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Physico-chemical Study of Surface Active Ionic Liquid (SAIL) in Aqueous Inulin Solutions: Density and Speed of Sound Measurements

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Colloidal formulations of surface active ionic liquid (SAIL) have substantial benefit as efficient carrier mainly for therapeutic/pharmaceutical agents. In this regard, density (ρ) and speed of sound (u) have been employed to evaluate the diverse interactions/association behaviour of greener SAIL tetrabutylammonium dodecylsulphate (TBADS) (0.222 to 2.2 mmol kg^{-1}) in aqueous inulin solutions (0.0, 0.2 and 0.3% w/w) at five different temperatures ranging from 293.15 K to 313.15 K. The volumetric and acoustic parameters *viz.* isentropic compressibility (κ_s), apparent molar volume (V_ϕ) and compressibility ($\kappa_{s,\phi}$), intermolecular free length (L_f), relative association (RA), specific acoustic impedance (Z) and molar sound number ([U]) have been calculated by using density (ρ) and speed of sound (u) values. The existence of hydrophilic/hydrophobic interactions for TBADS in aqueous inulin solution is suggested by the variations in volumetric parameters, which further supported by various calculated acoustic parameters. Thus, the interactional outcomes can offer implications that stabilized inulin in the presence of SAILs and can be utilized for the optimal biotic actions.

Keywords: Inulin, Tetrabutylammonium dodecylsulphate, Ionic liquids, Density, Relative association, Aggregation.

INTRODUCTION

Ionic liquids (ILs) are the non-molecular salts having meting point < 373 K possessing many interesting features like low vapour pressure and toxicity, recyclability, high chemical stability and polarity, excellent solvent capabilities, *etc*. [1-4]. These wonderful properties, enhance the potential of ionic liquids in diverse fields such as potential electrolyte in sodium and zinc ion batteries [5,6]/photochemical cells [7]/electrochemical sensors [8] with improved safety, efficiency and electrochemical stability, lubricants [9], antistatic agents for polymeric composites [10], green fuel for rockets in propellant chemistry [11], solvent in biofuel production [12], in selective lanthanide extraction from ores/nuclear waste with high radiolytic stability [13], pesticides extraction from water samples [14], removal/separation of CO_2 from natural gases [15]. Moreover, Ionic liquids can also be utilized in various biomedical applications like tissue engineering [16], customization of drug for most favourable skin penetration in transdermal delivery [17], as anticancer agents with superior selectivity for cancerous cells [18], template for the synthesis of metal nanoparticles used in cancer treatment [19], *etc*.

The customization of physico-chemical properties (viscosity, melting point, polarity, *etc*.) of ionic liquids can be achieved by blending different cations/anions resulting into preferred applications [20-23]. This kind of tuned/modified version of ionic liquids, called surface active ionic liquids (SAILs), which have aggregation capability to exist in different forms *i.e.* spherical/vesicles/bilayered structures, *etc*. above certain concentration identified as critical micellar concentration (CMC) and are characterized by the presence of both polar/apolar parts [24,25]. They also have ability to decline the surface tension of liquids by promoting wetting/spreading nature. SAILs are environmentally safer and exhibit better emulsifying and surface abilities as compared to conventional ones [26,27]. Such behaviour, extend their applications in several fields like in selective ADP detection over nucleotides [28], sensing of abnormally charged proteins [29], hydrocarbon solubilization [30], organic synthesis as medium with superior and selective conversion [31,32], extraction of chemicals from naturally occurring materials (piperidine, curcumin, triterpenic and oleanolic acid) [33-36], oil spill remediation [37], as efficient carrier of violacein in treatment of cancer [38], biomolecule and emulsion stabilizer [25], protecting agent [39], corrosion inhibitor [21,25], *etc*. In this study, tetraalkylammonium cation based SAIL is utilized because of low cost and toxicity than imidazolium based SAILs, wood preservative/antifungal properties and uses in greenhouse gas (CO_2) conversion [40,41]. The colloidal properties and applications of SAILs may get modify in the presence of various additives (electrolytes, amino acids, polymers). Recent years, biopolymer-surfactant blends have captured the attention of researchers due to their usage in cosmetic and pharmaceuticals industry [42], protein solubilization [43], *etc*.

Inulin is a non-toxic and biodegradable polysaccharide having low calorific value and flexible structure due to β-(2,1) linkage between glycosyl and repeated fructosyl parts [44-47]. Their degrees of polymerization affect/modify its physico-chemical properties, consequently enhances the food shelf life, texture *etc*. [47,48]. Therefore, it can be used as facilitator for drug delivery [47,49], mineral absorption and bioavailability [50,51], appetite regulator [52], foam stabilizer/fat replacer in dairy products [53,54] and reducer for gastrointestinal disease [55], *etc*. Thus in the colloidal forms, enhanced surface activity of SAILs on coupling with biopolymers like inulin may be applied in the field of detergents [56], coating and paints [25], material synthesis [57], medication encapsulation/solubilization [47], *etc*. Because of such interesting features of SAIL-biopolymer blend, in this work, the interactional studies of TBADS-inulin have been explored by density and speed of sound studies.

EXPERIMENTAL

Tetrabutylammonium dodecylsulfate (TBADS) have been used as synthesized in the prior work [41]. Extra pure inulin was procured from SRL Pvt. Ltd., India.

Measurements of density and speed of sound: High precision density and speed of sound analyzer, DSA-5000 instrument supplied by Anton Paar, Austria was utilized to compute the density (ρ) and speed of sound (u) values for TBADS in aqueous solution of inulin (0.0, 0.2 0.3% w/w). Samples injected in U-shaped tube, which was electronically excited at characteristic frequency depending upon the density values of sample. The working frequency was about 3 MHz to calculate speed of sound values with temperature precision about ± 0.001 K [58, 59].

RESULTS AND DISCUSSION

Volumetric and compressibility parameters: The density (ρ) and speed of sound (u) for TBADS in aqueous inulin solutions (0.2, 0.3% w/w) from 293.15-313.15 K have been illustrated in Table-1, whereas these values for TBADS in aqueous solution have already been reported in literature [60]. The data demonstrated the rising ρ values with varying [inulin], the trend shown by ρ values has been follow the order 0.3 > 0.2 > 0.0% w/w inulin. A decrease in the ρ value with temperature increment may be consequence of enhanced kinetic energy/volume expansion; moreover the interactional energy is less than thermal energy [61,62]. In addition, the obtained ρ and u values have applied to estimate the apparent molar volume (V_ϕ)/isentropic

TABLE-1
DENSITY (ρ) VALUES (kg m^{-3}) AND SPEED OF SOUND (u) VALUES (m s^{-1}) FOR TBADS IN AQUEOUS INULIN SOLUTIONS AT DIFFERENT TEMPERATURES (293.15-313.15 K)

[TBADS] (mmol kg^{-1})	ρ (kg m^{-3})					u (m s^{-1})				
	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K
0.2% w/w inulin										
0.000	999.077	997.911	996.510	994.893	993.068	1482.92	1496.99	1509.43	1520.14	1529.27
0.222	998.988	997.871	996.444	994.871	993.033	1483.78	1497.80	1510.09	1520.84	1529.98
0.444	999.019	997.893	996.500	994.883	993.053	1483.75	1497.74	1510.00	1520.70	1529.75
0.666	999.070	997.924	996.525	994.902	993.083	1483.75	1497.71	1509.92	1520.55	1529.58
0.888	999.063	997.915	996.515	994.905	993.070	1483.78	1497.73	1509.90	1520.57	1529.65
1.110	999.057	997.907	996.505	994.882	993.058	1483.82	1497.76	1509.91	1520.60	1529.72
1.332	999.051	997.903	996.500	994.879	993.057	1483.97	1497.82	1509.97	1520.6	1529.68
1.554	999.045	997.896	996.495	994.871	993.046	1483.98	1497.82	1509.99	1520.63	1529.71
1.776	999.044	997.900	996.496	994.873	993.049	1483.94	1497.82	1510.06	1520.63	1529.71
1.998	999.056	997.886	996.483	994.862	993.038	1483.93	1497.92	1510.37	1520.67	1529.68
2.220	999.041	997.874	996.468	994.846	993.026	1483.40	1497.42	1509.73	1520.43	1529.53
0.3% w/w inulin										
0.000	999.409	998.245	996.844	995.218	993.377	1482.99	1497.02	1509.50	1520.28	1529.45
0.222	999.256	998.136	996.616	995.166	993.315	1484.09	1498.11	1510.34	1521.08	1530.24
0.444	999.350	998.200	996.800	995.175	993.350	1483.70	1497.60	1509.88	1520.50	1529.63
0.666	999.345	998.193	996.790	995.171	993.345	1483.73	1497.65	1509.92	1520.55	1529.66
0.888	999.342	998.190	996.787	995.167	993.341	1483.80	1497.70	1509.95	1520.59	1529.69
1.110	999.339	998.187	996.785	995.164	993.337	1483.88	1497.75	1509.97	1520.63	1529.72
1.332	999.336	998.183	996.779	995.157	993.329	1483.88	1497.76	1509.98	1520.63	1529.72
1.554	999.272	998.169	996.771	995.153	993.325	1484.08	1497.83	1510.07	1520.68	1529.76
1.776	999.324	998.170	996.766	995.144	993.321	1484.13	1498.05	1510.15	1520.78	1529.78
1.998	999.329	998.179	996.771	995.151	993.324	1484.28	1497.95	1510.15	1520.79	1529.86
2.220	999.310	998.140	996.736	995.114	993.293	1483.46	1497.51	1509.88	1520.56	1529.63

Standard uncertainties (u) are u(T) = ± 0.01 K, u([TBADS]) = ± 0.002 mmol kg^{-1}, u(ρ) = ± 0.08 kg m^{-3}, u(u) = ± 0.1 m s^{-1}

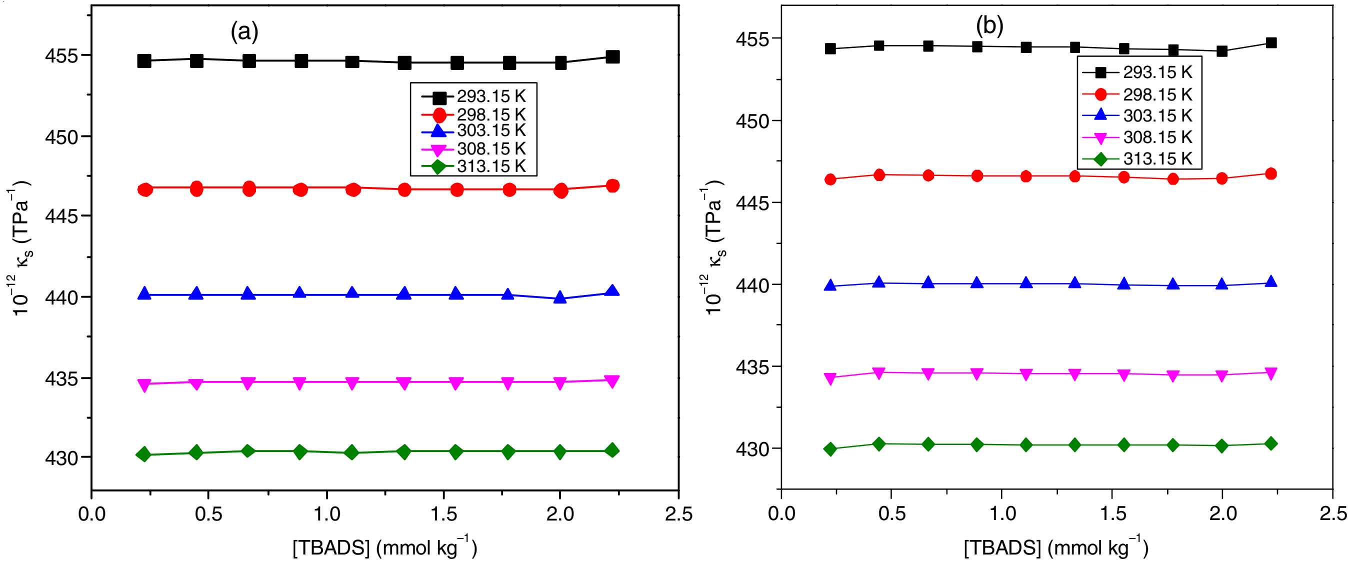

Fig. 1. Plots of κ_s *vs*. [TBADS] in (a) 0.2% w/w and (b) 0.3% w/w aqueous solution of inulin at different temperatures (293.15-313.15 K)

compressibility (κ_s)/apparent molar adiabatic compression ($\kappa_{s,\phi}$). Eqn. 1 has been employed to compute the isentropic compressibility (κ_s) [58,59]:

$$\kappa_s = \frac{1}{u^2\rho} \tag{1}$$

where ρ (kg m^{-3}) and u (m s^{-1}) denote the density and speed of sound for solutions, repectively.

The isentropic compressibility (κ_s) values of the colloidal solutions were expected to influenced by two key factors [63], (i) the compressibility of hydrophobic micellar core and (ii) interaction between the hydrophilic head portions of SAILs. Besides this, alterations in counter ion binding and the polarity of SAILs head portions have also contributed to compressibility [58,62]. Reduced κ_s with incremented temperature and [inulin] (0.3 > 0.2 > 0.0% w/w) has been observed in Fig. 1. The increasing amount of inulin may indicate a reduction in κ_s values (Table-2), suggesting increased molecular interaction and enhanced solute-solvent hydrogen bonding; while SAIL-solvent electrostatic interactions may justification for diminished κ_s with elevated temperature [58,64].

Further, the apparent molar volume (V_ϕ) and $\kappa_{s,\phi}$ were also calculated by utilizing eqns. 2 and 3 to explore the binding mechanism in SAIL-inulin-water mixture [59,62]. The plausible interactions in the TBADS + inulin system may include (i) $^{-}OSO_3/Bu_4N^+/Pr_4N^+$ *i.e.* ionic portions of SAILs and hydrophilic portions of inulin (–OH/-O-) (ii) hydrophobic parts of SAILs and inulin (iii) hydrophobic region of inulin and aforementioned ions of SAILs, and (iv) the inulin-water hydrogen bonding [58,59,61].

$$V_\phi = \frac{M}{\rho} - \left(\frac{(\rho-\rho_0)}{m\rho\rho_0}\right) \tag{2}$$

$$\kappa_{s,\phi} = \left(\frac{\kappa_s - \kappa_{s,0}}{m\rho_0}\right) + \kappa_s V_\phi \tag{3}$$

Fig. 2 demonstrated the non-linear behaviour of V_ϕ with [SAIL] in aqueous solution of inulin from 293.15-313.15 K.

TABLE-2
COMPRESSIBILITY COEFFICIENT (10^{-12} κ_s) VALUES (TPa^{-1}) FOR TBADS IN AQUEOUS INULIN SOLUTIONS AT DIFFERENT TEMPERATURES (293.15-313.15 K)

[TBADS] (mmol kg^{-1})	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K
0.0% w/w inulin					
0.222	455.26	447.78	441.50	436.42	432.66
0.444	454.82	446.79	440.08	434.51	430.09
0.666	454.68	446.75	440.17	434.81	430.72
0.888	454.98	447.14	440.57	435.15	430.81
1.110	455.10	447.16	440.53	435.09	430.74
1.332	455.08	447.25	440.65	435.23	430.87
1.554	455.14	447.28	440.67	435.24	430.86
1.776	455.13	447.19	440.63	435.22	430.85
1.998	455.64	447.60	440.89	435.38	431.00
2.220	455.75	447.69	440.93	435.59	431.02
0.2% w/w inulin					
0.222	454.67	446.70	440.09	434.58	430.19
0.444	454.68	446.73	440.12	434.65	430.32
0.666	454.66	446.73	440.15	434.73	430.40
0.888	454.64	446.72	440.17	434.72	430.36
1.110	454.62	446.71	440.17	434.71	430.33
1.332	454.53	446.68	440.14	434.71	430.35
1.554	454.53	446.68	440.13	434.70	430.34
1.776	454.55	446.68	440.08	434.70	430.34
1.998	454.55	446.62	439.91	434.68	430.36
2.220	454.88	446.93	440.29	434.82	430.45
0.3% w/w inulin					
0.222	454.36	446.40	439.87	434.31	429.93
0.444	454.56	446.67	440.06	434.64	430.25
0.666	454.54	446.65	440.04	434.61	430.24
0.888	454.50	446.62	440.02	434.59	430.22
1.110	454.45	446.59	440.01	434.57	430.21
1.332	454.46	446.59	440.01	434.57	430.21
1.554	454.36	446.55	439.96	434.54	430.19
1.776	454.31	446.42	439.91	434.49	430.18
1.998	454.21	446.47	439.91	434.48	430.14
2.220	454.72	446.75	440.08	434.63	430.28

Standard uncertainties (u) are u(T) = ± 0.01 K, u([TBADS]) = ± 0.002 mmol kg^{-1}, u (10^{-12}. κ_s) = ± 0.08 TPa^{-1}

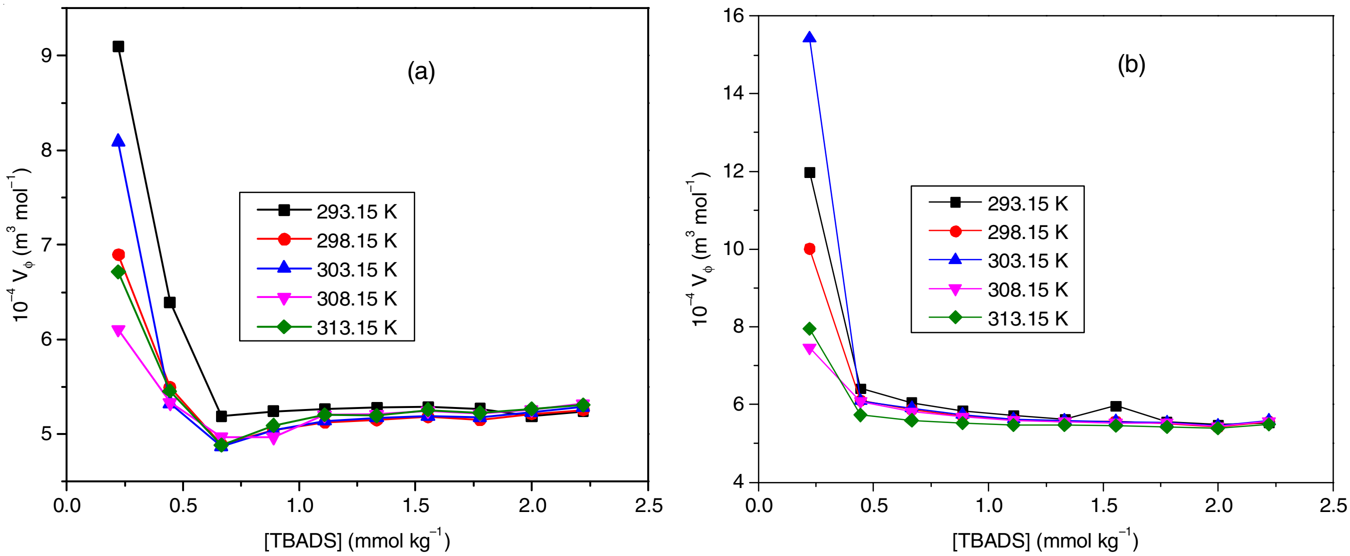

Fig. 2. Plots of V_ϕ *vs.* [TBADS] in (a) 0.2% w/w and (b) 0.3% w/w aqueous solution of inulin at different temperatures (293.15-313.15 K)

The reduction in V_ϕ values with [inulin] at [SAIL] = 0.222 mM may result from an enhanced overall water structure, that results from increased electrostatic hydration of the polar components of TBADS and inulin [58,59,65]. Also, affinity of hydrophobic/hydrophilic portions of TBADS towards polar/apolar parts of inulin may be enhanced, owing to increased electrostriction as existence of alkyl chains [58]. The aforementioned events may cause the rupture of water structures leading to the lower V_ϕ values [58,61]. In Table-3, the V_ϕ values increase with [inulin] for [SAIL] > 0.222 mM because the interactions between the ionic and polar sections of SAILs and inulin cause the volume to shrink due to the structure making behaviour of TBADS, which in turn improves the solvent structure and leads to higher V_ϕ values [58,59,66].

The $\kappa_{s,\phi}$ values of TBADS in aqueous inulin solution were non-linear and negative, which may become less negative (or positive) with increased [SAIL], [inulin] and temperature (Fig. 3). Such behaviour may be due to enhanced compressibility due to aggregated forms and intense solute-solvent binding [67,68]. Moreover, the compressibility of water molecules around SAILs is more than in bulk (Table-4) [58]. The reduced compressibility may attribute to robust electrostrictive forces resulting in the electrostrictive solvation [59,68].

Acoustical parameters: The calculated ρ and u values were also implemented to compute acoustical parameters by employing relations (eqns. 4-7), such as intermolecular free length (L_f), relative association (RA), specific acoustic impedance (Z) and molar sound number [U]. These parameters have favoured, since they confer supportive insight to interactions accessible in SAIL/inulin/water system [69,70]:

$$L_f = K\sqrt{\kappa_s} \tag{4}$$

$$RA = \left(\frac{\rho}{\rho_0}\right)\left(\frac{u_0}{u}\right)^{1/3} \tag{5}$$

$$Z = u \times \rho \tag{6}$$

TABLE-3
VALUES OF APPARENT MOLAR VOLUME (10^{-4} V_ϕ) (m^3 mol^{-1})
FOR TBADS IN AQUEOUS INULIN SOLUTIONS AT
DIFFERENT TEMPERATURES (293.15-313.15 K)

[TBADS] (mmol kg^{-1})	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K
0.0% w/w inulin					
0.222	26.890	66.627	106.716	155.334	232.216
0.444	3.708	2.487	2.396	2.441	2.487
0.666	4.017	3.431	3.464	4.090	5.362
0.888	4.160	3.824	3.805	3.763	3.848
1.110	4.183	4.105	4.091	4.060	4.084
1.332	4.379	4.330	4.487	4.850	4.843
1.554	4.544	4.413	4.425	4.437	4.451
1.776	4.629	4.521	4.538	4.527	4.523
1.998	4.730	4.625	4.625	4.617	4.609
2.220	4.780	4.699	4.686	4.684	4.674
0.2% w/w inulin					
0.222	9.100	6.898	8.090	6.106	6.712
0.444	6.392	5.496	5.323	5.332	5.456
0.666	5.188	4.893	4.869	4.968	4.885
0.888	5.241	5.044	5.039	4.968	5.091
1.110	5.263	5.125	5.141	5.204	5.205
1.332	5.279	5.149	5.172	5.210	5.197
1.554	5.289	5.186	5.193	5.247	5.257
1.776	5.269	5.151	5.175	5.218	5.222
1.998	5.188	5.215	5.232	5.261	5.266
2.220	5.245	5.256	5.287	5.318	5.306
0.3% w/w inulin					
0.222	11.983	10.015	15.433	7.468	7.943
0.444	6.412	6.104	6.092	6.081	5.728
0.666	6.044	5.871	5.910	5.815	5.599
0.888	5.837	5.709	5.741	5.683	5.523
1.110	5.713	5.612	5.629	5.594	5.477
1.332	5.630	5.555	5.586	5.565	5.477
1.554	5.965	5.578	5.567	5.525	5.451
1.776	5.561	5.511	5.537	5.524	5.432
1.998	5.482	5.419	5.462	5.441	5.381
2.220	5.528	5.562	5.584	5.576	5.496

Standard uncertainties (u) are u(T) = ± 0.01 K, u([TBADS]) = ± 0.002 mmol kg^{-1}, u (10^{-4} V_ϕ) = ± 0.06 m^3 mol^{-1}

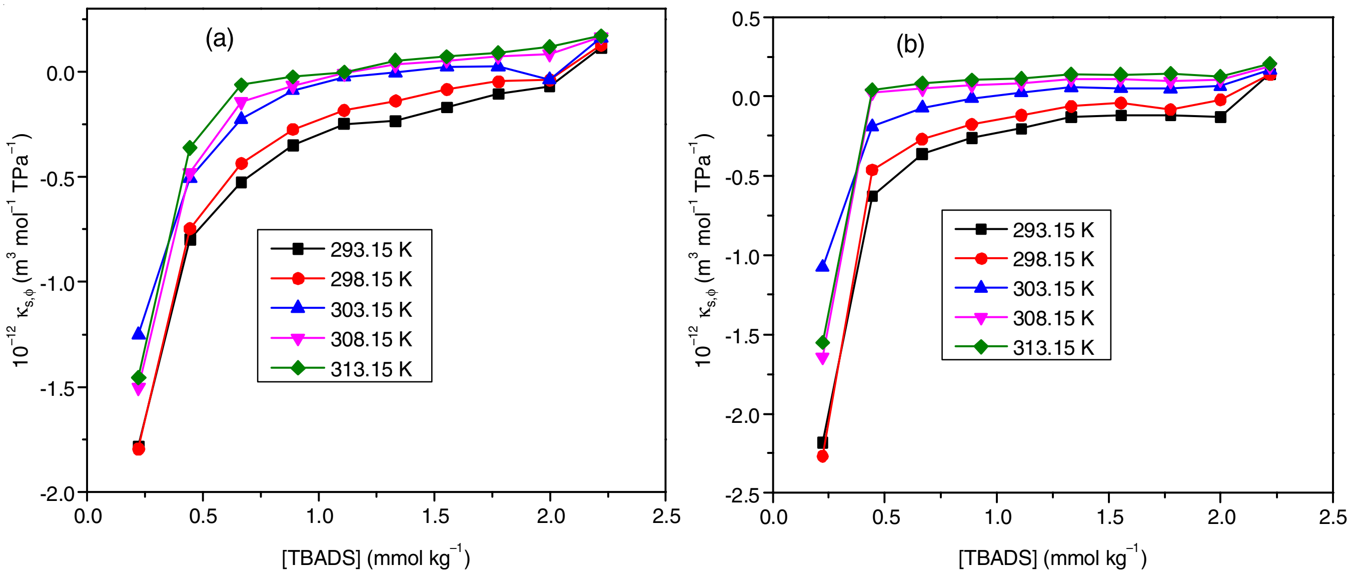

Fig. 3. Plots of $\kappa_{s,\phi}$ *vs*. [TBADS] in (a) 0.2% w/w and (b) 0.3% w/w aqueous solution of inulin at different temperatures (293.15-313.15 K)

TABLE-4
APPARENT MOLAR COMPRESSIBILITY (10^{-12} $\kappa_{s,\phi}$) VALUES (m^3 mol^{-1} TPa^{-1}) FOR TBADS IN AQUEOUS INULIN SOLUTIONS AT DIFFERENT TEMPERATURES (293.15-313.15 K)

[TBADS] (mmol kg^{-1})	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K
0.0% w/w inulin					
0.222	-0.971	3.223	6.783	10.484	16.651
0.444	-1.916	-2.002	-2.073	-2.357	-2.422
0.666	-1.426	-1.324	-1.161	-1.008	-0.492
0.888	-0.677	-0.500	-0.358	-0.343	-0.279
1.110	-0.394	-0.331	-0.276	-0.289	-0.242
1.332	-0.304	-0.165	-0.094	-0.068	-0.042
1.554	-0.186	-0.095	-0.046	-0.040	-0.031
1.776	-0.136	-0.100	-0.030	-0.020	-0.004
1.998	0.162	0.144	0.130	0.090	0.094
2.220	0.218	0.193	0.159	0.201	0.121
0.2% w/w inulin					
0.222	-1.782	-1.794	-1.252	-1.504	-1.455
0.444	-0.797	-0.747	-0.507	-0.483	-0.363
0.666	-0.524	-0.437	-0.226	-0.144	-0.063
0.888	-0.349	-0.275	-0.090	-0.068	-0.024
1.110	-0.250	-0.184	-0.025	-0.008	-0.002
1.332	-0.235	-0.140	-0.006	0.033	0.053
1.554	-0.169	-0.084	0.022	0.053	0.072
1.776	-0.105	-0.047	0.024	0.073	0.089
1.998	-0.070	-0.040	-0.039	0.083	0.117
2.220	0.113	0.127	0.162	0.165	0.170
0.3% w/w inulin					
0.222	-2.181	-2.267	-1.079	-1.642	-1.551
0.444	-0.629	-0.463	-0.189	0.022	0.043
0.666	-0.363	-0.268	-0.073	0.051	0.083
0.888	-0.260	-0.175	-0.015	0.072	0.102
1.110	-0.203	-0.119	0.024	0.083	0.114
1.332	-0.129	-0.063	0.057	0.111	0.137
1.554	-0.119	-0.041	0.051	0.111	0.136
1.776	-0.119	-0.082	0.049	0.097	0.142
1.998	-0.129	-0.021	0.066	0.105	0.127
2.220	0.142	0.138	0.167	0.19	0.207

Standard uncertainties (u) are u(T) = ± 0.01 K, u([TBADS]) = ± 0.002 mmol kg^{-1}, u(10^{-12} $\kappa_{s,\phi}$) = ± 0.03 m^3 mol^{-1} TPa^{-1}

TABLE-5
MEAN FREE LENGTH (10^{-11} L_f) VALUES (m) FOR TBADS IN AQUEOUS INULIN SOLUTIONS AT DIFFERENT TEMPERATURES (293.15-313.15 K)

[TBADS] (mmol kg^{-1})	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K
0.0% w/w inulin					
0.222	4.345	4.349	4.358	4.372	4.392
0.444	4.343	4.344	4.351	4.363	4.379
0.666	4.343	4.344	4.351	4.364	4.382
0.888	4.344	4.346	4.354	4.366	4.383
1.110	4.345	4.346	4.353	4.365	4.382
1.332	4.345	4.347	4.354	4.366	4.383
1.554	4.345	4.347	4.354	4.366	4.383
1.776	4.345	4.346	4.354	4.366	4.383
1.998	4.347	4.348	4.355	4.367	4.384
2.220	4.348	4.349	4.355	4.368	4.384
0.2% w/w inulin					
0.222	4.343	4.344	4.351	4.363	4.380
0.444	4.343	4.344	4.351	4.363	4.380
0.666	4.343	4.344	4.351	4.364	4.381
0.888	4.342	4.344	4.352	4.364	4.381
1.110	4.342	4.344	4.351	4.364	4.380
1.332	4.342	4.344	4.351	4.364	4.381
1.554	4.342	4.344	4.351	4.363	4.380
1.776	4.342	4.344	4.351	4.363	4.380
1.998	4.342	4.344	4.350	4.363	4.381
2.220	4.344	4.345	4.352	4.364	4.381
0.3% w/w inulin					
0.222	4.341	4.343	4.350	4.362	4.378
0.444	4.342	4.344	4.351	4.363	4.380
0.666	4.342	4.344	4.351	4.363	4.380
0.888	4.342	4.344	4.351	4.363	4.380
1.110	4.342	4.344	4.351	4.363	4.380
1.332	4.342	4.343	4.351	4.363	4.380
1.554	4.341	4.343	4.350	4.363	4.380
1.776	4.341	4.343	4.350	4.362	4.380
1.998	4.340	4.343	4.350	4.362	4.379
2.220	4.343	4.344	4.351	4.363	4.380

Standard uncertainties (u) are u(T) = ± 0.01 K, u([TBADS]) = ± 0.002 mmol kg^{-1}, u(10^{-11} L_f) = ± 0.008 m

$$[U] = \frac{(u - u_0)}{(u_0 \times m)} \quad (7)$$

where K = [(93.875 + 0.375 T) × 10^{-8}].

Table-5 demonstrated the correlation of L_f values with [SAIL]/[Polymer] and temperature. It is possible that the densely packed system, which results from the structural modification and the intense SAIL-inulin interactions, is responsible for the decreased L_f values with [inulin]. Moreover, rising temperature enhances the L_f values can be consequence of volume expansion due to the incremented thermal energy, which disorganized the molecular structure [69,70]. The relative association (RA) values are influenced by two factors: (i) the disruption of solvent structure caused by solute, leading to decreased RA values when [inulin] exceeds [SAIL] = 0.666 mM and (ii) increased RA values due to the ion solvation by freed solvent molecules [69]. Also, the RA values have found to be positive and close to unity as depicted in Table-6. Table-7 demonstrated the incremental Z values with [polymer] and temperature may be due to intense binding among SAIL-inulin-water system, which offers superior barrier to sound waves [69-71]. An further significant parameter, [U], providing fascinating information to explicate the intermolecular interactions and their modification in the solution constitution [69]. The non-linear behaviour and decreased [U] values with [SAIL]/temperature as shown in Fig. 4 may be the consequence of strong interactions in SAIL-inulin mixture (Table-8) [69,70].

TABLE-6
RELATIVE ASSOCIATION (RA) VALUES FOR TBADS IN AQUEOUS INULIN SOLUTIONS AT DIFFERENT TEMPERATURES (293.15-313.15 K)

[TBADS] (mmol kg^{-1})	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K
0.0% w/w inulin					
0.222	0.99926	0.99843	0.99756	0.99646	0.99475
0.444	0.99973	0.99979	0.99978	0.99972	0.99970
0.666	0.99969	0.99976	0.99980	0.99978	0.99980
0.888	0.99981	0.99991	0.99996	0.99997	0.99998
1.110	0.99988	0.99992	0.99994	0.99994	0.99995
1.332	0.99987	0.99994	0.99995	0.99990	0.99991
1.554	0.99986	0.99995	0.99998	0.99998	0.99999
1.776	0.99985	0.99992	0.99996	0.99997	0.99999
1.998	0.99986	1.00006	1.00005	1.00003	1.00004
2.220	0.99986	1.00009	1.00007	1.00011	1.00005
0.2% w/w inulin					
0.222	0.99972	0.99978	0.99979	0.99982	0.99981
0.444	0.99976	0.99982	0.99986	0.99987	0.99988
0.666	0.99981	0.99985	0.99991	0.99992	0.99995
0.888	0.99979	0.99984	0.99990	0.99992	0.99992
1.110	0.99978	0.99982	0.99989	0.99989	0.99989
1.332	0.99977	0.99981	0.99987	0.99989	0.99990
1.554	0.99977	0.99980	0.99986	0.99987	0.99988
1.776	0.99973	0.99980	0.99985	0.99987	0.99988
1.998	0.99974	0.99977	0.99977	0.99985	0.99988
2.220	0.99973	0.99987	0.99989	0.99989	0.99990
0.3% w/w inulin					
0.222	0.99960	0.99965	0.99959	0.99977	0.99977
0.444	0.99978	0.99983	0.99987	0.99991	0.99993
0.666	0.99977	0.99981	0.99985	0.99989	0.99992
0.888	0.99975	0.99979	0.99984	0.99988	0.99991
1.110	0.99973	0.99978	0.99984	0.99987	0.99990
1.332	0.99973	0.99977	0.99983	0.99986	0.99989
1.554	0.99966	0.99974	0.99980	0.99985	0.99988
1.776	0.99972	0.99970	0.99978	0.99982	0.99987
1.998	0.99968	0.99973	0.99978	0.99982	0.99986
2.220	0.99964	0.99979	0.99981	0.99983	0.99988

Standard uncertainties (u) are u(T) = ± 0.01 K, u([TBADS]) = ± 0.002 mmol kg^{-1}, u(RA) = ± 3 × 10^{-5}

TABLE-7
ACOUSTIC IMPEDANCE (10^{-5} Z) VALUES (kg m^{-2} s^{-1}) FOR TBADS IN AQUEOUS INULIN SOLUTIONS AT DIFFERENT TEMPERATURES (293.15-313.15 K)

[TBADS] (mmol kg^{-1})	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K
0.0% w/w inulin					
0.222	14.804	14.912	15.000	15.067	15.106
0.444	14.815	14.939	15.042	15.126	15.190
0.666	14.818	14.940	15.041	15.120	15.177
0.888	14.813	14.934	15.034	15.115	15.177
1.110	14.811	14.933	15.034	15.116	15.178
1.332	14.811	14.931	15.032	15.113	15.175
1.554	14.810	14.931	15.032	15.113	15.176
1.776	14.810	14.932	15.033	15.114	15.176
1.998	14.802	14.926	15.028	15.111	15.174
2.220	14.800	14.924	15.027	15.107	15.173
0.2% w/w inulin					
0.222	14.823	14.946	15.047	15.130	15.193
0.444	14.823	14.946	15.047	15.129	15.191
0.666	14.824	14.946	15.047	15.128	15.190
0.888	14.824	14.946	15.046	15.128	15.190
1.110	14.824	14.946	15.046	15.128	15.191
1.332	14.826	14.947	15.047	15.128	15.191
1.554	14.826	14.947	15.047	15.128	15.191
1.776	14.825	14.947	15.048	15.128	15.191
1.998	14.825	14.948	15.051	15.129	15.190
2.220	14.820	14.942	15.044	15.126	15.189
0.3% w/w inulin					
0.222	14.830	14.953	15.052	15.137	15.200
0.444	14.827	14.949	15.050	15.132	15.195
0.666	14.828	14.949	15.051	15.132	15.195
0.888	14.828	14.950	15.051	15.132	15.195
1.110	14.829	14.950	15.051	15.133	15.195
1.332	14.829	14.950	15.051	15.133	15.195
1.554	14.830	14.951	15.052	15.133	15.195
1.776	14.831	14.953	15.053	15.134	15.196
1.998	14.833	14.952	15.053	15.134	15.196
2.220	14.824	14.947	15.050	15.131	15.194

Standard uncertainties (u) are u(T) = ± 0.01 K, u([TBADS]) = ± 0.002 mmol kg^{-1}, u(10^{-5} Z) = ± 0.009 kg m^{-2} s^{-1}

Conclusion

Incorporation of non-immunogenic biopolymer has substantial impact on the deliberated parameters of sustainable SAIL (TBADS). The potential factors reliable in volumetric/acoustical parameters primarily originate from detached water framework around apolar tails, referable to the hydrophobic-hydrophobic/hydrophilic-hydrophilic interactions in TBADS-inulin mixture. The incremental compactness of analyzed SAIL-inulin system is predominantly ascribed to these interactions and the results imply divergent manner in both pre-post micellar segments. Consequently, the exploration of multifaceted molecular inter-

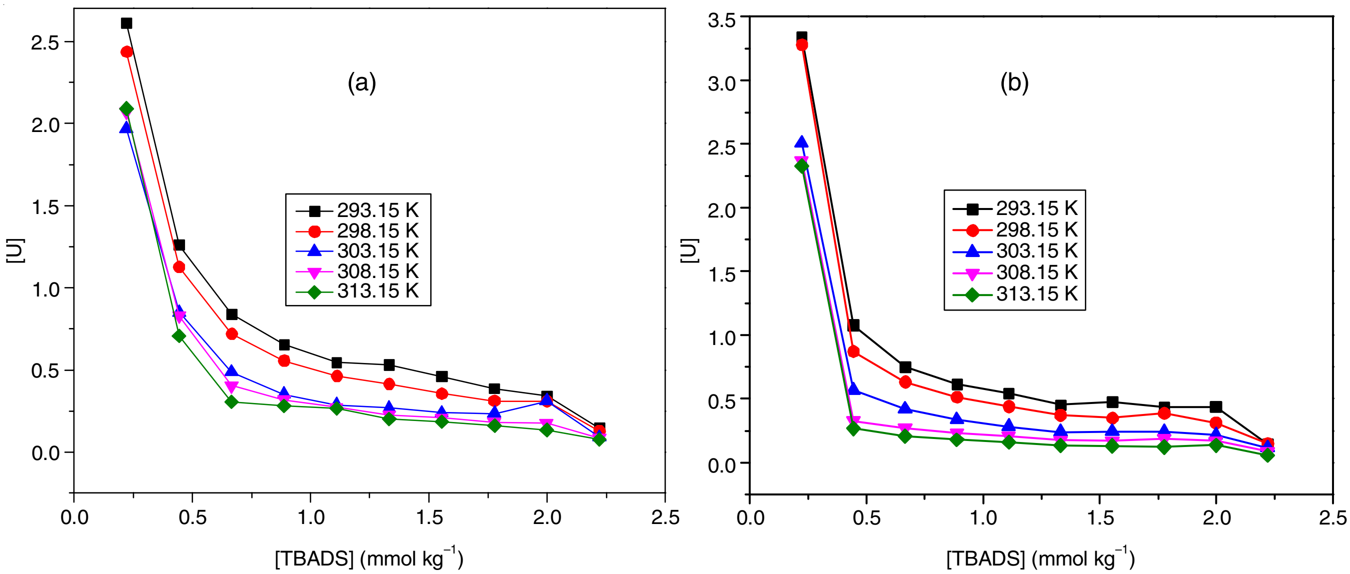

Fig. 4. Plots of [U] *vs.* [TBADS] in (a) 0.2% w/w and (b) 0.3% w/w aqueous solution of inulin at different temperatures (293.15-313.15 K)

TABLE-8
MOLAR SOUND NUMBER ([U]) VALUES FOR TBADS IN AQUEOUS INULIN SOLUTIONS AT DIFFERENT TEMPERATURES (293.15-313.15 K)

[TBADS] (mmol kg^{-1})	293.15 K	298.15 K	303.15 K	308.15 K	313.15 K
0.0% w/w inulin					
0.222	3.494	2.799	2.716	3.231	3.654
0.444	2.218	2.227	2.328	2.682	2.784
0.666	1.712	1.565	1.403	1.304	0.845
0.888	0.904	0.685	0.530	0.511	0.449
1.110	0.595	0.524	0.466	0.480	0.430
1.332	0.516	0.361	0.298	0.306	0.275
1.554	0.404	0.292	0.239	0.233	0.223
1.776	0.357	0.308	0.231	0.219	0.199
1.998	0.041	0.047	0.060	0.102	0.095
2.220	-0.015	0.000	0.033	-0.018	0.071
0.2% w/w inulin					
0.222	2.612	2.437	1.970	2.074	2.091
0.444	1.261	1.128	0.851	0.830	0.707
0.666	0.840	0.722	0.487	0.405	0.304
0.888	0.653	0.557	0.351	0.319	0.280
1.110	0.547	0.463	0.286	0.273	0.265
1.332	0.532	0.416	0.269	0.227	0.201
1.554	0.460	0.357	0.239	0.207	0.185
1.776	0.387	0.312	0.235	0.181	0.162
1.998	0.341	0.311	0.312	0.175	0.134
2.220	0.146	0.129	0.090	0.086	0.077
0.3% w/w inulin					
0.222	3.341	3.280	2.507	2.370	2.327
0.444	1.078	0.873	0.567	0.326	0.265
0.666	0.749	0.632	0.418	0.267	0.206
0.888	0.615	0.512	0.336	0.230	0.177
1.110	0.541	0.439	0.281	0.207	0.159
1.332	0.451	0.371	0.239	0.173	0.133
1.554	0.473	0.348	0.243	0.169	0.130
1.776	0.433	0.387	0.242	0.185	0.121
1.998	0.435	0.311	0.216	0.168	0.134
2.220	0.143	0.147	0.113	0.083	0.053

Standard uncertainties (u) are u(T) = ± 0.01 K, u([TBADS]) = ± 0.002 mmol kg^{-1}, u([U]) = ± 0.004

actions within the biocompatible organizations cooperatively contributes to designing a functional significance for the betterment of industrial/pharmaceutical domains, where SAILs have pivotal role.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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