtures of Cumene with Aromatic Hydrocarbons at 298.15 K, Der PharmaChemica, 2024, 16(2), pp. 301-306, https://www.derpharmachemica.com/archive/dpc-volume-16-issue-2-year-2024.html

[27] M. A. Saleh, M. Habibullah, M. Shamsuddin Ahmed, M. Ashraf Uddin, S. M. H. Uddin, M. Afsar Uddin and F. M. Khan, Excess molar volume and viscosities of some alkanols with Cumene, Physics and Chemistry of liquids, 2006, 44(1), pp. 31-43, https://doi.org/10.1080/00319100500287853

[28] S. Aktar, M. Abdur Rahman, M. ShahadatHossian, and S. Akhtar, Excess molar volume and deviation in viscosity of the binary liquid mixtures of 1-Pentanol + Aromatic Hydrocarbons at 298.15K, European Scientific Journal, 2015, 11(5), pp. 213-225, https://eujournal.org/index.php/esj

[29] M. Page, J. Huot, and A. Jolicoeur, Comprehensive thermodynamic investigation of water-ethanolamine mixtures at 10, 25 and 40 ℃. Canadian Journal of Chemistry, 1993, 45, pp. 1064-1072, https://www.sciencedirect.com/org/journal/canadian-journal-of-chemistry/issues

[30] N. G. Tsierkezos, M. M. Palaiologou, and I. E. Molinou, Densities and Viscosities of 1-Pentanol binary mixtures at 293.15K. Journal of ChemicalEngineering Data, 2000, 45, pp. 272-275, https://pubs.acs.org/doi/10.1021/je9902138

[31] M. Kumar, and V. K. Rattan, Thermophysical properties for binary mixture of Di methyl sulfoxide and isopropyl benzene at various temperatures, Journal of Thermodynamics, 2013, 23, https://onlinelibrary.wiley.com/journal/6962

[32] M. K. Hossani, A. Rahman, and S. Akhatar, Molar Interactions of Some Aromatic Hydrocarbons in n-Heptane by Viscometric Measurements at 298.15K, The Chittagong University Journal Science,2018, 40, pp. 97-110, https://doi.org/10.3329/cujs.v40i1.47918

[33] Sh. Fujii, K. Tamura, and S. Murakam, Thermodynamic properties of (an alkylbenzene+ cyclohexane) at the temperature 298.15 K, Journal of Chemical Thermodynamics,1995, 27(12), pp. 1319–28, https://www.sciencedirect.com/science/article/pii/S0021961485701401

[34] D. L. Prak, S. L. Graft, Th. R. Johnson, J. S. Cowart, and P. C. Trulove, Binary mixtures of aromatic compounds (n-Propylbenzene, 1, 3, 5-trimethylbenzene, and 1, 2, 4-trimethylbenzene) with 2, 2, 4, 6, 6-pentamethylheptane: densities, viscosities, speeds of sound, bulk moduli, surface tensions, and flash points at 0.1 MPa. Journal of Chemical Engineering Data, 2020, 65(5), pp. 2625-2641, https://pubs.acs.org/toc/jceaax/65/5

[35] R. Padmanaban, A. Gayathri, S. Kapoor, G. A. Iyengar, Dong-Eun Lee, V. Kannan, V. Karthikeyan, D. S. Assi, and A. L. Vellaisamy Roy, Comparative Evaluation of Thermophysical and Acoustical Properties of Binary Mixtures of Cumene + Methyl Acetate and Cumene + Ethyl Acetate over the Range of Molar Compositions and Temperatures from 298.15 to 318.15 K: Experimental Measurements and Application of Deviation Modeling, Journal of Chemical Engineering Data, 2025, 70, pp. 3491−3508, https://pubs.acs.org/toc/jceaax/70/9

[36] S. C. Bhatia, R. Ruman, and R. Bhatia, Viscosities, densities, speeds of sound and refractive indices of binary mixtures of o-xylene, m-xylene, p-xylene, ethylbenzene and mesitylene with 1-decanol at 298.15viscosity of the binary liquid mixtures of 1-Pentanol + Aromatic Hydrocarbons at 298.15K, European Scientific Journal, 2015, 11(5), pp. 213-225, https://eujournal.org/index.php/esj

[37] H. J. McSkimin, Ultrasonic Methods for Measuring the Mechanical Properties of Liquids and Solids. In: Mason, W. P., Ed., Physical Acoustics, Academic Press, New York, 1964, 271. https://www.scirp.org/reference/referencespapers?referenceid=1287201

[38] E. L Carstensen, Measurement of Dispersion of Velocity of Sound in Liquids, The Journal of the Acoustical Society of America, 1954, 26, pp. 858-861. https://doi.org/10.1121/1.1907429

[39] O. Redlich, and A. T. Kister, Algebraic representation of thermodynamic properties and the classification of solutions, Indian Engineering Chemistry,1948, 40, pp. 345–348, https://doi.org/10.1021/ie50458a036

[40] N. N. Padole, and N. N. Padole, Fundamentals of acoustics. Handbook of Vibroacoustics, Noise and Harshness, Singapore: Springer Nature Singapore, 2024, pp. 915–950, https://doi.org/10.1007/978-981-97-8100-3_40

[41] I. Mejri, T. Kouissi, A. Toumi, N. Ouerfelli, and M. Bounaz, Volumetric, ultrasonic and viscosimetric studies for the binary mixture (1, 4-Dioxane+Water) at T=(295.15, 298.15, 301.15, 304.15, 307.15, 310.15 and 313.15) K, Journal of Solution Chemistry, 2021, 50(9), pp. 1131–1168, https://doi.org/10.1007/s10953-021-01109-z

[42] H. Artigas, C. Lafuente, M. C. Lopez, F. M. Royo, and J. S. Urieta, Zeit. Calorimetric Behaviour of Primary Bromo butanes with Isomeric Butanols. Journal of Physics Chemistry, 2001, 215, pp. 933-942. http://doi.org/10.1524/zpch.2001.215.7.933

[43] I. Gascon, S. Martin, P. Cea, M. C. Lopez, and F. M. Royo, Density and Speed of Sound for Binary Mixtures of a Cyclic Ether with a ButanolIsomer, Journal of Solution Chemistry,2002, 31(11), pp. 905-915. https://link.springer.com/article/10.1023/A:1021467806352

[44] R. Alkins, K. Hynynen, 10.08–Ultrasound therapy, in: A. Brahme (Ed.), Comprehensive Biomedical Physics, 2014, pp. 153–168, https://doi.org/10.1016/B978-0-444-53632-7.01010-8

[45] S. K. Md. Nayeem, M. Kondaiah, K. Sreekanth, M. Srinivasa Reddy, and D. Krishna Rao, Thermoacoustic, volumetric, and viscometric investigations in the binary mixtures of 1, 4-dioxane with n-hexane or n-heptane or n-octane, Journal of Thermal Analysis Calorimetry, 2016, 123, pp. 2241–2255, https://doi.org/10.1007/s10973-015-4994-1

[46] R. Aurebach. Experimentia, 1948, 4, pp. 473, https://www.tandfonline.com/toc/gpch20/46/1?nav=tocList

[47] Hu, J. Relaxation time approximation revisited and pole/cut structure in retarded correlators." ArXiv preprint arXiv: 2409.05131, 2024, https://doi.org/10.1016/j.jpowsour.2024.236000

[48] S. S. Aswale, S. R. Aswale, and R. S. Hajare, Adiabatic compressibility, intermolecular free length and acoustic relaxation time of aqueous antibiotic cefotaxime sodium, Journal of Chemical and Pharmaceutical Research, 2012, 4(5), pp2671-2677, https://www.jocpr.com/articles

[49] J. F. Kincaid, and H. Eyring, Free volumes and free angle ratios of molecules in liquids, Journal of Chemistry Physics, 1938, 6(10), pp. 620–629, https://doi.org/10.1063/1.1750134u

[50] L. E. Kinsler. And A. R. Rray, Fundamental of Acoustic Wiley eastern, New Delhi, 1989. https://jontalle.web.engr.illinois.edu/Public/BOOKS/KinslerFreyCoopSanders.00.pdf

[51] A. Hyder, A. K. Nair A K, Indian journal of pure and applied Physics, 2000, 63(7), pp. 413.

[52] N. Das, M. Kumar Praharaj, and S. Panda, Understanding ultrasonic wave behavior in liquid Media: a comprehensive overview, Current Analytical Chemistry, 2025, 21(4), pp. 276–287, https://doi.org/10.2174/0115734110306958240620073537

[53] I. Saxena, Ultrasonic investigation of molecular interactions in poly methyl meth acrylate – toluene binary liquid mixture, Journal of Science Technology, 2024, 9, pp. 1–12, https://doi.org/10.46243/jst.2024.v9.i07

[54] A. Awasthi, M. Rastogi, M. Gupta, and J.P. Shukla, Ultrasonic investigation of molecular association in ternary mixtures, Journal of Molecular Liquid, 1999, 80(1), pp. 77–88, https://doi.org/10.1016/S0167-7322(99)00016-1

[55] M. S Reddy, S. k. Md. Nayeem, C. Soumini, K. Thomas, S. S. Raju, and B. HariBabu, Study of molecular interactions in binary liquid mixtures of [Emim] [BF4] with 2- methoxyethanol using thermo acoustic, volumetric and optical properties, ThermochimicaActa, 2016, 630, pp. 37–49, https://doi.org/10.1016/j.tca.2016.02.005

[56] G. A. Rodríguez, F. Martínez, and E. F. Vargas, Molar dissolution enthalpies of some sodium sulfonamides in water and normal saline solution at several temperatures, Journal of Thermal Analysis Calorimetry, 2025, pp. 1–14, https://doi.org/10.1007/s10973-025- 14044-8

[57] P. B. Nalle, S. D. Birajdar, B. R. Shinde, R. G. Dorik, and K. M. Jadhav, Effect of drug Piper nigrum on physicochemical properties of zinc chloride at varying concentration and temperature investigated through ultrasonic tool, Cogent. Chemistry, 2016, 2(1), pp. 1216721, https://doi.org/10.1080/23312009.2016.1216721

[58] A. J. A. Baskar, R. Kumar, R. Vijay Solomon, M. Sundararajan, V. Kannappan, D. Roop Singh, and M. Jaccob, Ultrasonic, spectrophotometric and theoretical studies of sigma and PI interactions of iodine with substituted benzene, RSC Adv., 2015, 5(56), pp. 44873–44885, https://doi.org/10.1039/C5RA03297K

[59] M. S. Reddy, K. Thomas, S. S. Raju, S. k. Md. Nayeem, I. Khan, K. B. M. Krishana, and B. HariBabu, Excess thermodynamic properties for binary mixtures of ionic liquid 1-ethyl-3-methylimidazolium ethyl sulfate and 2-methoxyethanol from T=(298.15 to 328.15) K at atmospheric pressure, Journal of Solution Chemistry, 2016, 45, pp. 675–701, https://doi.org/10.1007/s10953-016-0465-y

[60] A. Bagheri, M. Fazli, and M. Bakhshaei, Effect of temperature and composition on the surface tension and surface properties of binary mixtures containing DMSO and short chain alcohols, Journal of Chemical Thermodynamics, 2016, 101, pp. 236–324. https://doi.org/10.1016/j.jct.2016.06.004

[61] J. Nath, and A. D. Tripathi. Binary systems of 1,1,2,2-tetrachloroethane with benzene, toluene p-xylene acetone and cyclohexane. Excess Volumes, Ultrasonic Velocities, and Adiabatic Compressibilities at 298.15 and 308.15, Journal of Chemical Engineering Data, 1983, 28, pp. 263, https://doi.org/10.1021/je00032a038

[62] D. Drăgoescu, and S. Alexander, Thermophysical Properties for Binary Mixtures of Cumene and Linear/Cyclic Ketones, at Several Temperatures and Atmospheric Pressure, Journal of Solution Chemistry, 2025, 54, pp. 1–30, https://doi.org/10.1007/s10953-024-01403-6