Ultrasonic and Acoustic Investigation of Glutamic Acid and Aspartic Acid in Mixed Solvent Systems for Enhanced Drug Solubility and Bioavailability in Oral and Injectable Formulations

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KEYWORDS

Glutamic acid, Aspartic acid, Ultrasonic velocity, Thermoacoustic properties, Solvent interactions, Mixed solvent systems, Molecular dynamics.

ABSTRACT

The present study focuses on the ultrasonic and thermoacoustic investigation of glutamic acid and aspartic acid in various mixed solvent systems, including ethanol-water, DMSO-water, isopropanol-water, methanol-water, chloroform-water, and acetone-water. The research evaluates critical parameters such as density (ρ), ultrasonic velocity (U), viscosity (η), adiabatic compressibility (β), intermolecular free length (Lf), acoustic impedance (Z), free volume (Vf), internal pressure (πi), molar volume (Vm), Rao's constant (RC), and Wada's constant (WC). These parameters were analyzed over varying weight percentages (1%,3% and 5%) to understand solute-solvent and solvent-solvent interactions. The results demonstrate that the ultrasonic velocity and density generally increase with solute concentration, indicating stronger molecular interactions. The decrease in adiabatic compressibility and intermolecular free length reflects the formation of a tighter molecular network, reducing molecular free space. Variations in acoustic impedance and free volume further validate the interaction strength between amino acids and solvent molecules. Internal pressure analysis reveals insights into molecular cohesion, while molar volume, Rao's, and Wada's constants provide information on molecular packing and interaction dynamics. These findings contribute to a deeper understanding of the behavior of amino acids in mixed solvents, which is crucial for applications in biochemical, pharmaceutical, and industrial formulations.

Introduction

Amino acids are fundamental biomolecules that play a pivotal role in various biochemical processes, including neurotransmission, metabolism, and protein biosynthesis. Among them, Glutamic Acid and Aspartic Acid are classified as acidic amino acids due to the presence of additional carboxyl (-COOH) functional groups, which influence their solubility, intermolecular interactions, and pharmacokinetic properties. These amino acids are widely utilized in pharmaceutical formulations, particularly in oral and injectable drug delivery systems**,** where their solubility and bioavailability in different solvent environments critically impact drug stability, absorption, and therapeutic efficacy. The study of solute-solvent interactions through ultrasonic techniques provides valuable insights into the molecular behavior of pharmaceutical compounds in diverse solvent systems. Ultrasonic velocity, viscosity, and density measurements facilitate the evaluation of key thermoacoustic parameters**,** such as adiabatic compressibility, acoustic impedance, intermolecular free length, free volume, internal pressure, molar volume, Rao's constant, and Wada's constant**.** These parameters allow researchers to determine the strength of molecular interactions and the structural stability of drug formulations, which are crucial for optimizing solubility and bioavailability.

This research systematically investigates the behavior of Glutamic Acid and Aspartic Acid in a range of mixed solvent systems**,** including ethanol, methanol, acetone, chloroform, propanol, and dimethyl sulfoxide (DMSO)**,** all prepared in a 50:50 ratio with water. The study explores the effect of different solvents on the dissolution and structural stability of these amino acids at varying concentrations (1%, 3%, and 5% w/w), highlighting their potential role in pharmaceutical applications, particularly in the formulation of oral and injectable drugs**.** Solvent polarity significantly affects drug solubility and molecular interactions. Polar protic solvents like ethanol and methanol enhance hydrogen bonding**,** leading to stronger solute-solvent interactions and improved molecular stability. Polar aprotic solvents**,** such as DMSO, promote dipole-dipole interactions**,** improving solubility for acidic amino acids. In contrast, non-polar solvents like chloroform exhibit higher free volume and compressibility**,** indicating weaker molecular cohesion and reduced solubility. These solvent-dependent variations provide a scientific foundation for selecting appropriate solvent systems in pharmaceutical formulations to enhance drug solubility, absorption, and controlled release mechanisms**.**

A key objective of this study is to utilize ultrasonic techniques as an effective, non-invasive method for analyzing molecular interactions in solvent systems, with a focus on enhancing drug bioavailability in oral and injectable formulations. By identifying the optimal solvent conditions for Glutamic Acid and Aspartic Acid, this research contributes to personalized medicine**,** ensuring that drug formulations are tailored to maximize therapeutic efficacy while maintaining stability. The findings also pave the way for the development of more efficient pharmaceutical formulations**,** where solvent selection is optimized for sustained drug release, improved patient compliance, and reduced formulation instability**.** Ultimately, this study

underscores the significance of thermoacoustic investigations in pharmaceutical sciences and their applicability in real-time drug dissolution and stability monitoring**.** Future research should explore additional variables, such as temperature, ionic strength, and pH variations**,** to further refine solubility models and optimize formulations for clinical applications. The integration of computational modeling with ultrasonic studies could also enhance predictive capabilities, enabling a more systematic approach to drug formulation and delivery.

Literature Review

Amino acids, particularly L-glutamic acid and L-aspartic acid, are fundamental biomolecules involved in various physiological processes, including neurotransmission, metabolism, and protein biosynthesis. Their physicochemical characteristics, especially solubility and molecular interactions, are critical for pharmaceutical formulations, where enhanced drug solubility and bioavailability are paramount. Recent research emphasizes the application of ultrasonic and thermoacoustic techniques to investigate the molecular behavior of these amino acids in mixed solvent systems, providing essential insights into solute-solvent interactions and molecular dynamics.

Ultrasonic velocity measurements offer a non-invasive and effective approach to understanding molecular interactions in solutions. Kumar et al. conducted extensive ultrasonic and conductometric studies on L-aspartic acid and L-glutamic acid in aqueous sodium acetate solutions. Their findings indicated that ultrasonic velocities, along with parameters like adiabatic compressibility and intermolecular free length, effectively reflected solute-solvent interactions. A key observation was the decrease in compressibility with increasing solute concentration, suggesting stronger molecular cohesion. Additionally, the study of thermoacoustic parameters, including isentropic compressibility, acoustic impedance, and apparent molar volume, provided deeper insights into molecular dynamics. An increase in sodium acetate concentration resulted in lower isentropic compressibility and higher acoustic impedance, indicating intensified molecular interactions and reduced molecular free space [1].

Further, Dhal et al. explored the ultrasonic behavior of L-aspartic acid in aqueous sodium benzoate and ammonium acetate solutions. Their research highlighted that electrostriction effects influenced ultrasonic velocity, with increased solute concentration leading to decreased compressibility and intermolecular free length, implying tighter molecular packing and stronger solute-solvent interactions [2]. Umaley et al. investigated the volumetric, viscometric, acoustical, and optical properties of L-glutamic acid in aqueous zinc and copper chloride solutions. The study revealed that ultrasonic velocity increased with solute concentration, while adiabatic compressibility, molar volume, and intermolecular free length decreased. These findings suggested stronger solute-solvent interactions and enhanced molecular cohesion. The

complexation effect induced by zinc and copper ions resulted in tighter molecular packing, enhancing the understanding of coordination chemistry in biological systems [3].

Pattnaik and Dash conducted studies on the partial molar properties and thermoacoustic parameters of amino acids in aqueous methanol solutions containing sodium benzoate. Their research demonstrated that solvent polarity and solute concentration substantially influenced ultrasonic velocity and compressibility, revealing diverse molecular interaction intensities and solvation effects. Methanol's ability to enhance hydrogen bonding and sodium benzoate's contribution to ionic interactions collectively led to reduced compressibility and increased acoustic impedance, underscoring the significant role of solvent composition in molecular behavior [4]. Thirumaran and Karthikeyan conducted thermo-acoustic studies on interionic interactions of α-amino acids in aqueous sucrose solutions. Their research revealed that sucrose concentration considerably affected ultrasonic velocity and related acoustic parameters. The presence of sucrose reduced compressibility while enhancing molecular cohesion, signifying its substantial influence on molecular interactions and the structural stability of solutions [5].

Sonune et al. performed a thermo-acoustic analysis of molecular interactions involving L-histidine and potassium sulfate solutions at varying temperatures using ultrasonic techniques. Their results showed that both temperature and solute concentration significantly impacted acoustic parameters. Higher temperatures promoted stronger molecular interactions, resulting in reduced compressibility and increased acoustic impedance, while lower temperatures exhibited higher compressibility and lower impedance, indicating weaker molecular interactions. This study underscored the vital role of temperature in determining molecular bond strength and system stability [6]. Gaba et al. explored the solvation properties and taste behavior of amino acids in aqueous ionic liquid solutions using volumetric and acoustic methodologies. The study demonstrated that the introduction of ionic liquids significantly influenced molecular interactions, as reflected in variations in volumetric and acoustic parameters. These findings emphasized the importance of solvent selection in affecting solvation properties and taste behavior, contributing to optimizing solvent systems for pharmaceutical applications [7].

Giratkar et al. conducted ultrasonic studies on amino acids in aqueous solutions, yielding valuable information about the physicochemical properties of these systems. Their work contributed to a broader understanding of molecular interactions in biological contexts, further enriching the field of ultrasonic characterization of biomolecules [8]. Li et al. investigated ultrasound-assisted crystallization processes of L-glutamic acid, discovering that the application of ultrasound significantly reduced induction times and metastable zone widths. This led to enhanced nucleation rates and influenced polymorphic transformations, highlighting the role of ultrasound in controlling crystallization behavior and improving process efficiency [9].

Recent advances have expanded the understanding of ultrasonic and thermoacoustic behavior in complex solvent systems. The synergistic application of ultrasound in combination

with other technologies has been shown to enhance treatment outcomes. However, challenges such as high energy consumption and operational complexities still persist, necessitating further research for process optimization [10]. On a whole, ultrasonic and thermoacoustic techniques have proven effective in elucidating the molecular behavior of amino acids like L-glutamic acid and L-aspartic acid in mixed solvent systems. These methods provide critical insights into solute-solvent interactions, molecular dynamics, and structural properties, thereby contributing to the enhancement of drug solubility and bioavailability in pharmaceutical formulations.

3. Materials and Methods

3.1 Chemicals and Reagents Used

This study focuses on the thermoacoustic properties of Glutamic Acid and Aspartic Acid in diverse solvent systems using ultrasonic analysis. Glutamic Acid, a non-essential amino acid, is integral to protein synthesis and neurotransmission, while Aspartic Acid is involved in metabolic processes and plays a critical role in energy production. Both amino acids were obtained in high-purity crystalline forms (≥99%) from certified chemical suppliers to ensure the accuracy and reliability of experimental outcomes.

The selected solvents include absolute ethanol (analytical grade, ≥99.9% purity), acetone, dimethyl sulfoxide (DMSO), propanol, chloroform, and methanol. Each solvent was chosen based on specific physicochemical properties like polarity and hydrogen bonding potential, which significantly influence solute-solvent interactions. Ethanol and methanol, known for their hydrogen-bonding capabilities and distinct polarities, were included to study polar interactions. Acetone and propanol provided insight into non-aqueous solvation effects, while DMSO, a highly polar aprotic solvent, was selected to evaluate strong dipole interactions. Chloroform, representing a non-polar solvent, was used to assess hydrophobic interactions. Additionally, a 50% ethanol-water mixture was prepared to examine the influence of mixed solvent polarity. All solvents were freshly prepared, filtered, and degassed to eliminate contaminants and minimize experimental variability.

3.2 Preparation of Amino Acid Solutions

Solutions of Glutamic Acid and Aspartic Acid were prepared at concentrations of 1%, 3%, and 5% (w/w) in each selected solvent. The preparation process was meticulously executed to ensure consistency and reproducibility across various experimental conditions.

The selection of solvents was based on their physicochemical characteristics and their influence on solute-solvent interactions. Absolute ethanol (≥99.9% purity) and a 50:50 v/v ethanol-water mixture were employed to explore the impact of polarity and hydrogen bonding on

the thermoacoustic behavior of amino acids. Acetone and propanol were selected to investigate the effects of non-aqueous solvation, focusing on how these solvents interact with amino acids in the absence of water. DMSO, known for its strong dipole-dipole interactions, was used to examine the stabilization of solutes through polar interactions. Chloroform, a highly hydrophobic solvent, facilitated the study of non-polar environment impacts, while methanol provided additional insight into the role of hydrogen bonding in solute-solvent interactions.

Accurate weighing of amino acids was crucial for precise concentration preparation. High-purity Glutamic Acid and Aspartic Acid (≥99% purity) were carefully measured using an analytical balance with a precision of ±0.0001 g. The amino acids were weighed according to the target weight percentages (1%, 3%, and 5% w/w) to facilitate detailed analysis of concentration-dependent effects on ultrasonic velocity, density, viscosity, and derived thermoacoustic parameters. Precision in these measurements ensured consistency and reproducibility of results.

The dissolution process was systematically performed to ensure homogeneous solutions. The accurately weighed amino acid samples were transferred to pre-cleaned 50 mL glass beakers to prevent contamination. A measured volume of the selected solvent was then added, and the solution was stirred continuously at 500 rpm using a magnetic stirrer for 30 minutes at a controlled temperature of 303 K to achieve complete dissolution. Maintaining consistent stirring speed and temperature was essential to ensure uniformity across all samples.

Following dissolution, the solutions were subjected to filtration and degassing to ensure suitability for ultrasonic measurements. Solutions were filtered through a 0.45 µm membrane filter to eliminate any undissolved particles that could interfere with measurement accuracy. To remove air bubbles that might disrupt ultrasonic testing, the solutions were degassed in an ultrasonic bath for 10 minutes. This process ensured the elimination of microbubbles, thereby enhancing the precision and reliability of ultrasonic velocity measurements.

3.3 Instrumentation and Experimental Setup

3.3.1 Ultrasonic Velocity Measurement

Ultrasonic velocity (U) of the prepared amino acid solutions was measured using a single-crystal ultrasonic interferometer operating at a constant frequency of 2 MHz. The instrument features a high-frequency quartz crystal transducer that generates ultrasonic waves, which travel through the liquid sample held within a specially designed measuring cell. The velocity was determined by analyzing the interference patterns created by the reflected ultrasonic waves.

3.3.2 Viscosity Measurement

The viscosity (η) of the solutions was measured using an Ostwald viscometer. Prior to each measurement, the viscometer was meticulously cleaned with distilled water and dried to avoid contamination. The flow time of a fixed volume of solution passing between two calibration marks under gravitational influence was recorded with a digital stopwatch, providing an accuracy of ±0.01 seconds. The viscosity values were computed using standard viscometric equations, comparing the flow times of the test solution to those of distilled water as the reference liquid.

3.3.3 Density Measurement

Density (ρ) measurements were conducted using a 5 mL specific gravity bottle. The bottle was thoroughly cleaned, dried, and tared before each measurement to minimize systematic errors. It was then filled with the solution, and the mass was measured using a high-precision electronic balance with an accuracy of ±0.0001 g. Density was calculated by dividing the measured mass by the known volume of the bottle.

3.4 Experimental Conditions and Data Collection

All measurements were performed under controlled temperature conditions maintained at 303 K using a temperature-controlled water bath with an accuracy of ±0.1 K. Ultrasonic velocity, viscosity, and density were measured for each solution at concentrations of 1%, 3%, and 5% (w/w) across all solvent systems.

The collected experimental data were subsequently used to calculate various thermoacoustic properties, including adiabatic compressibility, acoustic impedance, free volume, and intermolecular free length. These derived parameters offer valuable insights into solute-solvent interactions, molecular dynamics, structural properties, and intermolecular forces that influence the physicochemical behavior of amino acids in different solvent environments. The interpretation of these calculations aids in understanding hydrogen bonding effects, solvation mechanisms, compressibility, and molecular stability under varying conditions.

3.5 Computational Analysis

The computational and statistical analysis of the experimental data was performed to derive key thermoacoustical parameters and evaluate the reliability of the obtained measurements. Various mathematical models and statistical tools were employed to interpret

solute-solvent interactions, molecular dynamics, and structural behavior of Phenylalanine and DL-Alanine in different solvent environments. The analysis primarily focused on the determination of adiabatic compressibility (β), acoustic impedance (Z), intermolecular free length (Lf), and free volume (Vf) using experimentally measured ultrasonic velocity (U), density (ρ), and viscosity (η).

The thermoacoustical parameters were derived using standard theoretical formulations based on fundamental principles of ultrasonic and molecular interactions. The adiabatic compressibility (β) was computed using Newton-Laplace's equation:

$$\beta_a = 1 / \rho U^2 \quad N\ m^{-2}$$

Where, βa = Adiabatic compressibility (Pa^{-1} or $N^{-1}m^2$), ρ = Density of the solution (kg/m^3) and U = Ultrasonic velocity in the medium (m/s)

Acoustic impedance (Z), an important characteristic that influences the transmission and reflection of ultrasonic waves at phase boundaries, was determined using the expression:

$$Z = \rho U \qquad kgm^{-2}s^{-1}$$

Where, Z = Acoustic impedance ($kgm^{-2}s^{-1}$). Intermolecular free length (Lf), which serves as an indicator of molecular packing and cohesive forces in the solution, was estimated using the equation:

$$L_f = k (\beta_a)^{1\backslash 2} \qquad m$$

Where, L_f = Intermolecular free length (m), K = Jacobson's constant (temperature-dependent, in $m/Pa^{1/2}$). Similarly, free volume (Vf), which characterizes the spatial distribution and interaction potential of solvent molecules, was calculated using:

$$V_f = (M\ U / K\eta)^{3\backslash 2} \quad m^3mol^{-1}$$

Where, V_f = Free volume (m^3/mol), M = Effective molecular weight of the solute (g/mol), U = Ultrasonic velocity (m/s), K = Temperature-dependent constant, η = Viscosity of the solution (Pa·s). Internal pressure (πi) provides information about the strength of intermolecular forces and the cohesive energy density in a solution. It plays a significant role in predicting solubility, diffusion behavior, and biomolecular stability**.**

$$\pi_i = BRT(K\eta \setminus U)^{1\backslash 2} (\rho^{2\backslash 3} \setminus (M_{eff})^{7\backslash 6}) \quad N\ m^{-2}$$

Where, π_i = Internal pressure (N/m^2), B = Dimensionless structure factor, R = Universal gas constant ($J\ mol^{-1}K^{-1}$), T = Absolute temperature (K), M_{eff} = Effective molecular weight of the solute (g/mol). Rao's constant (R) is used to analyze the molar sound velocity of a system**,** which provides insights into molecular interactions and solute-induced solvent modifications**.**

$$R = (m / \rho) U^{1\backslash 3} \quad m^3mol^{-1}(m/s)^{1/3}$$

Where, R = Rao's constant ($m^3mol^{-1}m/s^{1/3}$), m = Molar mass of solute (g/mol), ρ = Density of solution (kg/m^3), U = Ultrasonic velocity (m/s). Wada's constant (W) is related to molar compressibility and is useful in understanding the structural properties of solutions**.**

$$W = (m / \rho) \beta^{-1\backslash 7} \quad m^3mol^{-1}kg^{-1}ms^2$$

Where, W = Wada's constant ($m^3mol^{-1}kg^{-1}ms^2$). Additionally, molar volume (V_m), which represents the volume occupied by one mole of solute in the solution, was derived as follows:

$$V_m = M / \rho \quad (m^3\ mol^{-1})$$

Where, V_m is the molar volume, M is the molar mass of the solute, and ρ is the density of the

Solvent	Wt %	U	η	ρ	β_a $x10^{-10}$	Z $x10^{6}$	L_f $x10^{-11}$	V_f $x10^{-7}$	π_i $x10^{6}$	V_m	R	W
Ethanol + Water	1	928.25	1528	1.5913	4.6141	4.286	1.8964	1.4184	0.1585	2.6479	1.7816	3.2141
	3	940.43	1531	1.6353	4.5365	4.2498	1.8258	1.4398	0.1565	2.7049	1.7596	3.1801
	5	944.52	1547.4	1.6606	4.4216	4.1957	1.813	1.4616	0.1558	2.7191	1.7582	3.1777
DMSO + Water	1	1019.24	1697.8	1.8831	3.4037	3.6811	1.7255	1.7305	0.1444	2.9081	1.6799	3.0546
	3	1082.5	1700.4	2.012	3.195	3.5665	1.5659	1.8407	0.1359	3.1265	1.5825	2.9017
	5	1116.68	1701	2.1206	3.095	3.5103	1.448	1.8995	0.1318	3.2762	1.5343	2.8254
Methanol + Water	1	913.82	1526.6	1.3778	4.6956	4.3237	2.3507	1.395	0.161	2.4395	1.8091	3.2569
	3	927.74	1527.4	1.233	4.6203	4.2889	2.7789	1.417	0.1586	2.3307	1.7823	3.2153
	5	939.61	1534.8	1.1845	4.518	4.2411	2.9728	1.4421	0.1566	2.2983	1.7626	3.1846
Propanol + Water	1	920.98	1481.4	1.9206	4.9477	4.4382	1.3653	1.3643	0.1598	2.9386	1.7774	3.208
	3	932.04	1482	1.9872	4.8851	4.41	1.2981	1.3813	0.1579	3.0123	1.7565	3.1756
	5	933.67	1483	2.038	4.8699	4.4032	1.2511	1.3846	0.1576	3.0531	1.7538	3.1714
Chloroform + Water	1	1452.2	1537.8	0.6866	2.9119	3.4048	6.7559	2.2332	0.1013	2.3367	1.1412	2.1912
	3	1468.17	1551.8	0.7714	2.8285	3.3557	5.7507	2.2783	0.1002	2.4835	1.1321	2.1762
	5	1537.97	1563.8	1.2255	2.6588	3.2535	2.9053	2.4051	0.0957	3.2155	1.0835	2.0955
Acetone	1	928.56	1529	0.9485	4.6065	4.2825	4.1252	1.4198	0.1585	2.0446	1.7813	3.2138

solution. Molar volume is a key parameter for understanding molecular packing, solvation dynamics, and intermolecular interactions in different solvent systems.

4. Results and Discussions

The ultrasonic velocity, viscosity, and density data for each solution were recorded at specified concentrations (1%, 3%, and 5% w/w) across all solvent systems. The variations in key thermoacoustic and physicochemical parameters—including adiabatic compressibility, intermolecular free length, free volume, acoustic impedance, density, viscosity, ultrasonic velocity, molar volume, internal pressure, Rao's constant, and Wada's constant—as a function of solute concentration in different solvents are presented in Table 1 for Glutamic Acid and in Table 2 for Aspartic Acid.

+	3	931.83	1539.8	0.996	4.5262	4.245	3.8743	1.4348	0.1579	2.0926	1.7792	3.2104
Water	5	947.34	1542	1.0464	4.4394	4.2041	3.6055	1.4608	0.1553	2.167	1.7509	3.1664

Table 1: Thermoacoustic parameters of Glutamic Acid in various solvent systems at different concentrations.

Solvent	**Wt %**	**ρ**	**U**	**η**	**βa x10^{-10}**	**L_f x10^{-11}**	**V_f x10^{-7}**	**Z x10^{6}**	**V_m**	**π_i x10^{6}**	**R**	**W**
Ethanol + Water	1	926.51	1481.6	1.5182	4.9169	4.4244	1.6719	1.3727	0.1437	2.9483	1.5983	2.8873
	3	953.33	1500.2	1.5977	4.6608	4.3076	1.5779	1.4302	0.1396	3.0633	1.5598	2.8272
	5	980.96	1530.8	1.682	4.3502	4.1616	1.5057	1.5017	0.1357	3.1712	1.526	2.7742
DMSO + Water	1	1068.17	1695.6	1.9886	3.2562	3.6005	1.3654	1.8112	0.1246	3.4674	1.4495	2.6531
	3	1076.56	1697.8	2.0594	3.2225	3.5818	1.2981	1.8278	0.1236	3.5446	1.4388	2.6363
	5	1095.8	1699.4	2.1331	3.1599	3.5469	1.2332	1.8622	0.1215	3.6485	1.414	2.5971
Methanol + Water	1	945.96	1521.2	1.1701	4.5683	4.2647	2.5707	1.439	0.1407	2.5903	1.5792	2.8572
	3	950.87	1533.4	1.2299	4.4727	4.2198	2.4142	1.4581	0.1399	2.6542	1.5752	2.8509
	5	952.51	1557.8	1.2522	4.3262	4.1501	2.4063	1.4838	0.1397	2.6601	1.5807	2.8593
Propanol + Water	1	915.86	1476.2	1.8156	5.0105	4.4663	1.2714	1.352	0.1453	3.2049	1.615	2.9132
	3	919.55	1462	1.9102	5.0878	4.5006	1.1612	1.3444	0.1447	3.3121	1.6034	2.8953
	5	924.26	1449.8	2.0853	5.1474	4.5269	1.0053	1.3399	0.1440	3.4867	1.5908	2.8758
Chloroform + Water	1	1437.26	1527.2	0.6133	2.9831	3.4462	6.8145	2.195	0.0926	2.4737	1.0407	1.9961
	3	1469.6	1524.6	0.6503	2.9274	3.4139	6.2254	2.2406	0.0906	2.5874	1.0172	1.9574
	5	1492.53	1522.2	0.676	2.8916	3.3929	5.8599	2.2719	0.0892	2.6674	1.0011	1.9306
Acetone + Water	1	944.73	1539.8	0.9846	4.4644	4.2159	3.3916	1.4547	0.1409	2.3599	1.5876	2.8701
	3	948.41	1535	1.0145	4.4749	4.2209	3.2276	1.4558	0.1403	2.4054	1.5798	2.8581
	5	950.87	1532	1.0548	4.4809	4.2237	3.0355	1.4567	0.1399	2.4593	1.5747	2.8501

Table 2: Thermoacoustic parameters of Aspartic Acid in various solvent systems at different concentrations.

Analysis of Parameters for Glutamic Acid in Different Solvent Systems

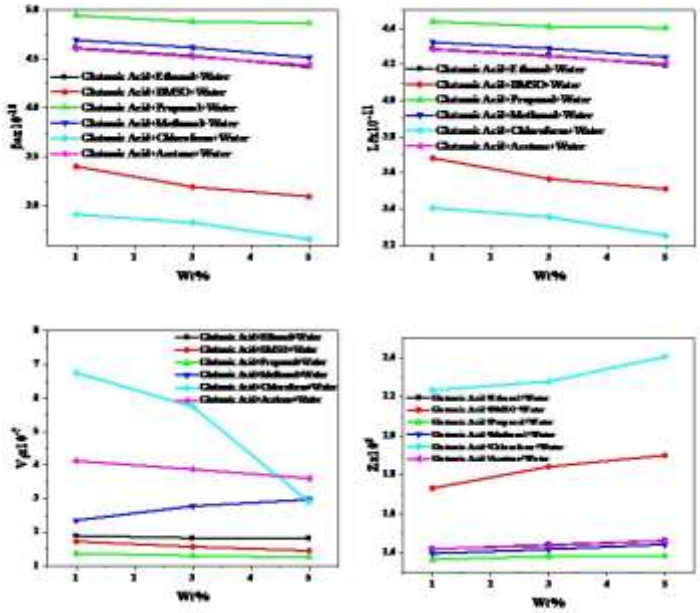

Figure 1: Variation of adiabatic compressibility (βa), intermolecular free length (L_f), free volume (V_f), and acoustic impedance (Z) of glutamic acid solutions across different solvents as a function of concentration (wt%).

The presented image in figure 1 illustrates the variations in four physicochemical parameters—adiabatic compressibility (βa), intermolecular free length (Lf), free volume (Vf), and acoustic impedance (Z)—with increasing weight percentage (Wt%) of glutamic acid in different solvent systems. The solvents studied include ethanol-water, DMSO-water, propanol-water, methanol-water, chloroform-water, and acetone-water. These graphs provide insights into the nature of solute-solvent interactions and the structural behavior of glutamic acid within these mixtures.

In the top-left graph, the trend of adiabatic compressibility (βa) with increasing glutamic acid concentration is depicted. Adiabatic compressibility measures the ease with which a medium can be compressed. The data show a consistent decrease in compressibility as the concentration of glutamic acid rises across most solvent systems. This decline suggests stronger solute-solvent interactions, leading to tighter molecular packing and reduced intermolecular spaces. The effect is more pronounced in polar solvents like ethanol-water and DMSO-water, indicating stronger molecular associations. Conversely, solvents like chloroform-water show relatively less significant changes, possibly due to weaker interaction forces.

The intermolecular free length (L_f)**,** presented in the top-right graph, also displays a decreasing trend with increasing glutamic acid concentration. Intermolecular free length relates to the average distance between molecules in a solution. The reduction in L_f with higher Wt% indicates that the addition of glutamic acid enhances molecular packing, reducing the available

free space within the solution. This behavior is particularly notable in polar solvent systems, suggesting stronger hydrogen bonding and cohesive forces, while less polar solvents exhibit smaller variations.

The bottom-left graph shows the changes in free volume (V_f) as the concentration of glutamic acid increases. Free volume reflects the available space within the molecular structure that allows for molecular movement. The observed trends are somewhat varied across different solvents. While polar solvents like ethanol-water and DMSO-water show a decline in free volume with increasing glutamic acid concentration—indicating denser molecular arrangements—non-polar solvents exhibit more erratic behavior, possibly due to weaker solute-solvent interactions. The significant decrease in chloroform-water suggests considerable molecular compaction at higher concentrations.

Lastly, the bottom-right graph illustrates the behavior of acoustic impedance (Z) with respect to glutamic acid concentration. Acoustic impedance is a measure of how much resistance a medium offers to the passage of sound waves. The results indicate an increasing trend in impedance with higher glutamic acid concentration, particularly in polar solvents. This increase aligns with the observed reduction in compressibility and free length, as denser molecular arrangements resist sound propagation more effectively. Non-polar solvents show more moderate variations, again reflecting weaker interaction forces. In conclusion, the data highlight that the molecular interactions and structural organization of glutamic acid are significantly influenced by the nature of the solvent and its concentration. Polar solvents exhibit stronger interactions, leading to reduced compressibility, shorter free length, lower free volume, and higher acoustic impedance. These trends underline the role of molecular cohesion and solute-solvent dynamics in shaping the physicochemical properties of glutamic acid solutions.

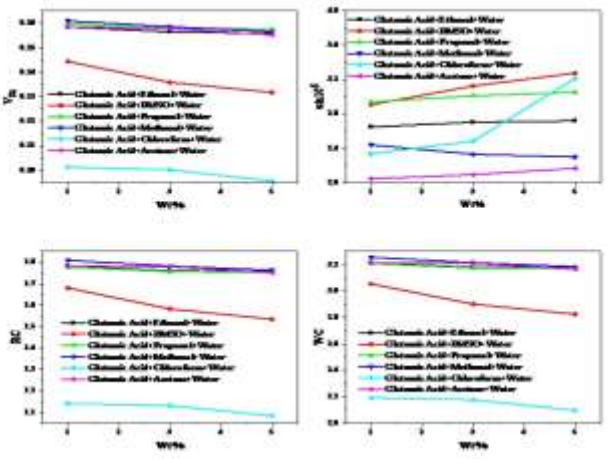

Figure 2: Concentration-dependent variations in molar volume (Vm), internal pressure (Pi), Rao's constant (RC), and Wada's constant (WC) for glutamic acid solutions in different solvents.

The provided image in figure 2 illustrates the variations in four key thermodynamic and acoustic parameters—molar volume (V_m), internal pressure (π_i), Rao's constant (RC), and Wada's constant (WC)—with increasing weight percentages (Wt%) of glutamic acid in various solvent systems. The solvents examined include ethanol-water, DMSO-water, propanol-water, methanol-water, chloroform-water, and acetone-water. These graphical trends offer insight into the solute-solvent interactions and the molecular behavior of glutamic acid in mixed solvent systems.

The top-left graph presents the trend of molar volume (V_m)**,** which reflects the volume occupied by one mole of the solute in solution. As the concentration of glutamic acid increases, there is a general decrease in molar volume across most solvent systems, particularly in acetone-water and DMSO-water mixtures. This reduction suggests that with higher solute concentration, molecules are more tightly packed, reducing the overall volume occupied. The decrease is more pronounced in polar solvents, indicating stronger solute-solvent interactions that enhance molecular compactness. Non-polar solvents like chloroform-water show relatively minimal changes, suggesting weaker interactions.

In the top-right graph**,** the behavior of internal pressure (π_i) with increasing concentration is depicted. Internal pressure is associated with the cohesive forces between molecules. The trend shows an overall increase in πi for most solvent systems, indicating stronger molecular interactions and tighter binding as the glutamic acid concentration rises. Notably, the acetone-water and methanol-water mixtures exhibit significant increases, suggesting enhanced intermolecular attractions. In contrast, some solvent systems, like chloroform-water, show less variation, likely due to weaker cohesive forces.

The bottom-left graph illustrates Rao's constant (RC)**,** which relates to the solubility and interaction capacity of the solute in the solvent. The results show that RC values generally decline with an increase in glutamic acid concentration, particularly in DMSO-water and acetone-water systems. This suggests a reduction in solvation capacity and molecular free movement, consistent with denser molecular structures. However, ethanol-water and methanol-water mixtures show relatively stable RC values, indicating consistent solute-solvent interaction patterns across the concentration range.

The bottom-right graph focuses on Wada's constant (WC)**,** an indicator of the molecular volume contribution to acoustic properties. A general decrease in WC values is observed with increasing glutamic acid concentration, especially in DMSO-water and acetone-water systems. This trend further supports the notion of enhanced molecular packing and reduced free volume in these mixtures. In contrast, solvents like ethanol-water exhibit minor changes, suggesting that the structural arrangement remains relatively stable despite the increase in solute concentration. In summary, the results indicate that the molecular behavior and interaction dynamics of glutamic acid in different solvent systems are significantly influenced by the solvent's polarity and the concentration of the solute. Polar solvents tend to promote stronger interactions, leading to reduced molar volume, higher internal pressure, and lower acoustic constants. These trends

highlight the critical role of solute-solvent interactions in determining the structural and acoustic properties of glutamic acid solutions.

The presented image in figure 3 showcases the variation of three fundamental physical parameters—density (ρ), viscosity (η), and ultrasonic velocity (U)—with increasing weight percentages (Wt%) of glutamic acid in different solvent systems. The solvent mixtures explored include ethanol-water, DMSO-water, propanol-water, methanol-water, chloroform-water, and acetone-water. These parameters provide insights into the molecular behavior and interaction dynamics of glutamic acid within these mixed solvents.

The top-left graph represents the variation of density (ρ) with increasing concentration of glutamic acid. The results show a consistent rise in density across all solvent systems, with the most notable increase observed in the acetone-water and DMSO-water mixtures. This trend suggests that as the concentration of glutamic acid increases, the solution becomes denser, likely due to the stronger packing of molecules and reduced free space within the solvent. The substantial rise in density for acetone-water indicates stronger solute-solvent interactions, while minimal changes in polar solvents like ethanol-water suggest weaker interaction forces.

In the top-right graph**,** the behavior of viscosity (η) with varying concentrations is depicted. Viscosity indicates the internal resistance of the solution to flow, which is influenced by molecular interactions. The graph demonstrates that viscosity generally increases with the concentration of glutamic acid, especially in DMSO-water and propanol-water mixtures. This suggests stronger intermolecular forces and greater interaction between glutamic acid and these solvents, leading to a more resistant flow. Interestingly, solvents like chloroform-water and acetone-water display relatively lower viscosity changes, indicating weaker bonding and less structural resistance within the mixture.

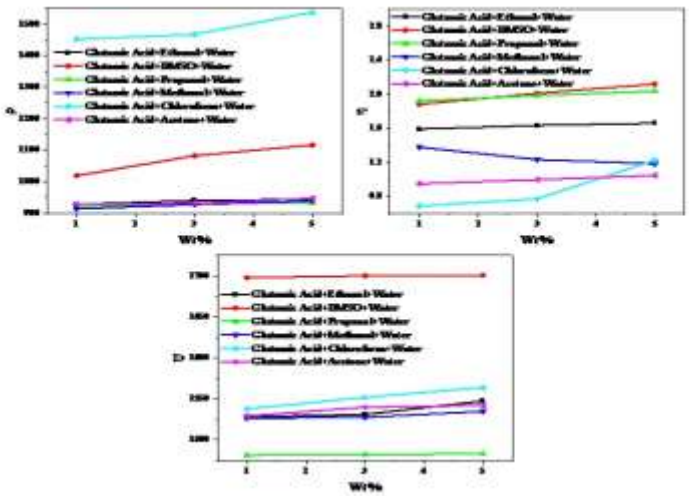

Figure 3: Influence of solute concentration on density (ρ), viscosity (η), and ultrasonic velocity (U) of glutamic acid solutions across various solvent systems.

The bottom graph illustrates the variation of ultrasonic velocity (U)**,** reflecting how quickly sound waves propagate through the solution. The data show that ultrasonic velocity increases with glutamic acid concentration, particularly in DMSO-water and acetone-water systems. This increase signifies stronger solute-solvent interactions, as tighter molecular packing facilitates faster sound wave propagation. In contrast, solvents like propanol-water and chloroform-water exhibit relatively stable ultrasonic velocity, indicating minimal structural changes in these mixtures. In conclusion, the analysis of these three parameters reveals that solvent polarity and molecular interaction strength significantly affect the physical properties of glutamic acid solutions. Solvent systems with stronger interactions, like DMSO-water and acetone-water, display notable increases in density, viscosity, and ultrasonic velocity, highlighting the role of molecular arrangement and interaction in determining solution behavior. These observations contribute to understanding how glutamic acid interacts in various chemical environments, which is crucial for its practical applications.

Analysis of Parameters for Aspartic Acid in Different Solvent Systems

The graphical data presented in figure 4 illustrate the influence of varying weight percentages (Wt%) of aspartic acid in different solvent systems—ethanol-water, DMSO-water, propanol-water, hexanol-water, methanol-water, chloroform-water, and acetone-water—on key acoustic and molecular parameters, namely adiabatic compressibility (β_a), intermolecular free length (L_f), free volume (V_f), and acoustic impedance (Z). These variations provide insight into the molecular interactions and structural behavior of the solutions as a function of concentration.

Adiabatic compressibility (β_a) is an essential parameter indicating how a medium responds to pressure changes. The graphical trend demonstrates a general decrease in compressibility with an increase in the concentration of aspartic acid. This reduction suggests that the molecular arrangement within the solution becomes denser as the concentration rises, leading to a less compressible medium. The stronger solute-solvent interactions at higher concentrations restrict the mobility of solvent molecules, contributing to a tighter molecular configuration. The extent of this decrease, however, varies across different solvent systems, indicating that solvent polarity and molecular structure significantly influence the interaction strength. For example, solvents with higher polarity may facilitate stronger hydrogen bonding with aspartic acid, resulting in a more notable decrease in compressibility.

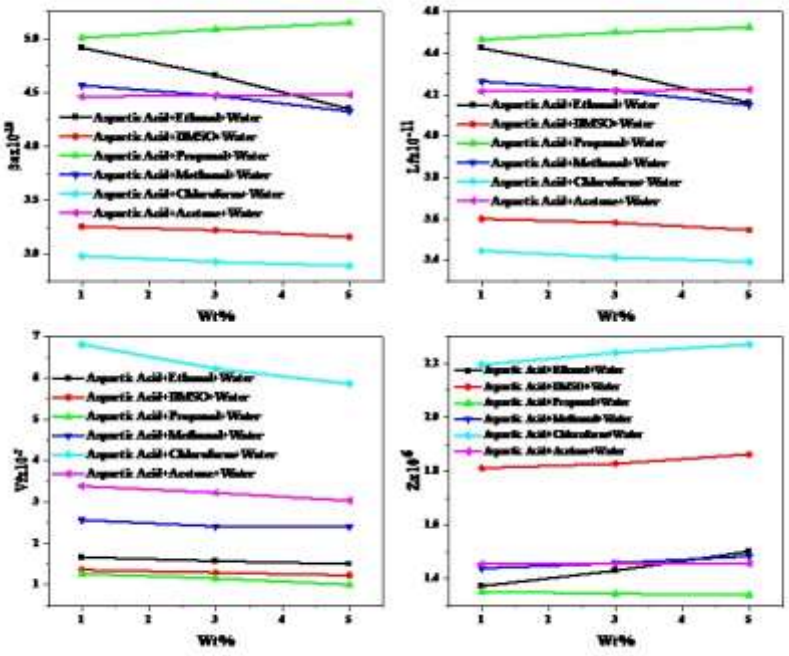

Figure 4: Variation of adiabatic compressibility (βa), intermolecular free length (L_f), free volume (V_f), and acoustic impedance (Z) of aspartic acid solutions across different solvents as a function of concentration (wt%).

Intermolecular free length (L_f), which reflects the average distance between interacting molecules, also shows a decreasing trend with increasing aspartic acid concentration. This behavior indicates that as more solute is introduced, the molecules pack more closely together, reducing the free space available for movement. The decreasing free length can be attributed to stronger solute-solvent interactions, particularly hydrogen bonding, which leads to a denser molecular arrangement. The rate of this decrease differs among the solvent systems, which is likely due to variations in solvent polarity and the ability to facilitate molecular associations with aspartic acid. Solvents that promote stronger interaction, such as polar solvents, tend to exhibit a steeper decline in free length.

Free volume (V_f) is indicative of the available space within the molecular structure for particle movement. The observed data reveal a general decrease in free volume with increasing aspartic acid concentration. This trend suggests that the presence of the solute constrains molecular motion by reducing the voids or gaps within the solution. Strong molecular interactions at higher concentrations lead to more efficient packing, thereby minimizing the free volume. However, this reduction is not uniform across all solvents. For instance, non-polar solvents like chloroform exhibit a less pronounced decrease, likely due to weaker interaction forces between the solvent molecules and aspartic acid. The variation in trends emphasizes the role of solvent characteristics in determining the structural configuration of the solution.

Acoustic impedance (Z), which measures the resistance of a medium to sound wave propagation, exhibits an increasing trend with higher Wt% of aspartic acid. This increase suggests that the solution becomes denser and more resistant to acoustic waves as the concentration of aspartic acid rises. The observed behavior correlates with the reduction in compressibility and free length, indicating that stronger solute-solvent interactions result in a more rigid and compact medium. Consequently, the propagation of acoustic waves faces higher resistance, reflected in the elevated impedance values. The rate of increase differs among solvents, highlighting the influence of solvent-solute compatibility and interaction strength. Solvents that foster stronger molecular associations display a more significant rise in acoustic impedance. In summary, the observed variations in adiabatic compressibility, intermolecular free length, free volume, and acoustic impedance collectively underscore the impact of aspartic acid concentration and solvent nature on the molecular dynamics of the solution. Stronger solute-solvent interactions result in tighter molecular packing, reduced compressibility, decreased free volume, and higher acoustic impedance, revealing the complex interplay of molecular forces within these binary mixtures. These insights are valuable for understanding the physicochemical behavior of amino acid solutions in diverse solvent environments.

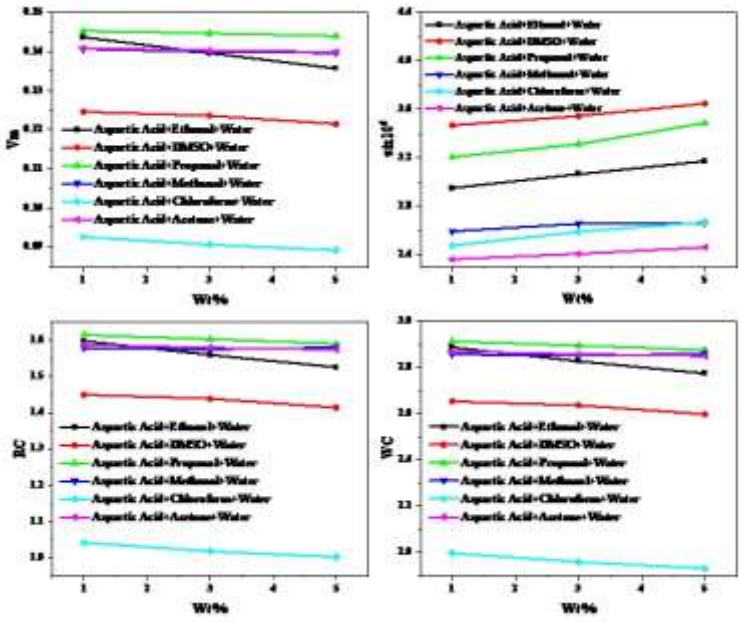

Figure 5: Concentration-dependent variations in molar volume (V_m), internal pressure (π_i), Rao's constant (RC), and Wada's constant (WC) for aspartic acid solutions in different solvents.

The provided image in figure 5 presents four graphical analyses illustrating the variation of key thermodynamic parameters—molar volume (V_m), internal pressure (π_i), Rao's constant (RC), and Wada's constant (WC)—for aspartic acid in different solvent systems. The solvents include ethanol-water, DMSO-water, propanol-water, hexanol-water, methanol-water,

chloroform-water, and acetone-water, with the variations observed across increasing weight percentages (Wt%) of aspartic acid. These trends reflect the interaction behavior and structural modifications occurring within the solutions.

The molar volume (V_m) graph, shown in the top-left quadrant, indicates a general decrease in Vm with an increase in aspartic acid concentration across most solvent systems. Molar volume represents the volume occupied by one mole of solute in the solution, and its reduction signifies a tighter molecular packing as more aspartic acid is introduced. This decrease suggests stronger solute-solvent interactions that facilitate closer molecular association, leading to a denser solution structure. However, the rate of reduction varies among the solvents. For instance, polar solvents like ethanol and DMSO exhibit more pronounced decreases in molar volume due to stronger hydrogen bonding with aspartic acid, whereas non-polar systems like chloroform-water show relatively minor changes, indicating weaker interaction forces.

In the top-right graph, the variation of internal pressure (π_i) with concentration is displayed. Internal pressure is a measure of the cohesive forces within the liquid. An increasing trend of πi is observed with rising Wt% of aspartic acid, suggesting that higher solute concentrations enhance the cohesive forces within the solution. This increase can be attributed to stronger molecular interactions that restrict molecular movement and lead to denser molecular arrangements. The extent of this rise is more significant in polar solvents, highlighting the role of hydrogen bonding in enhancing internal molecular cohesion. In contrast, solvents with lower polarity, such as acetone-water, show a relatively modest increase, indicating weaker molecular associations.

The bottom-left graph illustrates the behavior of Rao's constant (RC)**,** a parameter associated with the molecular interaction and structure of the liquid. The trends indicate a slight decrease in RC with increasing concentration of aspartic acid for most solvents. This decrease suggests that the addition of aspartic acid slightly reduces the effective molecular interaction volume, possibly due to stronger molecular association that minimizes free spaces within the solution. The rate of reduction varies among the solvents, with polar solvents showing a more significant decrease, indicating stronger solvation effects. In contrast, less polar solvents exhibit minor changes, reflecting weaker interaction forces.

Finally, the bottom-right graph shows the variation of Wada's constant (WC)**,** which correlates with the overall compressibility of the solution. A gradual decline in WC values is noted with increasing Wt% of aspartic acid in most solvent systems. This reduction signifies a decrease in the solution's compressibility, likely due to enhanced molecular interactions that result in tighter packing and reduced free volume. Solvents that engage in stronger interactions with aspartic acid, such as ethanol-water and DMSO-water, display a more significant decline in WC. Conversely, in solvents like chloroform-water, the change is less pronounced, indicating relatively weaker interactions and greater molecular freedom. In summary, the trends observed across molar volume, internal pressure, Rao's constant, and Wada's constant reveal the significant impact of aspartic acid concentration and solvent nature on the structural and thermodynamic properties of the solutions. Stronger solute-solvent interactions, especially in

polar solvents, lead to denser molecular arrangements, increased internal pressure, and reduced compressibility, highlighting the fundamental role of molecular forces in governing the behavior of these binary mixtures.

The provided image in figure 6 presents graphical representations of how three key physicochemical parameters—density (ρ), ultrasonic velocity (U), and viscosity (η)—vary with increasing weight percentage (Wt%) of aspartic acid in various solvent systems. These solvents include ethanol-water, DMSO-water, propanol-water, hexanol-water, methanol-water, chloroform-water, and acetone-water. The observed trends offer insights into the molecular interactions and structural behavior of aspartic acid in these mixed solvent environments. In the density (ρ) graph, located at the bottom, it is observed that the density generally increases with an increase in the concentration of aspartic acid across most solvent systems. Density, being a measure of mass per unit volume, increases as more aspartic acid molecules are introduced, leading to enhanced molecular packing and reduced free volume within the solution. The increment is more prominent in polar solvents like ethanol-water and DMSO-water, indicating strong solute-solvent interactions that enhance molecular cohesion. In contrast, less polar solvents such as hexanol-water and chloroform-water show relatively smaller changes, suggesting weaker interaction forces and greater molecular freedom.

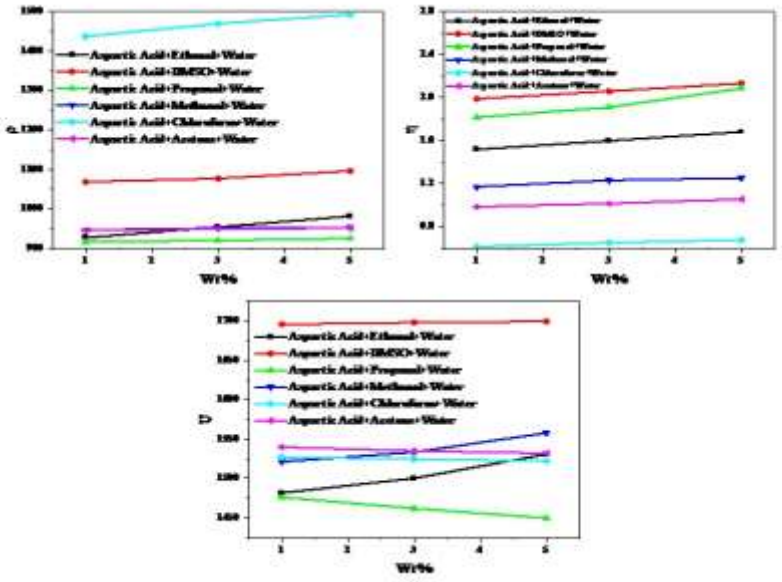

Figure 6: Influence of solute concentration on density (ρ), viscosity (η), and ultrasonic velocity (U) of aspartic acid solutions across various solvent systems.

The ultrasonic velocity (U) variation is displayed in the top-left graph. Ultrasonic velocity measures the speed at which sound waves propagate through the solution, and it is directly influenced by the medium's density and compressibility. The results show an increasing trend of ultrasonic velocity with rising concentrations of aspartic acid in most solvents. This

suggests that the addition of aspartic acid strengthens molecular associations, making the medium less compressible and more rigid, thus facilitating faster sound propagation. The most significant increases are noted in solvents like chloroform-water and DMSO-water, implying stronger solute-solvent binding, while non-polar or less interactive solvents display relatively modest changes.

The top-right graph illustrates the behavior of viscosity (η) with increasing aspartic acid concentration. Viscosity reflects the internal resistance to flow and is significantly influenced by molecular interactions within the solution. The graph shows that viscosity generally increases as the concentration of aspartic acid rises, particularly in polar solvents like ethanol-water and DMSO-water. This increase indicates stronger intermolecular forces and more structured arrangements that hinder the flow of molecules. On the other hand, solvents with lower polarity, such as acetone-water and chloroform-water, exhibit relatively smaller changes, suggesting weaker interactions and less structural hindrance to flow. In summary, the observed trends in density, ultrasonic velocity, and viscosity highlight the significant role of solvent nature and aspartic acid concentration in influencing molecular interactions. The increase in density and ultrasonic velocity, coupled with higher viscosity, particularly in polar solvent systems, underscores the strong binding and structural organization induced by aspartic acid. These findings collectively provide valuable insights into the solute-solvent dynamics and the structural behavior of aspartic acid in varied solvent environments.

Conclusion

The ultrasonic and thermoacoustic investigation of glutamic acid and aspartic acid in various mixed solvent systems has provided comprehensive insights into the molecular interactions and structural dynamics of these amino acids. Key parameters such as ultrasonic velocity, density, viscosity, adiabatic compressibility, acoustic impedance, free volume, internal pressure, molar volume, Rao's constant, and Wada's constant were analyzed to understand the influence of solvent composition and solute concentration. The observed increase in ultrasonic velocity and density with rising solute concentration indicates stronger solute-solvent interactions and enhanced molecular structuring. Conversely, the decrease in adiabatic compressibility and intermolecular free length suggests tighter molecular packing and reduced free space within the solution. Additionally, variations in internal pressure and acoustic impedance reflect the cohesive forces and compressibility resistance of the molecular system. These results emphasize the role of solvent polarity, hydrogen bonding, and molecular cohesion in influencing interaction dynamics. Overall, the findings contribute to a deeper understanding of amino acid behavior in mixed solvent environments, which is essential for various biochemical, pharmaceutical, and industrial applications.

Future research can focus on extending this study by examining the effects of temperature variations to better understand molecular interactions under dynamic thermal conditions. Investigating other amino acids and their responses in complex solvent systems could broaden the research scope. Employing molecular dynamics simulations would provide additional insights into the mechanisms of interaction at the molecular level. Further, exploring

the influence of factors like ionic strength, pH variations, and pressure conditions can offer critical data for understanding amino acid behavior in diverse environments. The implications of this research are significant across multiple domains. In pharmaceuticals, insights into solute-solvent interactions can assist in enhancing drug solubility and stability. The food industry can utilize this understanding to optimize protein formulation and nutrient preservation. In biochemical research, the findings are relevant for studies involving protein folding, enzyme-substrate interactions, and solvent-mediated biochemical processes. Additionally, this research can aid in designing efficient solvent systems for amino acid extraction and purification in industrial applications.

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