

Dielectric and Acoustical Investigations of Molecular Interactions in Binary Liquid Mixtures: A Comprehensive Review

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Abstract

Binary liquid mixtures provide a convenient platform for examining molecular association, structural rearrangement, hydrogen bonding, dipolar correlation and non-ideal mixing. Dielectric spectroscopy probes the response of molecular dipoles to an alternating electric field, whereas ultrasonic or acoustical measurements respond to changes in density, compressibility and molecular packing. When these two approaches are interpreted together, information obtained from static dielectric permittivity, dielectric relaxation time, Kirkwood correlation factors, ultrasonic velocity, adiabatic compressibility, intermolecular free length and excess acoustical properties can be related to the same underlying molecular processes. This review summarizes the physical basis of dielectric and acoustical measurements in binary liquid mixtures, the principal equations used to derive interaction-sensitive parameters, and the interpretation of positive and negative excess quantities. Particular attention is given to polar–polar, polar–non-polar, alcohol-containing and hydrogen-bonded systems. Literature demonstrates that deviations from ideal mixing are often more informative than the absolute values of individual properties. Dielectric excess quantities reveal changes in effective dipolar organization, while excess acoustical parameters reveal changes in molecular packing and cohesive forces. Recent studies combining broadband dielectric measurements, advanced relaxation models, thermodynamic analysis and complementary structural calculations show the increasing value of multimodal characterization. The review identifies the need for consistent definitions of ideal reference states, careful treatment of temperature and composition, and direct correlation of dielectric and acoustic observables with molecular-level models.

Keywords: binary liquid mixtures; dielectric relaxation; ultrasonic velocity; acoustical parameters; molecular interactions; hydrogen bonding; Kirkwood correlation factor; excess properties.

1. Introduction

A liquid mixture is rarely a simple physical combination of two pure liquids. On mixing, like–like and unlike molecular interactions compete, and the resulting microscopic organization can differ substantially from that of either component. Binary mixtures are therefore widely used as model systems for investigating solvation, association, hydrogen bonding, dipole–dipole interactions, dispersion forces, charge-transfer effects and changes in molecular packing. Reviews of dielectric and ultrasonic studies have emphasized that both composition and temperature strongly influence these properties and that non-ideal behavior can be used to infer molecular interactions [1–3].

Dielectric spectroscopy and acoustical measurements examine different physical manifestations of the same molecular environment. Dielectric response is associated primarily with polarization and the temporal reorientation of molecular dipoles. Acoustic response is connected with the propagation of pressure disturbances and therefore depends on density, compressibility and the cohesive structure of the liquid. A combined approach can consequently distinguish changes in dipolar orientation from changes in mechanical packing. This is especially useful for mixtures containing alcohols, amides, sulfoxides, nitriles, aromatic compounds and water, where hydrogen bonding and polarity may change simultaneously.

The molecular interactions developed in a binary mixture depend strongly on the chemical nature, size, shape and polarity of the constituent molecules. When two liquids are mixed, the original interaction network of each pure component is disturbed and new unlike interactions is established. The balance between these interactions determines whether the mixture exhibits

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positive or negative deviations from ideality. For example, in mixtures containing alcohols and polar aprotic solvents, hydrogen-bonded structures may be progressively disrupted or reorganized as the composition changes. Similarly, the addition of water to an organic liquid can produce extensive changes in local molecular organization because of water's strong self-association and its ability to participate in hydrogen bonding with the second component. Such molecular rearrangements may appear experimentally as anomalous variations in dielectric constant, relaxation time, ultrasonic velocity, compressibility or related excess properties.

The objective of this review is to present a unified framework for interpreting dielectric and acoustical measurements of binary liquid mixtures, emphasizing parameters that are experimentally accessible and scientifically meaningful. The discussion also highlights limitations of simple sign-based interpretations and proposes a more rigorous strategy for connecting measured excess properties with molecular models.

2. Dielectric Response of Binary Liquid Mixtures

For a liquid exposed to an alternating electric field, the complex relative permittivity is conventionally written as

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega),$$

where ε' describes the energy stored through polarization and ε'' represents dielectric loss. The frequency dependence reflects the inability of molecular dipoles and other polarization mechanisms to follow the applied field instantaneously. In polar liquids at microwave frequencies, rotational relaxation of permanent dipoles is commonly a major contribution.

2.1 Debye and generalized relaxation models

For a single ideal Debye relaxation process, the complex permittivity is expressed as:

$$\varepsilon^*(\omega) = \varepsilon_\infty + (\varepsilon_0 - \varepsilon_\infty)/(1 + j\omega\tau)$$

Here ε_0 is the low-frequency or static limiting permittivity, ε_∞ is the high-frequency limiting permittivity, ω is angular frequency and τ is the characteristic relaxation time. Real liquid mixtures frequently exhibit broader or asymmetric relaxation spectra because molecules experience different local environments and because several relaxation processes may overlap. Cole–Davidson, Cole–Cole and Havriliak–Negami representations are therefore often employed. In recent binary-mixture studies, broadband time-domain or vector-network-analyzer measurements have been fitted with these models to obtain ε_0 , ε_∞ and τ [4–7].

2.2 Excess dielectric properties

The departure of a mixture from a chosen ideal reference can be quantified through an excess property. A simple concentration-weighted expression is:

$$(\varepsilon_0^E) = (\varepsilon_0)_m - [(\varepsilon_0)_A X_A + (\varepsilon_0)_B (1 - X_A)]$$

where x_A and x_B are mole or volume fractions, depending on the adopted definition. More rigorous treatments may use a thermodynamic ideal-mixture reference rather than a simple linear mixing rule. This distinction is important because excess quantities depend on the definition of the reference state [8]. In general, $\varepsilon_0^E = 0$ corresponds to agreement with the selected ideal model, while positive or negative deviations indicate enhanced or reduced polarization relative to that reference. The sign should not, however, be interpreted as a unique molecular mechanism without considering composition, density, refractive index and other evidence.

2.3 Relaxation time and molecular dynamics

The relaxation time provides information about the rate of dipolar reorientation. A decrease in τ generally corresponds to faster rotational relaxation, whereas an increase indicates greater dynamical restriction. Temperature commonly accelerates molecular motion and reduces τ , although strong association can modify the magnitude and composition dependence. The inverse relaxation time, $1/\tau$, is therefore frequently analyzed through an excess quantity because it emphasizes deviations in dynamics rather than static polarization alone. Broadband studies of alcohol-containing binary mixtures have shown that composition-dependent changes in τ can be associated with hydrogen-bond restructuring and cooperative dipolar motion [4–7].

In binary liquid systems, the observed relaxation behavior is governed not only by the intrinsic rotational mobility of the individual molecules but also by the extent of intermolecular association and changes in the local molecular environment. Consequently, variations in τ with

composition can provide useful information about the formation or disruption of hydrogen-bonded structures, dipole–dipole interactions, and changes in the degree of molecular co-operativity.

2.4 Kirkwood correlation factor (g_K)

The Kirkwood correlation factor is used to describe orientational correlation between molecular dipoles. In its conceptual form, it is related to the average angular correlation of neighboring dipoles. Values above unity are commonly associated with predominantly parallel or cooperative correlation, whereas values below unity can indicate antiparallel or destructive correlation. For mixtures, however, the definition of the ideal reference and the treatment of component-specific dipoles matter substantially. Extended Onsager–Kirkwood–Fröhlich formalisms show that mixture correlation factors can be separated into ideal and excess contributions [9]. Thus, g_K should be interpreted together with dielectric and structural information rather than as an isolated indicator of hydrogen bonding.

The physical significance of (g_K) arises from the fact that the dielectric response of a polar liquid is influenced not only by the magnitude of individual molecular dipole moments but also by their mutual orientation. In an idealized system of completely independent dipoles, the orientational correlations are weak and the corresponding Kirkwood factor approaches unity. Deviations from unity therefore provide evidence that neighboring molecules do not behave as completely independent rotating dipoles. A value greater than unity suggests that the local molecular arrangement favors parallel or cooperative dipolar orientation, while a value lower than unity may indicate preferential antiparallel arrangements or other configurations that reduce the net dipolar correlation. The magnitude of this deviation is dependent on the local structure, molecular geometry, concentration, temperature, and the nature of intermolecular interactions.

3. Acoustical Investigation of Binary Mixtures

Ultrasonic waves are mechanical pressure waves whose velocity in a liquid depends on the medium's density and elastic response. Because intermolecular forces determine how readily molecules can be displaced under pressure, ultrasonic measurements are sensitive to molecular association and packing. Recent reviews identify ultrasonic velocity, density and viscosity as the principal experimental quantities from which a broad range of acoustical and thermodynamic parameters can be obtained [1–3].

3.1 Fundamental acoustical parameters

For a liquid of density ρ and ultrasonic velocity u , the adiabatic compressibility is given by the Newton–Laplace relation:

$$\beta_{ad} = 1/(\rho u^2)$$

The acoustic impedance is:

$$Z = \rho u$$

The intermolecular free length can be represented through the Jacobson relation in the form:

$$L_f = KJ \sqrt{\beta_{ad}}$$

where KJ is a temperature-dependent Jacobson constant. These parameters have a direct physical interpretation. A lower β_{ad} indicates that the liquid is less compressible, while a lower L_f is generally associated with closer molecular packing. Acoustic impedance combines density and velocity and is sensitive to changes in the cohesive state of the liquid.

3.2 Excess acoustical parameters

Measured properties of mixtures are often compared with an ideal or composition-based reference. For example, an excess property may be written generally as:

$$Y_E = Y_{exp} - Y_{ideal}$$

Depending on the system and property, positive and negative excess values can indicate contraction or expansion, enhanced or reduced compressibility, or changes in molecular association. Excess ultrasonic velocity, excess adiabatic compressibility, excess free length, excess acoustic impedance and excess molar volume have been widely used to examine binary mixtures. Experimental studies have demonstrated that the simultaneous behavior of several excess parameters is more reliable than interpreting one curve in isolation [10–13].

3.3 Molecular interpretation

When two unlike molecules interact more strongly than the corresponding like interactions, the mixture may exhibit contraction, reduced free volume and increased resistance to compression. Hydrogen-bond formation, dipole–dipole attraction, donor–acceptor association and charge-transfer interactions can all contribute. Conversely, disruption of self-association or poor packing may produce positive excess volume and related acoustic signatures. The exact sign pattern depends on molecular size, shape, polarity, hydrogen-bond functionality and composition.

3.4 Temperature and composition

Acoustical properties are highly temperature dependent. Increasing temperature generally increases molecular mobility and may weaken or rearrange association networks. Consequently, the magnitude of an excess property can decrease, increase or change sign with temperature. Composition is equally important because a binary mixture may pass through regions where one component is dilute, an intermediate composition produces maximum unlike interaction, and the other component becomes dominant. This is why complete composition ranges are preferable to measurements at only one or two concentrations.

3.5 Experimental considerations

Reliable acoustical interpretation requires accurate temperature control, density measurement and ultrasonic velocity determination. Interferometric techniques at MHz frequencies are frequently used. Sample purity, degassing, thermal equilibration and avoidance of evaporation are important because even small compositional changes can affect velocity and density. Independent measurements should be repeated to assess experimental uncertainty.

4. Linking Dielectric and Acoustical Observables

Dielectric and acoustical methods are complementary because they respond to different aspects of molecular organization. Dielectric relaxation emphasizes the rotational dynamics and orientational correlation of dipolar species, whereas acoustical measurements emphasize density, compressibility and collective mechanical response. A combined analysis can therefore provide a more complete picture of binary-mixture structure.

4.1 Hydrogen-bonded systems

Alcohol–alcohol, alcohol–amide, alcohol–sulfoxide and alcohol–water mixtures are particularly informative because hydrogen bonding modifies both dipolar correlations and mechanical packing. Formation of unlike hydrogen bonds can alter ϵ_0 and τ while simultaneously changing density and compressibility. A negative dielectric excess may arise when association reduces the number or effectiveness of independently responding dipoles, whereas a positive value can arise when the chosen reference underestimates the effective dipolar response. The acoustic response can independently reveal contraction or expansion of the liquid structure. Recent dielectric work on ethylene glycol–1-propanol and methanol/ethanol–ethylene glycol mixtures demonstrates how broadband relaxation parameters and correlation factors can be combined to discuss hydrogen-bond restructuring [4,5].

4.2 Polar–non-polar mixtures

Mixtures of a polar liquid with a non-polar liquid provide a different structural situation. Addition of a non-polar component can disrupt polar self-association and alter local dipole orientation. Studies of toluene with alcohols have reported negative excess dielectric behavior over the composition range, demonstrating that mixing can substantially reduce the effective dielectric response relative to a simple ideal reference [14]. Similar dielectric studies of ethyl acetate–xylene mixtures have used excess permittivity, relaxation time and Kirkwood correlation factors to analyze molecular organization [15].

4.3 Dipole–dipole and donor–acceptor interactions

Strongly polar molecules such as amides, nitriles, sulfoxides and carbonyl compounds can form specific interactions with alcohols or other donors. TDR studies of amide–alcohol mixtures found systematic changes in relaxation time, Kirkwood factors and excess dielectric properties, with deviations from simple mixing behavior attributed to molecular interactions [16]. Acoustical measurements provide an independent test because association can alter

compressibility and free length. Agreement between dielectric and acoustic trends strengthens a molecular interpretation; disagreement can be equally informative because it may indicate that rotational dynamics and mechanical packing respond differently.

4.4 A practical integrated workflow

A robust study of a binary system should begin with pure-component characterization, followed by measurements across the full composition range at controlled temperatures. Dielectric spectra should be fitted using an appropriate relaxation model, and the quality of fit should be reported. Static permittivity, ϵ_∞ and τ should then be combined with density and refractive-index information to calculate selected correlation and excess parameters. In parallel, ultrasonic velocity and density should be used to obtain β_{ad} , Z and L_f , followed by excess analysis. Finally, the composition dependence of all parameters should be compared rather than discussed independently.

Table 1. Complementary information obtained from dielectric and acoustical measurements

Measurement/parameter	Primary sensitivity	Typical molecular information
ϵ_0, ϵ'	Polarization	Dipolar response and composition dependence
T	Rotational dynamics	Dipole reorientation and local mobility
gK / g_{eff}	Orientational correlation	Cooperative or antiparallel dipolar organization
U	Elastic response	Collective propagation and molecular packing
β_{ad}	Compressibility	Cohesive structure and free volume
L_f	Intermolecular spacing	Packing and association
Z	Density $\times$ velocity	Changes in cohesive/elastic state
Excess properties	Deviation from reference	Non-ideal mixing and unlike interactions

5. Representative Literature and Emerging Directions

The literature demonstrates the broad applicability of dielectric and ultrasonic methods to binary mixtures. Early acoustical studies established the usefulness of ultrasonic velocity, density and viscosity for extracting excess compressibility, free length, acoustic impedance and related quantities [10–13]. Later dielectric investigations increasingly employed broadband time-domain reflectometry, allowing relaxation spectra to be measured over wide frequency intervals and enabling composition- and temperature-dependent studies of τ and correlation factors [15,16].

Recent work has extended this approach by combining dielectric spectroscopy with quantum-chemical calculations, molecular descriptors and data-driven prediction. For example, recent studies of n-hexanol–DMF mixtures combined broadband dielectric measurements with Kirkwood and Bruggeman parameters and density-functional calculations to relate macroscopic dielectric behavior to molecular-level characteristics [17–32]. Machine-learning-assisted dielectric analysis has also been reported for binary alcohol/amide systems, illustrating a possible route toward reducing the number of experimental measurements required once a sufficiently broad training dataset is available [18].

5.1 What the combined literature indicates

Several recurring patterns emerge. First, binary mixtures frequently show pronounced non-ideal behavior, especially when the components differ strongly in polarity, hydrogen-bonding ability or molecular size. Second, the strongest deviations are often found at intermediate compositions rather than at the pure-component limits. Third, temperature can shift both the magnitude and location of extrema because molecular association and thermal motion compete. Fourth, no single observable uniquely identifies an interaction mechanism. Dielectric and acoustic parameters should therefore be interpreted as mutually constraining evidence.

5.2 Limitations in existing studies

A persistent limitation is inconsistent treatment of the ideal reference state for excess dielectric quantities. Linear mole-fraction mixing is convenient but does not always represent a physically rigorous ideal dielectric mixture. Different definitions can consequently change the magnitude and even the apparent significance of an excess property [8,9]. Another limitation is that sign-based statements such as “negative means strong interaction” are often too general. The sign depends on the property, reference state and molecular system. A second issue is incomplete uncertainty analysis: many studies report smooth composition curves without sufficiently discussing experimental error, temperature stability or uncertainty propagation.

A further limitation is the separation of dielectric and acoustical literature. Many studies use only one technique, even though the two approaches provide complementary information. Direct combined experiments on exactly the same samples, at identical temperatures and compositions, can substantially improve interpretation. In addition, molecular simulation, infrared/Raman spectroscopy, NMR, refractive-index measurements and calorimetry can be used to test the molecular mechanisms inferred from dielectric and acoustic data.

5.3 Recommended framework for future studies

Future investigations should adopt a multimodal strategy: (i) characterize pure liquids and mixtures over the complete composition range; (ii) control temperature tightly; (iii) obtain broadband dielectric spectra rather than a single-frequency dielectric constant; (iv) fit the spectra using a model justified by residual analysis; (v) report uncertainty and goodness-of-fit; (vi) measure density and ultrasonic velocity on the same compositions; (vii) calculate both ordinary and excess parameters using a clearly stated reference model; and (viii) validate the proposed molecular mechanism using an independent structural or spectroscopic technique. Such a workflow would move the field from qualitative curve interpretation toward quantitatively testable molecular models.

6. Conclusions

Dielectric and acoustical measurements provide two complementary windows into molecular interactions in binary liquid mixtures. Dielectric spectroscopy probes polarization, dipolar reorientation and orientational correlation, while ultrasonic measurements probe density, compressibility and collective molecular packing. Parameters such as ϵ_0 , ϵ_∞ , τ and Kirkwood correlation factors can reveal changes in molecular dynamics and dipolar organization, whereas ultrasonic velocity, β_{ad} , L_f , Z and their excess values provide information on mechanical response and intermolecular spacing.

The most meaningful interpretation is obtained from the simultaneous composition and temperature dependence of several parameters. Excess properties are particularly useful because they quantify departures from a defined ideal reference; however, their physical interpretation must explicitly state the reference model. Positive or negative values should not be treated as universal signatures of one specific interaction. Hydrogen bonding, dipole–dipole association, disruption of self-association, steric effects and changes in molecular packing may contribute simultaneously.

The current literature supports a shift toward integrated experimental and computational approaches. Broadband dielectric spectroscopy, acoustical measurements, thermodynamic analysis and molecular simulation can be combined to distinguish static association from dynamic reorientation and mechanical restructuring. Such studies are relevant not only to fundamental liquid-state physics and physical chemistry but also to mixed-solvent design, separation processes, chemical processing, dielectric materials and microwave applications. A carefully controlled combined dielectric–acoustical methodology therefore remains a powerful route for understanding the microscopic organization of binary liquid mixtures.

Conflict of Interest

The author declares no conflict of interest related to this review.

References

- [1] Das, N., Praharaj, M.K., and Panda, S., "Exploring ultrasonic wave transmission in liquids and liquid mixtures: A comprehensive overview," *Journal of Molecular Liquids*, 403 (2024) 124841. DOI: 10.1016/j.molliq.2024.124841.
- [2] Panda, R., Panda, S., and Biswal, S.K., "A Review of Ultrasonic Wave Propagation through Liquid Solutions," *Current Microwave Chemistry*, 11(1) (2024), 2–15. DOI: 10.2174/0122133356288437240131061541.
- [3] Ganjare, P.J., "A Review on Molecular Interactions in Binary Liquid Mixtures Investigated by Ultrasonic Studies," *International Journal for Research in Applied Science and Engineering Technology*, 14(7) (2026), 1317–1320. DOI: 10.22214/ijraset.2026.84291.
- [4] "Dielectric relaxation and molecular interactions in ethylene glycol–1-propanol binary mixtures at microwave frequencies," *Spectroscopy Letters* (2026). DOI: 10.1080/00387010.2026.2659934.
- [5] "Dielectric relaxation and thermodynamic studies of methanol–ethylene glycol and ethanol–ethylene glycol binary mixtures using time domain reflectometry," *Spectroscopy Letters* (2026). DOI: 10.1080/00387010.2026.2727130.
- [6] Chaudhary, N.A., et al., "Insights into molecular interactions: Dielectric relaxation and DFT based studies on n-hexanol/N,N-dimethylformamide binary mixtures," *Journal of Molecular Liquids*, 418 (2025) 126675. DOI: 10.1016/j.molliq.2024.126675.
- [7] "Dielectric relaxation study of 1-pentanol–ethanol binary mixtures at 10 MHz–50 GHz frequency range using TDR technique," *Physics and Chemistry of Liquids*, 60(1) (2022). DOI: 10.1080/00319104.2021.1888380.
- [8] Buep, A.H., "Dielectric properties of binary systems 10. Ideal dielectric behavior and excess dielectric properties," *Journal of Molecular Liquids*, 51(3–4) (1992), 279–306. DOI: 10.1016/0167-7322(92)80089-Z.
- [9] Reis, J.C.R. and Iglesias, T.P., "Kirkwood correlation factors in liquid mixtures from an extended Onsager–Kirkwood–Fröhlich equation," *Physical Chemistry Chemical Physics* (2011). DOI: 10.1039/C1CP20142E.
- [10] Reis, J.C.R., "Chemical Thermodynamics of Ultrasound Speed in Solutions and Liquid Mixtures," *ChemPhysChem* (2010). DOI: 10.1002/cphc.200900709.
- [11] Uvarani, R. and Sivapragasam, J., "Acoustical Studies on Molecular Interactions in Binary Liquid Mixtures at 303 K," *E-Journal of Chemistry*, 6(4) (2009), 1150–1152. DOI: 10.1155/2009/329818.
- [12] "Studies on molecular interactions in binary liquid mixtures by viscosity and ultrasonic velocity measurements at 303.15 K," *Journal of Molecular Liquids*, 79(2) (1999), 89–99. DOI: 10.1016/S0167-7322(98)00105-6.
- [13] Bedare, G.R., "Ultrasonic Investigation of Molecular Interactions in Binary Liquid Mixtures at 298 K," *Journal of Applied Chemical Science International*, 5(2) (2016), 59–63.
- [14] "Dielectric and excess dielectric constants in non polar + polar binary liquid mixtures of toluene with alcohols at 303, 313 and 323 K," *Journal of Molecular Liquids* (2013).
- [15] "Dielectric relaxation behaviour of ethyl acetate-xylene mixtures using time domain reflectometry," *Physics and Chemistry of Liquids*, 59(4) (2021). DOI: 10.1080/00319104.2020.1743702.
- [16] "Dielectric Relaxation Study of Amide-Alcohol Mixtures by Using Time Domain Reflectometry," *Acta Physico-Chimica Sinica*, 23(10) (2007), 1508–1515. DOI: 10.1016/S1872-1508(07)60076-X.
- [17] Chaudhary, N.A., Vaja, C.R., Agheda, K.J., Shah, K.N., Rana, V.A., and Prajapati, A.N., "Insights into molecular interactions: Dielectric relaxation and DFT based studies on n-hexanol/N,N-dimethylformamide binary mixtures," *Journal of Molecular Liquids*, 418 (2025) 126675.
- [18] "Exploring molecular interactions and dielectric relaxation in n-octanol/DMF binary mixtures: a machine learning-enhanced VNA study," *Journal of Molecular Liquids* (2025).

- [19] Bokhare, A. D., Garad, N. P., Lokhande, M. P., & Kumbharkhane, A. C. (2024). Dielectric relaxation and hydrogen bonding interactions study of aqueous D-sorbitol using time domain reflectometry. *Physics and Chemistry of Liquids*, 62(1), 1-8.
- [20] Bokhare, A. D., Garad, N. P., Lokhande, M. P., & Kumbharkhane, A. C. (2024). Molecular interaction and dielectric relaxation study of DMSO-Water binary mixtures using a TDR. *Indian Journal of Chemistry (IJC)*, 63(7), 678-684.
- [21] Dhage, H. M., Bokhare, A. D., Garad, N. P., Lokhande, M. P., & Kumbharkhane, A. C. (2024). Dielectric relaxation studies of 1-nitropropane-dimethyl sulfoxide mixtures using a time domain reflectometry. *Physics and Chemistry of Liquids*, 62(4), 367-376.
- [22] Bokhare, A. D., Patange, S. S., Garad, N. P., Kumbharkhane, N. A., Lokhande, M. P., & Kumbharkhane, A. C. (2025). Dielectric characterisation and intermolecular interactions in propionitrile-dimethyl sulphoxide mixtures using a time domain reflectometry. *Physics and Chemistry of Liquids*, 63(2), 204-212.
- [23] Awankar, A. D., Bokhare, A. D., Konmare, P. R., Garad, N., Lokhande, M. P., & Kumbharkhane, A. C. (2026). Dielectric relaxation and molecular interactions in ethylene glycol-1-propanol binary mixtures at microwave frequencies. *Spectroscopy Letters*, 1-10.
- [24] Patange, S. S., Bokhare, A. D., & Kumbharkhane, A. C. (2026). Microwave dielectric dispersion and hydration studies of maltitol-water binary mixture using time domain reflectometry: *Indian Journal of Physics*, 1-9.
- [25] Patange, S. S., Bokhare, A. D., & Kumbharkhane, A. C. (2025). Comparative dielectric studies of aqueous D-arabitol and xylitol solution using a time domain reflectometry technique (TDR). *Journal of the Indian Chemical Society*, 101916.
- [26] Konmare, P. R., Bokhare, A. D., & Kumbharkhane, A. C. (2026). Dielectric properties and molecular interactions of 2-isopropoxyethanol and dimethyl sulfoxide (DMSO) binary mixtures using TDR. *Physics and Chemistry of Liquids*, 1-11.
- [27] Patange, S. S., Bokhare, A. D., & Kumbharkhane, A. C. (2025). Temperature Dependent Dielectric Relaxation and Hydration Studies of a Dulcitol–Water Binary Mixture Utilizing Time Domain Reflectometry. *Journal of Solution Chemistry*, 1-13.
- [28] Konmare, P. R., Bokhare, A. D., Garad, N. P., Hambarde, P. D., Kumbharkhane, N. A., & Kumbharkhane, A. C. (2025). Picosecond dielectric relaxation studies on binary mixtures of dihydric alcohols with DMSO using TDR. *Journal of Microwave Power and Electromagnetic Energy*, 59(4), 321-335.
- [29] Konmare, P. R., Bokhare, A. D., Garad, N. P., Hambarde, P. D., Kumbharkhane, N. A., & Kumbharkhane, A. C. (2025). Picosecond dielectric relaxation studies on binary mixtures of dihydric alcohols with DMSO using TDR. *Journal of Microwave Power and Electromagnetic Energy*, 59(4), 321-335.
- [30] Patange, S. S., Hambarde, P. D., Bokhare, A. D., Garad, N. P., & Kumbharkhane, A. C. (2025). Hydrogen Bonding Studies in Aqueous Meso-erythritol Solutions Using Time Domain Reflectometry (TDR) Technique. *Brazilian Journal of Physics*, 55(5), 214.
- [31] Saknure, S. H., Bokhare, A. D., & Kumbharkhane, A. C. (2025). Dielectric properties of aqueous cellulose using time domain reflectometry. *Cellulose*, 32(15), 8757-8765.
- [32] Saknure, S. H., Bokhare, A. D., Konmare, P. R., Patange, S. S., Hambarde, P. D., & Kumbharkhane, A. C. (2026). Dielectric relaxation and hydration study of aqueous cellulose derivative using time domain reflectometry (TDR). *Spectroscopy Letters*, 59(3), 193-199.