Studies on Volumetric and Viscometric Properties of L-Glutamic Acid in Aqueous Solution of Glucose over a Range of Temperatures (298K to 323K)

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Abstract: In this work, volumetric and viscometric properties of L-glutamic acid in water and aqueous glucose solutions (5%, 10%, 15%, and 20% of glucose, w/w in water) have been measured as a function of molal concentration (0.02 mol.kg\(^{-1}\) to 0.16 mol.kg\(^{-1}\)) of L-glutamic acid at different temperatures \(T=\) (293.15, 303.15, 308.15, 313.15 and 323.15) K. By using experimental densities (\(\rho\)) and viscosities (\(\eta\)) data, apparent molar volume (\(\phi_v\)), experimental slope (\(S_v\)), limiting apparent molar volume (\(\phi_v^0\)), limiting apparent molar volume transfer (\(\Delta\phi_v^0\)), temperature (\(\delta\phi_v^0/\delta T\))p, Falkenhagen coefficient A, and Jones-Dole coefficient B have been computed. Gibbs free energies of activation of viscous flow per mole of solvent (\(\mu_1^0\)) and per mole of solute (\(\mu_2^0\)), hydration number (\(H_n\)) is also calculated. The results are discussed based on solute-solute and solute-solvent interactions in these systems. From the results, it is observed that there exists a structure making propensity of L-glutamic acid in water and in the different mass fraction of aqueous glucose solutions, which increases with the increase of glucose concentrations.

Keywords: Apparent molar volume; Hepler’s constant; Jones-Dole coefficient B; L-glutamic acid; molecular interactions.

1. Introduction

Macromolecules especially, carbohydrates, lipids, proteins, and nucleic acids, are well-known biological compounds, which trigger several physiological functions in the human body [1]. Among these, proteins molecules are the most important building block of cytoplasm and cell membranes. The properties of a protein can be well understood by studying the acid-base property of amino acids in aqueous solution [2]. Due to the presence of several non-covalent interactions, including hydrogen-bonding, electrostatic attraction, and hydrophobic interaction, the native structure of a globular protein becomes stable. The stability of protein molecules depends on these non-covalent interactions, which could be affected by the surrounding solute and solvent molecules [3-5]. In addition, direct solute-solvent interaction and/or alteration of water molecules may affect the physicochemical properties of proteins [6-7].

Carbohydrates also act as a stabilizing agent for the native conformation of globular proteins and enzymes [8-9]. Among the different types of carbohydrates, glucose is the most
abundant monosaccharide that contains both the hydroxyl group (-OH) and the aldehyde group (-CHO). However, glucose plays a pivotal role as an energy source, metabolic intermediary, and important step in cellular respiration [10-13]. Moreover, glucose acts as receptors for the bioactive structures of enzymes, antibodies, hormones, viruses, etc. [14-15].

The protein-carbohydrates interactions are very important in immunology, biosynthesis, pharmacology, medicine, and the cosmetic industry [16-17]. Therefore, extensive studies of amino acids in aqueous carbohydrate solutions are required for a better understanding of solute-solvent interactions [18-19]. Due to the large size of protein macromolecules, the direct study of the physicochemical properties of proteins is difficult. To overcome this problem, the repeating unit of protein molecules such as amino acids, peptides are considered as a model compound for physicochemical studies [20-21]. Based on the nature of the solute-solute and solute-solvent interaction of amino acid in aqueous solutions, the characteristics of a large size protein molecule are easily understood [22-24].

During several decades, researchers are trying to explore new concepts regarding carbohydrate-protein interaction between different solutes and solvents. In a study, Riyazudddeen et al. [25-26] have studied “the interactions in (aqueous sucrose/ aqueous glucose + L-threonine/ L-alanine/) systems at (298.15–323.15) K” and “the densities, viscosities, and speed of sound of L-Proline in aqueous sucrose and glucose solutions”. In a similar study, Nain et al. [27-31] have investigated the “solute-solvent and solute-solute interactions of L-serine, L-phenylalanine, L-arginine, L-histidine, and L-threonine in aqueous sucrose, arabinose, and glucose solutions using viscometric and volumetric measurements”. Other groups of researchers, Ali et al. [32], have examined “the viscosity, density and refractive index of DL-alanine, glycine, DL-valine, and L-serine in aqueous glucose solution”. Being inspired by this research works, Palani and Geetha [33] have determined “the ultrasonic velocity, density, and viscosity of L-asparagine, L-glutamine and L-serine in aqueous glucose solutions”.

To date, there is no volumetric and viscometric data available regarding L-glutamic acid in aqueous carbohydrates solution of different mass fractions at different temperatures. This consideration leads us to undertake this study of L-glutamic acid in aqueous glucose solutions. L-Glutamic acid is an important dicarboxylic amino acid that acts as a neurotransmitter [34]. This paper aims to examine the densities (ρ) and viscosities (η) of L-glutamic acid in water and aqueous glucose (5%, 10%, 15%, and 20% of glucose, w/w in water) at T=(298.15, 303.15, 308.15, 313.15, 318.15 and 323.15)K. Using the experimental data of (ρ) and (η) data, the volumetric properties such as apparent molar volume (φa), limiting apparent molar volume (φa0), limiting apparent molar volume transfer (Δφa0)re, limiting apparent molar expansibilities (Ea0) and Hepler’s constant (δEa0/δT)a have been determined and viscometric properties like Falkenhagen coefficient of A and Jones-Dole coefficient B, Gibbs free energies of activation of viscous flow per mole of solvent (μ10#) and per mole of solute (μ20#), hydration number (Hn) is also determined. These parameters have been recognized as being sensitive to structural change due to the use to discuss the solute-solute and solute-solvent interactions in these systems.

2. Materials and Methods

Highly purified (mass fraction ≥ 99%) L-glutamic acid and glucose were purchased from E. Merck (India) (table 1). Using ethanol and water mixture, L-glutamic acid was
recrystallized, and after drying at 383.15K, it was placed for at least 72 h in a vacuum desiccator over P$_2$O$_5$. Solvent, aqueous glucose (5, 10, 15 and 20% of glucose, w/w in water) solutions were prepared through doubly distilled water (conductivity less than 1× 10$^{-6}$ S/cm) and these solvents were used to make different molal concentrations (0.02mol/kg to 0.16mol/kg) of L-glutamic acid solutions [30]. Moreover, all the mass measurements were carried out by electronic balance with uncertainty ±0.0001g. For density measurement, a double-arm Ostwald-Sprengel type pycnometer of about 25 cm$^3$ capacity was used, which were calibrated with distilled water at different temperatures. After reaching thermal equilibrium (temperatures 298.15 to 323.15K) of the water bath, the densities of the prepared solutions were determined from the mass of the solution in the density bottle.

To measure viscosity, calibrated British standard U-type Ostwald viscometer was used. The test solution containing a viscometer was placed vertically in the water bath. An electronic watch with an accuracy of ±0.1s was used to record the efflux times of flow after the stability of the desired temperature of the water bath. The final efflux time was taken from the average of at least three readings reproducible within ±0.1s, and the viscosity ($\eta$) was calculated by using the following equation,

$$\eta = A \rho t$$

(1)

Where $A = \frac{\pi^4 h g}{8l v}$ is the viscometer, $\rho$ is density, and $t$ is the final efflux time. However, water viscosities were taken from the literature [35] for calibration purposes.

### Table 1. Sample description.

| Chemical name        | Molecular mass | Purification method | Source          | Mass fraction purity |
|----------------------|----------------|---------------------|-----------------|----------------------|
| Glucose              | 147.13 g/mol   | Used as received    | E. Merck (India)| ≥ 98%                |
| L-glutamic acid      | 180.16 g/mol   | Re-crystallization  | E. Merck (India)| ≥ 99%                |

### 3. Results and Discussion

#### 3.1. Volumetric properties.

The experimentally measured density ($\rho$), and viscosity ($\eta$) for a binary and ternary system of L-glutamic acid in water and aqueous-glucose solution as a function of the molal concentration of L-glutamic acid and temperature: (298.15K, 303.15K, 308.15K, 313.15K, 318.15K, and 323.15K) are listed in table 2.

By using experimental densities, the apparent molar volume ($\varphi_v$), the apparent molar volumes at infinite dilution ($\varphi_v^0$), and the limiting apparent molar volume transfer ($\Delta\varphi_v^0$) of L-glutamic acid were calculated in solutions with different percentage of aqueous glucose.

### Table 2. Densities ($\rho$), and viscosities ($\eta$) of solutions of L-glutamic acid in water and (glucose + water) (5%, 10%, 15% and 20% glucose, w/w) solutions as functions of molality, m of L-glutamic acid and temperatures (298.15-323.15) K.

| m/(mol.kg$^{-1}$) | T/K   | L-glutamic acid in Water |
|-------------------|-------|--------------------------|
|                   | 298.15| 303.15 | 308.15 | 313.15 | 318.15 | 323.15 |
| $\rho$/kg.m$^{-3}$|       |         |         |         |         |         |
| 0.0000            | 1004.00| 1002.80| 1001.20| 999.60 | 997.60 | 995.20 |
| 0.0191            | 1004.82| 1003.53| 1001.87| 1000.23| 998.18 | 995.71 |
| 0.0403            | 1005.67| 1004.27| 1002.55| 1000.86| 998.76 | 996.23 |
| 0.0610            | 1006.45| 1004.94| 1003.15| 1001.43| 999.29 | 996.68 |
| 0.0786            | 1007.05| 1005.48| 1003.63| 1001.87| 999.68 | 997.06 |
| 0.1005            | 1007.73| 1006.08| 1004.20| 1002.38| 1000.13| 997.47 |
| 0.1190            | 1008.24| 1006.52| 1004.62| 1002.78| 1000.52| 997.81 |
| m/(mol.kg\(^{-1}\)) | 298.15 | 303.15 | 308.15 | T/K | 313.15 | 318.15 | 323.15 |
|---------------------|--------|--------|--------|-----|--------|--------|--------|
| 0.1398              | 1008.74 | 1007.02 | 1005.02 | 1003.14 | 1000.84 | 998.13 |
| 0.1601              | 1009.26 | 1007.43 | 1005.42 | 1003.42 | 1001.15 | 998.36 |

\(\eta/\text{mPa.s}\) |
|---------------------|--------|--------|--------|-----|--------|--------|--------|
| 0.0000              | 0.8702 | 0.7828 | 0.7134 | 0.6510 | 0.5792 | 0.5143 |
| 0.0191              | 0.8869 | 0.7996 | 0.7276 | 0.6583 | 0.5930 | 0.5248 |
| 0.0403              | 0.9015 | 0.8159 | 0.7392 | 0.6683 | 0.6028 | 0.5401 |
| 0.0610              | 0.9216 | 0.8328 | 0.7579 | 0.6856 | 0.6150 | 0.5541 |
| 0.0786              | 0.9342 | 0.8470 | 0.7682 | 0.6972 | 0.6261 | 0.5643 |
| 0.1005              | 0.9511 | 0.8637 | 0.7830 | 0.7146 | 0.6436 | 0.5745 |
| 0.1190              | 0.9662 | 0.8821 | 0.8037 | 0.7287 | 0.6555 | 0.5880 |
| 0.1398              | 0.9837 | 0.8980 | 0.8232 | 0.7361 | 0.6723 | 0.6073 |
| 0.1601              | 1.0102 | 0.9166 | 0.8347 | 0.7538 | 0.6828 | 0.6281 |

L-glutamic acid in 5% aqu. glucose

\(\rho/(kg.m^3)\) |
|---------------------|--------|--------|--------|-----|--------|--------|--------|
| 0.0000              | 1017.61 | 1016.02 | 1014.82 | 1013.27 | 1011.23 | 1009.34 |
| 0.0199              | 1018.56 | 1016.91 | 1015.66 | 1014.07 | 1011.99 | 1010.05 |
| 0.0392              | 1019.42 | 1017.71 | 1016.41 | 1014.78 | 1012.65 | 1010.65 |
| 0.0609              | 1020.32 | 1018.52 | 1017.16 | 1015.49 | 1013.33 | 1011.26 |
| 0.0800              | 1021.04 | 1019.17 | 1017.78 | 1016.04 | 1013.83 | 1011.72 |
| 0.1002              | 1021.76 | 1019.83 | 1018.34 | 1016.58 | 1014.31 | 1012.16 |
| 0.1194              | 1022.43 | 1020.37 | 1018.87 | 1017.01 | 1014.73 | 1012.56 |
| 0.1393              | 1023.04 | 1020.94 | 1019.35 | 1017.43 | 1015.13 | 1012.91 |
| 0.1594              | 1023.62 | 1021.46 | 1019.84 | 1017.84 | 1015.43 | 1013.23 |

L-glutamic acid in 10% aqu. glucose

\(\rho/(kg.m^3)\) |
|---------------------|--------|--------|--------|-----|--------|--------|--------|
| 0.0000              | 1040.23 | 1038.54 | 1037.02 | 1035.40 | 1033.02 | 1031.20 |
| 0.0201              | 1041.31 | 1039.51 | 1038.88 | 1036.18 | 1033.72 | 1031.83 |
| 0.0407              | 1042.33 | 1040.42 | 1038.67 | 1036.89 | 1034.36 | 1032.41 |
| 0.0599              | 1043.22 | 1041.21 | 1039.36 | 1037.51 | 1034.91 | 1032.92 |
| 0.0797              | 1044.08 | 1041.93 | 1040.03 | 1038.12 | 1035.43 | 1033.43 |
| 0.0998              | 1044.86 | 1042.62 | 1040.67 | 1038.65 | 1035.93 | 1033.89 |
| 0.1200              | 1045.54 | 1043.28 | 1041.25 | 1039.18 | 1036.43 | 1034.35 |
| 0.1406              | 1046.25 | 1043.93 | 1041.82 | 1039.74 | 1036.95 | 1034.76 |
| 0.1601              | 1046.91 | 1044.48 | 1042.24 | 1040.16 | 1037.42 | 1035.14 |

L-glutamic acid in 15% aqu. glucose

\(\rho/(kg.m^3)\) |
|---------------------|--------|--------|--------|-----|--------|--------|--------|
| 0.0000              | 1.0776 | 0.9964 | 0.9130 | 0.8179 | 0.7347 | 0.6696 |
| 0.0201              | 1.0958 | 1.0094 | 0.9307 | 0.8361 | 0.7514 | 0.6822 |
| 0.0407              | 1.1124 | 1.0236 | 0.9451 | 0.8623 | 0.7758 | 0.6987 |
| 0.0599              | 1.1305 | 1.0385 | 0.9651 | 0.8837 | 0.7977 | 0.7181 |
| 0.0797              | 1.1460 | 1.0532 | 0.9786 | 0.9072 | 0.8157 | 0.7371 |
| 0.0998              | 1.1650 | 1.0684 | 0.9965 | 0.9270 | 0.8420 | 0.7522 |
| 0.1200              | 1.1839 | 1.0855 | 1.0170 | 0.9466 | 0.8651 | 0.7754 |
| 0.1406              | 1.2043 | 1.1018 | 1.0364 | 0.9719 | 0.8905 | 0.7963 |
| 0.1601              | 1.2286 | 1.1176 | 1.0526 | 0.9931 | 0.9154 | 0.8195 |

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https://nanobioletters.com/
### Table 1: Molar Volumes of L-glutamic acid in 20% aq. glucose

| m/(mol.kg⁻¹) | 298.15 | 303.15 | 308.15 | 313.15 | 318.15 | 323.15 |
|--------------|--------|--------|--------|--------|--------|--------|
| η/(mPa.s)    |        |        |        |        |        |        |
| 0.0000       | 1.3403 | 1.2120 | 1.0717 | 0.9447 | 0.8451 | 0.7642 |
| 0.0199       | 1.3575 | 1.2290 | 1.0879 | 0.9659 | 0.8623 | 0.7759 |
| 0.0391       | 1.3797 | 1.2457 | 1.1091 | 0.9844 | 0.8794 | 0.7902 |
| 0.0604       | 1.4017 | 1.2581 | 1.1285 | 1.0109 | 0.9013 | 0.8104 |
| 0.0999       | 1.4409 | 1.3053 | 1.1729 | 1.0537 | 0.9361 | 0.8353 |
| 0.1201       | 1.4704 | 1.3294 | 1.1949 | 1.0850 | 0.9548 | 0.8474 |
| 0.1409       | 1.4899 | 1.3570 | 1.2159 | 1.1146 | 0.9724 | 0.8649 |
| 0.1599       | 1.5132 | 1.3825 | 1.2357 | 1.1409 | 0.9934 | 0.8827 |

3.1.1. Apparent molar volume.

The apparent molar volume ($\varphi_v$), of L-glutamic acid, was calculated by using the relation,

$$
\varphi_v = \left( \frac{\rho_s - \rho}{m \rho_0} \right) + \frac{M}{\rho}
$$

Where, $m$ = molality (mol.kg⁻¹) of the solution, $M$ = molar mass of the solute (kg.mol⁻¹), $\rho_0$ and $\rho$ = densities of solvent and solution, respectively. The variations of $\varphi_v$ as a function of L-glutamic acid at various concentrations and temperatures are represented in figure 1.
Figure 1. Variations of apparent molar volume, $\Phi_V$ vs. molality, $m$ of l-glutamic acid in water and in aqueous glucose (w/w) solutions, (a) water (b) 5% glucose, (c) 10% glucose, (d) 15% glucose, (e) 20% glucose, at temperatures, $T/K = 293.15$, ♦; $T/K = 298.15$, ■; $T/K = 303.15$, ▲; $T/K = 308.15$, ◊; $T/K = 313.15$, □; $T/K = 318.15$, Δ.
From this figure, it is seen that the curves of $\varphi_v$ vs. m are linear for L-glutamic acid in water and in all the four aqueous-glucose solvents in the studies concentration range and at each investigated temperature. Moreover, the $\varphi_v$ for L-glutamic acid increase with arising the concentration of L-glutamic acid and increasing temperature, but these values are reduced by increasing the percentage of glucose. A similar phenomenon is noticed in the case of L-proline in aqueous metformin hydrochloride solutions [36]. These types of results indicate the presence of strong interaction between L-glutamic acid and glucose molecules.

3.1.2. Limiting apparent molar volume.

The limiting apparent molar volumes or apparent molar volumes at infinite dilution ($\varphi_v^0$) were calculated using the Masson equation [37].

$$\varphi_v = \varphi_v^0 + S_m m$$  \hspace{1cm} (3)

Where $S_m$ = the experimental slope or volumetric pairwise interaction coefficient [38], which gives an idea about the solute-solute interaction, the $\varphi_v^0$ provides information regarding solute-solvent interaction, and $m$ is the molality of L-glutamic acid in aqueous glucose solution. The values of $\varphi_v^0$ and $S_m$ are listed in Table 3. According to this table, it can be seen that the values of $S_m$ for L-glutamic acid in different percentages of glucose from a range of temperatures (298.15 to 323.15) K are positive, indicating the existence of solute-solute interactions. The values of $\varphi_v^0$ are positive for all the systems, which is an indication of the presence of solute-solvent interactions. The values of $\varphi_v^0$ increase with rising temperature due to the reduction of electrostriction of water. The smaller values of $S_m$ as compared to $\varphi_v^0$ suggest the dominance of solute-solvent interaction over the solute-solute interaction. The findings of the present study are supported by the researches of other researchers [39-41].

**Table 3.** Limiting apparent molar volumes at infinite dilution ($\varphi_v^0$), experimental slope ($S_m$), limiting apparent molar volume transfer ($\Delta \varphi_v^0$), and limiting apparent molar expansibilities ($E_v^0$) of L-glutamic acid in water and (glucose + water) (5%, 10%, 15% and 20% glucose, w/w) solutions at temperatures (298.15-323.15) K.

| T/K     | $10^6\varphi_v^0$ (m$^3$/mol$^1$) | $10^6S_m$ (m$^3$/mol$^2$kg) | $10^6(\Delta \varphi_v^0)_{\text{tr}}$ (m$^3$/mol$^1$) | $10^6E_v^0$ (m$^3$/mol$^1$.K$^1$) | $10^6(\Delta E_v^0/\Delta T)^{\text{tr}}$ (m$^3$/mol$^1$.K$^{-2}$) |
|---------|---------------------------------|-----------------------------|-----------------------------------------------|---------------------------------|-----------------------------------|
| 298.15  | 102.41(±0.1466)                 | 69.30(±1.6437)              | -                                             | 49.55                           | 0.54                              |
| 303.15  | 107.69(±0.1324)                 | 61.52(±1.4849)              | -                                             | 54.95                           |                                   |
| 308.15  | 111.05(±0.1633)                 | 57.90(±1.8306)              | -                                             | 57.65                           |                                   |
| 313.15  | 113.20(±0.1496)                 | 59.51(±1.6775)              | -                                             | 60.35                           |                                   |
| 318.15  | 116.11(±0.1707)                 | 54.86(±1.9135)              | -                                             | 63.05                           |                                   |
| 323.15  | 120.10(±0.1453)                 | 45.54(±1.6291)              | -                                             | 65.75                           |                                   |
| 298.15  | 97.32(±0.1652)                  | 65.44(±1.8513)              | -5.09                                          | 27.20                           | 0.94                              |
| 303.15  | 100.30(±0.2130)                 | 70.74(±2.3869)              | -7.39                                          | 36.56                           |                                   |
| 308.15  | 102.78(±0.1937)                 | 72.46(±2.1704)              | -8.27                                          | 41.24                           |                                   |
| 313.15  | 104.59(±0.1243)                 | 78.95(±1.3928)              | -8.60                                          | 45.92                           |                                   |
| 318.15  | 106.77(±0.2102)                 | 79.65(±2.3559)              | -9.34                                          | 50.60                           |                                   |
| 323.15  | 109.81(±0.3190)                 | 75.39(±3.5749)              | -10.29                                         | 55.28                           |                                   |
| 298.15  | 90.38(±0.1394)                  | 76.80(±1.5565)              | -12.03                                         | 68.48                           | 0.63                              |
| 303.15  | 95.87(±0.2790)                  | 70.37(±3.1152)              | -11.83                                         | 74.74                           |                                   |
| 308.15  | 101.35(±0.2923)                 | 60.75(±3.2645)              | -9.71                                          | 77.07                           |                                   |
| 313.15  | 105.41(±0.3662)                 | 55.10(±4.0899)              | -7.79                                          | 81.00                           |                                   |
| 318.15  | 109.64(±0.4289)                 | 45.37(±4.7892)              | -6.48                                          | 84.13                           |                                   |
| 323.15  | 112.77(±0.2173)                 | 40.68(±2.4268)              | -7.33                                          | 87.26                           |                                   |
| 298.15  | 84.79(±0.0609)                  | 66.12(±0.6792)              | -17.62                                         | 34.00                           |                                   |
| 303.15  | 88.47(±0.1148)                  | 75.15(±1.2815)              | -19.22                                         | 56.80                           |                                   |
The Limiting apparent molar volume transfer \((\Delta \phi^0)_{\text{tra}}\) for L-glutamic acid from water to the aqueous glucose mixture can be calculated from the following equation, \([42]\):
\[
(\Delta \phi^0)_{\text{tra}} = \phi^0_{\text{L-glutamic acid in aq. glucose solution}} - \phi^0_{\text{L-glutamic acid in water}} \tag{4}
\]

The \((\Delta \phi^0)_{\text{tra}}\) is free from solute-solute interactions but only depends on the solute-solvent interactions \([43]\). In this study, the interaction occurring between L-glutamic acid and aqueous glucose solution could be categorized as follows \([30, 44, 45]\):

I. -OH groups of glucose interact with zwitterions (\(\text{NH}_3^+, \text{COO}^-\)) of amino acids through ionic-hydrophilic interaction.
II. Hydrophilic-hydrophilic interactions present in OH groups of glucose and side-chain OH groups of L-glutamic acid through H-bonding.
III. Non-polar groups of glucose (alkyl chain) and zwitterionic groups (\(\text{NH}_3^+, \text{COO}^-\)) of L-glutamic acid interrelate with hydrophobic-ionic interaction.
IV. Hydrophobic-hydrophobic interactions link-up between non-polar (-CH\(_3\)) in the side chain of L-glutamic acid and alkyl chain of glucose.
V. Hydrophobic-hydrophilic interactions linkage between non-polar groups of L-glutamic acid and the -OH groups of glucose.

Type (I) and (II) interaction are responsible for a positive contribution to the \((\Delta \phi^0)_{\text{tra}}\), since the overlap of the hydration co-sphere of charged ions (\(\text{NH}_3^+, \text{COO}^-\)), hydrophilic groups (-NH\(_2\), -OH) and -OH groups could lead to the reduction of electrostriction of water molecules lying in the proximity of these amino acids and type (III), (IV), and (V) contribute negatively to the \((\Delta \phi^0)_{\text{tra}}\) due to disruption of side group hydration by that of the charged end \([45]\).

From table 3, it is observed that all values of the limiting apparent molar volume transfer \((\Delta \phi^0)_{\text{tra}}\) are negative. So it indicates that the interactions of type (3), (4), and (5) are dominated in the studied systems.

### 3.1.4. Limiting apparent molar volume expansibilities \(E^0\) and Hepler Constant \((\delta E^0/\delta T)_p\)

The variation of \(\phi^0\) with the temperature at infinite dilution can be represented by the following polynomial equation \([46]\):
\[
\phi^0_{\text{v}} = a + b \ (T - T_m) + c \ (T - T_m)^2 \tag{5}
\]
Where \(T = \) temperature (Kelvin), \(T_m = \) the average temperature (Kelvin), and \(a, b,\) and \(c\) are the empirical constants. The limiting apparent molar expansibilities or first derivatives of the temperature dependence of limiting apparent molar volumes are obtained as follows:
\[
\frac{\delta (\phi^0_{\text{v}})}{\delta (T - T_m)} = E^0 = b + 2c \ (T - T_m) \tag{6}
\]
The calculated values of $E_\phi^0$ are listed in table 3. The values of $E_\phi^0$ of any solute expose the solute-solvent interaction [47]. From this table, the values of $E_\phi^0$ are positive for L-glutamic acid in water and all four systems of aqueous solutions of glucose, suggesting the presence of solute-solvent interactions in these systems, as already indicated by apparent molar volume data. Yan et al. [48] have found a similar trend of $E_\phi^0$ in some amino acids and a pharmaceutically active ionic liquid domiphen DL-mandelic acid in aqueous medium at temperatures from 293.15 K to 313.15 K.

Hepler [49] developed the general thermo-dynamic expression to determine the capacity of solute as a structure maker or structure breaker in a mixed solvent system using the general thermodynamic expression:

$$\frac{\delta^2 (\phi_0^2)}{\delta^2 (T-T_m)} = (\delta E_\phi^0/\delta T)_p = 2c$$  \hspace{1cm} (7)

Solute acts as structure-maker when the values of $(\delta E_\phi^0/\delta T)_p$ are positive, whereas a solute acts as structure-breaker when the values of $(\delta E_\phi^0/\delta T)_p$ are negative [50]. In this work, the values of $(\delta E_\phi^0/\delta T)_p$ are positive, which are indexed in table 3, and that indicates the structure-maker property of L-glutamic acid in water and aqueous glucose solutions.

3.2. Viscometric properties.

3.2.1. Viscosity coefficient- B and A.

Viscosities of L-glutamic acid in aqueous and in aqueous glucose solutions are measured at 293.15, 298.15, 303.15, 308.15, and 313.15 K respectively and indexed in table 2. It is observed that the viscosities increase with increasing the concentration of L-glutamic acid and decrease with increasing the temperature. When a solute is subjected to dissolved in a solvent, some of the solvents molecules interact with the solutes, as the result of solute-solvent interaction that slows down the mobility of the liquid for this the value of viscosities are increased with increasing the concentration of L-glutamic acid [51]. As the temperature increasing, the kinetic energy of the molecule is increased, which increases the mobility of the liquid; therefore, the values of viscosities are decreased with increasing temperature. Increasing the viscosities by adding the solute indicates the structure making ability of the solute [52]. The detailed information about solute-solute and solute-solvent interaction of the system is provided by the resulting Falkenhagen and Jones–Dole viscosity B-coefficients [53-54]. There is a linear relationship between the viscosity and the molality of the L-glutamic acid in aqueous glucose system. So, the coefficient A (Falkenhagen coefficient) and Jones–Dole viscosity B-coefficient are calculated from the Jones-Dole equation that is given below:

$$\frac{\eta_r - 1}{\sqrt{m}} = A + B\sqrt{m}$$  \hspace{1cm} (8)

Where, $\eta_r$ = the relative viscosity of the solution and m molality of L-glutamic acid, A and B = the Falkenhagen and Jones–Dole coefficients, respectively. From the intercept and slope of the plots of $(\eta_r - 1)/m^{1/2}$ versus $m^{1/2}$, the values of A and B coefficient is measured and displayed in table 4. The positive value of B-coefficient is associated with strong solute-solvent interaction and also with structure making ability of solute, while a negative value of B-coefficient is associated with structure-breaking properties between solute and solvent [55-56]. The coefficient-A represents the solute-solute interaction associated with the size and shape of the solute. The negative values of the A coefficient indicate the presence of very weak solute–solute interactions; the positive values of the A coefficient indicate the presence of significant solute–solute interactions [57].
Table 4. The viscosity coefficient values B, A, and hydration number, (Hₙ) for L-glutamic acid in water and (glucose + water) (5%, 10%, 15%, and 20% glucose, w/w) solutions at temperatures (298.15-323.15) K.

| T/K   | B/(kg.mol⁻¹) | A/(kg¹/₂·mol⁻¹/₂) | Hₙ  |
|-------|--------------|-------------------|-----|
|       | L-glutamic acid in water |                     |     |
| 298.15| 0.9671(±0.032) | -0.0054(±0.009)   | 0.94|
| 303.15| 1.0415(±0.027) | 0.0042(±0.008)    | 0.97|
| 308.15| 1.1391(±0.088) | -0.0326(±0.025)   | 1.03|
| 313.15| 1.2343(±0.074) | -0.0952(±0.021)   | 1.09|
| 318.15| 1.1376(±0.095) | -0.0119(±0.027)   | 0.98|
| 323.15| 1.4169(±0.081) | -0.0479(±0.023)   | 1.18|
|       | L-glutamic acid in 5% aq. glucose |                     |     |
| 298.15| 1.2164(±0.053) | -0.0607(±0.015)   | 1.25|
| 303.15| 1.2655(±0.086) | -0.0333(±0.024)   | 1.28|
| 308.15| 1.0717(±0.080) | -0.0464(±0.023)   | 1.04|
| 313.15| 1.3418(±0.054) | -0.0455(±0.015)   | 1.28|
| 318.15| 1.3351(±0.051) | -0.0168(±0.014)   | 1.25|
| 323.15| 1.1899(±0.077) | -0.0407(±0.022)   | 1.08|
|       | L-glutamic acid in 10% aq. glucose |                     |     |
| 298.15| 0.8773(±0.023) | -0.0144(±0.007)   | 0.97|
| 303.15| 0.8280(±0.013) | -0.0296(±0.004)   | 0.86|
| 308.15| 0.9800(±0.046) | -0.0129(±0.013)   | 0.97|
| 313.15| 1.4175(±0.062) | -0.0271(±0.017)   | 1.34|
| 318.15| 1.7199(±0.046) | -0.0796(±0.013)   | 1.57|
| 323.15| 1.6353(±0.043) | -0.1079(±0.012)   | 1.45|
|       | L-glutamic acid in 15% aq. glucose |                     |     |
| 298.15| 0.8878(±0.036) | -0.0319(±0.010)   | 1.04|
| 303.15| 0.9861(±0.078) | -0.0578(±0.022)   | 1.11|
| 308.15| 1.0658(±0.050) | -0.0434(±0.014)   | 1.15|
| 313.15| 1.4043(±0.065) | -0.0563(±0.018)   | 1.46|
| 318.15| 1.1184(±0.023) | -0.0123(±0.007)   | 1.12|
| 323.15| 1.0217(±0.061) | -0.0268(±0.017)   | 0.97|
|       | L-glutamic acid in 20% aq. glucose |                     |     |
| 298.15| 0.9463(±0.097) | -0.0717(±0.027)   | 1.15|
| 303.15| 0.9991(±0.069) | -0.0591(±0.020)   | 1.17|
| 308.15| 1.3533(±0.089) | -0.1307(±0.025)   | 1.53|
| 313.15| 1.2355(±0.038) | -0.0405(±0.011)   | 1.36|
| 318.15| 1.1600(±0.124) | -0.062(±0.035)    | 1.24|
| 323.15| 1.1873(±0.146) | -0.0112(±0.041)   | 1.24|

In this study, the values of B-coefficients are positive for all systems; so, strong solute-solvent interaction exists in L-glutamic acid in water as well as in aqueous glucose solutions of different mass fractions. Contrarily, the values of the A-coefficient are negative for all systems at different temperatures, which indicates the presence of weak solute-solute interaction. Khanuja et al. reported a similar structure-making tendency for amino acids in aqueous glucose solution [58].

3.2.2. Hydration number.

The hydration number, (Hₙ) values of L-glutamic acid in aqueous-glucose solutions are also determined by using the equation [30, 59–61],

\[ H_n = \frac{B}{\phi V_0} \]  

(9)

The values of Hₙ are indexed in table 4. The table discloses that the values of Hₙ raise with raising glucose concentration for most of the studied systems, which indicates the enhancement of hydration of L-glutamic acid in the studied solution. Actually, the water molecules are substituted by glucose and act as a structure-maker by H-bonding. Hₙ values also increase with increasing temperature indicates the presence of solute-solvent interaction in these studied systems. Jones-Dole coefficient- B and ϕV₀ values also support the trend of hydration number, Hₙ values.
3.3. Thermodynamics of viscous flow.

Gibbs free energy of activation for a per mol of solute ($\Delta\mu_1^0$) and solvent ($\Delta\mu_2^0$) was calculated based on the transition state theory of the relative viscosity proposed by Feakins et al. [62-67]. According to this theory, the B-coefficient could be express by the relation,

$$B = \frac{(V_1^0 - V_2^0)}{1000} + \frac{V_1^0(\Delta\mu_2^0 - \Delta\mu_2^0)}{1000RT}$$  \hspace{1cm} (10)

$$\Delta\mu_1^0 = RT\ln\left(\frac{\nu_1}{\nu_2}\right)$$  \hspace{1cm} (11)

$$\Delta\mu_2^0 = \Delta\mu_1^0 + \left(\frac{RT}{V_1^0}\right)[1000B - (V_1^0 - V_2^0)]$$  \hspace{1cm} (12)

Where, $V_1^0$ = the apparent molar volume of the solute (aqueous-sucrose) and $V_2^0$ = the limiting apparent molar volume of the solvent, respectively. $h$ and $N$ are Planck’s constant and Avogadro number, respectively.

Table 5. Free energies of activation of viscous flow per mol of solvent, ($\Delta\mu_1^0$) and per mol of solute, ($\Delta\mu_2^0$) for L-glutamic acid in in water and (glucose + water) (5%, 10%, 15% and 20% glucose, w/w) solutions at temperatures (298.15-323.15) K.

| Parameters | $\Delta\mu_1^0$/kJ.mol$^{-1}$ | $\Delta\mu_2^0$/kJ.mol$^{-1}$ |
|------------|-----------------|-----------------|
| L-glutamic acid in water | 9.09 | 154.48 |
| | 8.98 | 167.82 |
| | 8.89 | 184.48 |
| | 8.80 | 201.02 |
| | 8.64 | 189.78 |
| | 8.46 | 234.08 |
| L-glutamic acid in 5% aq. glucose | 9.39 | 182.60 |
| | 9.50 | 192.21 |
| | 9.21 | 168.54 |
| | 9.12 | 208.82 |
| | 8.98 | 210.83 |
| | 8.89 | 193.06 |
| L-glutamic acid in 10% aq. glucose | 9.77 | 133.13 |
| | 9.74 | 129.17 |
| | 9.68 | 152.00 |
| | 9.55 | 213.99 |
| | 9.43 | 258.90 |
| | 9.33 | 250.89 |
| L-glutamic acid in 15% aq. glucose | 10.41 | 128.69 |
| | 10.34 | 144.48 |
| | 10.20 | 157.13 |
| | 10.04 | 203.88 |
| | 9.91 | 168.97 |
| | 9.80 | 158.53 |
| L-glutamic acid in 20% aq. glucose | 10.93 | 133.11 |
| | 10.84 | 141.67 |
| | 10.69 | 187.78 |
| | 10.50 | 175.48 |
| | 10.41 | 168.20 |
| | 10.25 | 174.00 |

The ($\Delta\mu_1^0$) and ($\Delta\mu_2^0$) values are listed in table 5. It is observed that the value of ($\Delta\mu_1^0$) and ($\Delta\mu_2^0$) for L-glutamic acid are positive and the ($\Delta\mu_2^0$) values are much higher than ($\Delta\mu_1^0$) in aqueous glucose solutions. This indicates the presence of strong interaction between L-glutamic acid and solvent (5, 10, 15, 20% w/w, aqueous glucose), and the interaction is greater in the ground state than in the transition state. So, it is evident that the solvation of the L-glutamic acid molecule is not as much preferred in free energy terms in the transition state [68]. The ($\Delta\mu_2^0$) values increase with an increase in temperature for most of the systems as well as increase the solute-solvent interaction that makes it hard to flow the solute molecules.

4. Conclusions

This work represents the temperature based volumetric and viscometric properties of L-glutamic acid solution in water and in aqueous glucose solutions (5, 10, 15, and 20% of glucose, w/w in water). Various volumetric and viscometric parameters like $\phi_v$, $\phi_v^0$, ($\Delta\phi_v^0$)$_{tra}$, $E_o^0$, ($\Delta E_o^0$)/$\Delta T$)$_{tra}$, coefficients-A, B, H$_o$, ($\Delta\mu_1^0$) and ($\Delta\mu_2^0$) were calculated from experimental data. The results narrate the presence of strong solute-solvent interactions in these studied
systems. Hence, it is concluded from Hepler constant ($\delta E_q^0/\delta T)_p$ and Jones-Dole coefficient-B values that L-glutamic acid act as a structure-maker in aqueous glucose solutions as well as in water.

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**Conflicts of Interest**

The authors declare no conflict of interest.

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