

Research Article

SOLUTE-SOLVENT INTERACTIONS OF D-(+)-MALTOSE MONOHYDRATE IN AQUEOUS SODIUM SACCHARIN AT $T = (298.15-313.15)$ K: VOLUMETRIC AND VISCOMETRIC APPROACH

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ABSTRACT

Objective: The aim of the research is to explore the volumetric and viscometric properties of D(+)-maltose monohydrate and sodium saccharin.

Methods: These properties were assessed at temperatures between 298.15 K and 313.15 K in water and aqueous sodium saccharin (0.05, 0.15, and 0.3) mol·kg⁻¹. The thermodynamic parameters of density (ρ) and viscosity (η), such as partial molar volume (V_ϕ^0), Masson's coefficients (S_ϕ), expansion coefficient (E^∞), transfer volume ($\Delta_{trs}V_\phi^0$), Hepler's Constant ($\partial^2 V_\phi^0 / \partial T^2$), apparent specific volume (ASV), Jones-Dole B -coefficient (B), and temperature-dependence dB/dT were calculated from the experimental data.

Results: The positive values of V_ϕ^0 , S_ϕ , E^∞ , $\Delta_{trs}V_\phi^0$, B suggests that D(+)-maltose monohydrate can form structures in water and at various concentrations of aqueous sodium saccharin and increase as the concentration of the cosolute rises. Similarly, negative values of $(\partial^2 V_\phi^0 / \partial T^2)$, and dB/dT suggest the solute's (D(+)-maltose monohydrate) ability to form structures with cosolute at studied concentrations.

Conclusion: Substantial interactions between the hydrophilic groups of the solute (D(+)-maltose monohydrate) and the Na⁺ ion of the cosolute (sodium saccharin) were found. The studied disaccharide retained its sweetness when combined with sodium saccharin.

Keywords-D-(+)-maltose monohydrate, Sodium saccharin, Density, Viscosity, Thermodynamic parameters

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INTRODUCTION

Saccharides, or carbohydrates, are organic compounds composed of carbon, hydrogen, and oxygen, primarily serving as an energy source for muscles and the central nervous system [1-3]. They are classified based on the number of saccharide units into monosaccharides, disaccharides, and polysaccharides. Saccharides play a crucial role in biological and physiological processes, contributing to hydration properties and stability in food and medicine [4-8].

Artificial sweeteners [9-13], such as aspartame, sucralose, and saccharin, provide a low-calorie alternative to natural sugars. Sodium saccharin, which is 300 times sweeter than sucrose, is widely used in food and pharmaceutical industries due to its solubility and stability. An artificial sweetener blend with saccharides to enhance taste reduces costs and caters to diabetic patients [14-16].

The thermodynamic properties of saccharides and sweeteners, such as density and viscosity, are important for understanding their molecular interactions in aqueous solutions. These properties influence the solute-solvent interactions, impacting taste perception and structural behavior in biological and food systems [17-20]. Studies have examined how saccharides interact with water and other solutes, revealing their role in hydration, taste enhancement, and stability in various applications.

Continuation of earlier research [21, 22], this study extends the investigation to a disaccharide. The densities and viscosities were evaluated at $T = (298.15-313.15)$ K in water and in aqueous saccharin Na salt with molalities of 0.05, 0.15, and 0.3 m. The interactions between D-(+)-maltose monohydrate-saccharin sodium salt were discovered through partial molar volumes, transfer characteristics, apparent specific volumes and B -coefficients.

MATERIALS AND METHODS

Chemicals and reagents

D-(+)-maltose monohydrate and sodium saccharin were purchased from Sigma-Aldrich with a purity of 99.0% and used without further purification.

Solution preparation

Solutions were prepared with triply distilled water in airtight glass bottles. Measurements were made using an analytical Dhone balance (± 0.0001 g). Water was the solvent, and saccharide was the solute in both binary and ternary solutions, with sodium saccharin at concentrations of (0.05, 0.15, and 0.3) mol·kg⁻¹ as the stock solution.

Physical measurement

The measurements were conducted in a glass-walled water bath with a constant temperature (± 0.01 K). The densities (ρ) and viscosities (η) of D-(+)-maltose monohydrate in water and in aqueous sodium saccharin were measured by using a Bi-capillary Pycnometer [23-26] and Ubbelohde Viscometer [27-30] at $T = (298.15-313.15)$ K, respectively. The Pycnometer was calibrated with organic solvents, showing good agreement with reported values. The solvent density at the studied temperature was obtained from published data [31, 32].

RESULTS AND DISCUSSION

Volumetric study

At $T = (298.15 \text{ K to } 313.15) \text{ K}$, the density (ρ) of D-(+)-maltose monohydrate in aqueous sodium saccharin were studied. The apparent molar volumes (V_ϕ) of the D-(+)-maltose monohydrate were calculated using an equation [33] that relates molar mass, solution density, and molality.

$$V_\phi = M/\rho - (\rho - \rho_o)/(m\rho\rho_o) \dots (1)$$

The ρ and V_ϕ of D-(+)-maltose monohydrate in water and in aqueous sodium saccharin with molality values of 0.05, 0.15, and 0.3 were measured over temperatures from 298.15 K to 313.15 K are shown in table 1. Results showed that the densities and apparent molar volumes depend on concentration and vary linearly with solute and cosolute concentrations.

Using Masson's equation [34, 35], a relationship between V_ϕ for D-(+)-maltose monohydrate in water and in aqueous sodium saccharin is presented. The partial molar volumes (V_ϕ^0) of D-(+)-maltose monohydrate in water matched well with published data [36] as summarized in table 2.

$$V_\phi = V_\phi^0 + S_v \cdot m \dots (2)$$

The positive V_ϕ^0 values, suggesting significant solute-solvent interactions compared to Masson's coefficients (S_v) representing solute-solute interactions in the binary and ternary system [37, 38]. Fig. 1 show the V_ϕ^0 obtained at experimental temperature for 0.05 m sodium saccharin.

Table 1: Densities ($\rho/\text{kg}\cdot\text{m}^{-3}$), and apparent molar volumes (V_ϕ) of D-(+)-maltose monohydrate) in water and aqueous solutions of (0.05, 0.15, and 0.3) m Na saccharin at $T = (298.15\text{-}313.15) \text{ K}$

m (mol·kg ⁻¹)	(T/K)							
	298.15		303.15		308.15		313.15	
	ρ (kg·m ⁻³)	$V_\phi \cdot 10^6$ (m ³ ·mol ⁻¹)	ρ (kg·m ⁻³)	$V_\phi \cdot 10^6$ (m ³ ·mol ⁻¹)	ρ (kg·m ⁻³)	$V_\phi \cdot 10^6$ (m ³ ·mol ⁻¹)	ρ (kg·m ⁻³)	$V_\phi \cdot 10^6$ (m ³ ·mol ⁻¹)
D-(+)-maltose monohydrate+water								
0.0000	997.05		995.65		994.03		992.22	
0.0405	1002.35	228.52	1000.92	229.41	999.28	230.07	997.45	230.88
0.0806	1007.48	228.81	1006.02	229.71	1004.35	230.50	1002.49	231.32
0.1205	1012.48	229.02	1010.97	230.09	1009.27	230.94	1007.40	231.63
0.1606	1017.38	229.36	1015.80	230.52	1014.12	231.20	1012.21	232.03
0.2005	1022.17	229.56	1020.54	230.89	1018.81	231.62	1016.89	232.38
D-(+)-maltose monohydrate+0.05 m Na saccharin								
0.0000	1001.20		999.69		998.07		997.50	
0.0399	1006.39	229.00	1004.85	229.81	1003.20	230.75	1002.60	231.57
0.0796	1011.44	229.20	1009.88	230.05	1008.19	231.04	1007.56	231.86
0.1199	1016.45	229.53	1014.86	230.36	1013.14	231.37	1012.47	232.28
0.1599	1021.31	229.80	1019.69	230.65	1018.40	231.79	1017.22	232.67
0.1998	1026.06	230.02	1024.90	230.99	1022.58	232.13	1021.86	232.97
D-(+)-maltose monohydrate+0.15 m Na saccharin								
0.0000	1008.57		1007.01		1005.27		1003.39	
0.0405	1013.79	229.38	1012.21	230.15	1010.44	230.95	1008.76	231.78
0.0800	1018.76	229.65	1017.15	230.43	1015.35	231.36	1013.42	232.18
0.1199	1023.68	229.95	1022.03	230.86	1020.21	231.71	1018.25	232.58
0.1598	1028.45	230.41	1026.79	231.21	1024.93	232.15	1022.96	232.92
0.1998	1033.12	230.81	1031.44	231.58	1029.55	232.53	1027.55	233.34
D-(+)-maltose monohydrate+0.3 m Na saccharin								
0.0000	1021.10		1018.32		1016.82		1014.79	
0.0401	1026.20	229.74	1023.39	230.71	1021.86	231.69	1019.80	232.59
0.0805	1031.21	230.08	1028.39	230.97	1026.81	232.04	1024.72	232.99
0.1208	1036.10	230.39	1033.23	231.41	1031.62	232.47	1029.51	233.35
0.1602	1040.75	230.78	1037.85	231.82	1036.21	232.84	1034.07	233.78
0.2004	1045.38	231.17	1042.45	232.21	1040.77	233.27	1038.83	234.18

Partial molar volume, V_ϕ^0 are related to temperature as

$$E^\infty = (\partial V_\phi^0 / \partial T) = a_1 + 2 a_2 T \dots (3)$$

In the above equation a_1 , and a_2 are constants. The expansion coefficient E^∞ can be calculated using the above formula.

As the temperature rises, E^∞ values increase for the given system. The E^∞ outcomes are positive and rise in accordance with increasing cosolute concentration [39] as shown in table 2, suggesting the stronger solute-solvent interactions.

Partial molar volume of transfer at infinite dilution ($\Delta_{tr} V_\phi^0$) is plotted against the molality of sodium saccharin for each studied temperature, suggesting an increase with higher co-solute concentrations [40]. The interactions between D-maltose and aqueous sodium saccharin can be classified into two types:

- I) Hydrophilic-ionic interaction: These take place between cosolute ion and hydrophilic groups of maltose (-C=O, -OH, and -O-).
- II) Hydrophobic-ionic interaction: These take place between the cosolute ion and the hydrophobic group of maltose.

The "co-sphere overlap model"[41-43] states that type (I) interactions positively contribute to the transfer volume ($\Delta_{trs}V_\phi^0$) while type (II) interactions negatively contribute to it. The positive values obtained for the studied system suggest that the type (I) interactions predominate over type (II).

Hepler's constant ($\partial^2 V_\phi^0 / \partial T^2$), data for the studied system are tabulated in table 2 are positive, indicating solute's ability to build structure and it decrease with the increasing sodium saccharin concentration [44, 45].

Aqueous solutions are categorized into salt, sweet, bitter, and sour based on taste, as classified by Shamil and Birch [46]. The apparent specific volume (ASV) of solutes in solvent and cosolute is calculated using the equation $ASV = V_\phi^0 / M$. According to Parke *et al.* [47], the ASV range for sweet molecules is in the range $(0.51 \text{ to } 0.71) \times 10^{-6} \text{ m}^3 \cdot \text{kg}^{-1}$, with an ideal value of $0.618 \times 10^{-6} \text{ m}^3 \cdot \text{kg}^{-1}$. The table 2 shows the ASV values for studied system. For maltose, the ASV values ranged from 0.634 to $0.644 \times 10^{-6} \text{ m}^3 \cdot \text{kg}^{-1}$. The maltose retained their sweetness when mixed with sodium saccharin stock solutions.

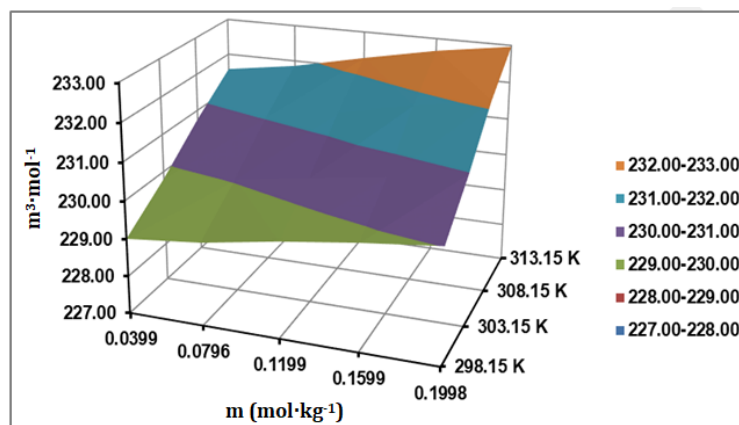


Fig. 1: Variation of V_ϕ ($\text{m}^3 \cdot \text{mol}^{-1}$) of D-(+)-maltose monohydrate in sodium saccharin with molality 0.05 m ($\text{mol} \cdot \text{kg}^{-1}$)

Table 2: (V_ϕ^0), (S_v), E^∞ , ASV, ($\partial^2 V_\phi^0 / \partial T^2$)_p, and ($\Delta_{trs}V_\phi^0$) of disaccharide, D-(+)-maltose monohydrate in water and aqueous Na saccharin (0.05, 0.15, and 0.3) m ($\text{mol} \cdot \text{kg}^{-1}$) at $T = (298.15, 303.15, 308.15, \text{ and } 313.15) \text{ K}$

System	Parameters	(T/K)			
		298.15	303.15	308.15	313.15
D-(+)-maltose monohydrate+water	$10^6 \cdot (V_\phi^0)$	228.262	228.985	229.717	230.526
	$10^6 \cdot (S_v)$	6.58	9.44	9.52	9.30
	$10^7 \cdot E^\infty$	0.1376	0.1462	0.1547	0.1633
	$10^6 \cdot \text{ASV}$	0.634	0.636	0.638	0.640
	$10^8 \cdot (\partial^2 V_\phi^0 / \partial T^2)_p$	0.001715			
D-(+)-maltose monohydrate + 0.05 m Na saccharin	$10^6 \cdot (V_\phi^0)$	228.723	229.482	230.363	231.188
	$10^6 \cdot (S_v)$	6.560	7.410	8.793	9.010
	$10^7 \cdot E^\infty$	0.1555	0.1622	0.1688	0.1755
	$10^6 \cdot \text{ASV}$	0.635	0.637	0.639	0.642
	$10^6 \cdot (\Delta_{trs}V_\phi^0)$	0.460	0.497	0.645	0.662
D-(+)-maltose monohydrate+ 0.15 m Na saccharin	$10^8 \cdot (\partial^2 V_\phi^0 / \partial T^2)_p$	0.001329			
	$10^6 \cdot (V_\phi^0)$	228.949	229.749	230.544	231.397
	$10^6 \cdot (S_v)$	9.10	9.13	9.94	9.68
	$10^7 \cdot E^\infty$	0.1550	0.1602	0.1654	0.1707
	$10^6 \cdot \text{ASV}$	0.635	0.638	0.640	0.642
D-(+)-maltose monohydrate+ 0.3 m Na saccharin	$10^6 \cdot (\Delta_{trs}V_\phi^0)$	0.686	0.764	0.827	0.872
	$10^8 \cdot (\partial^2 V_\phi^0 / \partial T^2)_p$	0.001047			
	$10^6 \cdot (V_\phi^0)$	229.362	230.264	231.272	232.184
	$10^6 \cdot (S_v)$	8.88	9.63	9.89	9.92
	$10^7 \cdot E^\infty$	0.1880	0.1889	0.1899	0.1909
	$10^6 \cdot \text{ASV}$	0.637	0.639	0.642	0.644
	$10^6 \cdot (\Delta_{trs}V_\phi^0)$	1.100	1.279	1.554	1.658
	$10^8 \cdot (\partial^2 V_\phi^0 / \partial T^2)_p$	0.000197			

Volumetric study

The viscosities (η) of D-(+)-maltose monohydrate in water and aqueous sodium saccharin were measured at temperatures (298.15, 303.15, 308.15, and 313.15) K and concentrations ($m = 0.05, 0.15, \text{ and } 0.30$). The result indicates that viscosity decreases with increasing temperature but increases as the co-solute concentration (sodium saccharin) rises. The relative viscosities (η_r) were calculated by comparing the viscosity in the ternary

solution, η (maltose+sodium saccharin+water), to that in the solvent mixture (sodium saccharin+water) η_0 , as shown in table 3. These values were then used to calculate B -coefficients using the Jones-Dole equation [48-50] as:

$$\eta_r = \eta/\eta_0 = 1 + BC \dots\dots (5)$$

The B -coefficients, which characterize solute-solvent interactions, were determined from the slope of relative viscosity versus molality plots. The B -coefficients for the studied system at the different temperatures showed a decrease as temperature increased (table 4), suggesting the solute (maltose) contributes to structure formation due to the ordered hydrogen-bonded structure around it [51]. Fig. 2 shows the variation of relative viscosity, η_r of maltose monohydrate in Na saccharin with molality 0.05 m (mol·kg⁻¹). Similar results were obtained for (0.15 and 0.30) m sodium saccharin. Positive B -coefficient values indicate stronger solute-solvent interactions compared to solute-solute interactions. The results also provide insight into the ion solvation behaviour and the ability of solutes to form structures.

The dB/dT ratio is an important factor in determining a solute's capacity to form or break structures derived from temperature-dependent B -coefficients [52]. Table 4 shows the dB/dT values for the studied saccharide in both water and aqueous sodium saccharin at studied concentrations and temperatures. The negative dB/dT values observed for studied systems suggest that the solute is more likely to form structures [53].

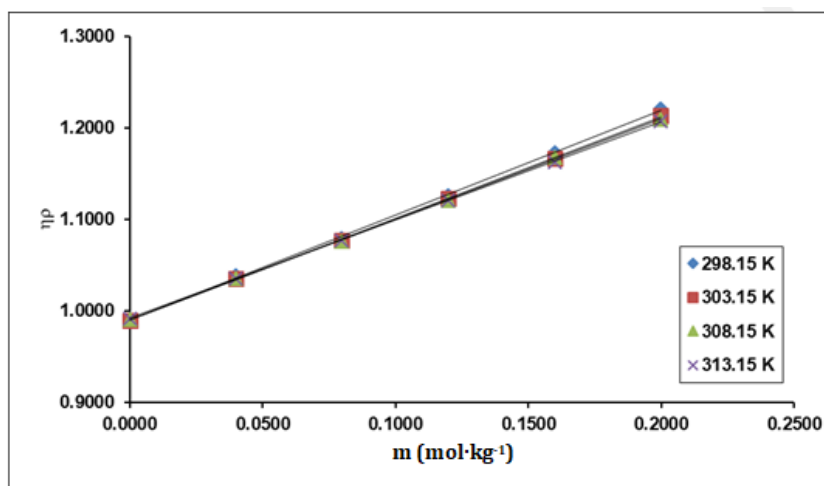


Fig. 2: Variation of relative viscosity, η_r of maltose monohydrate in Na saccharin with molality 0.05 m (mol·kg⁻¹)

Table 3: Viscosities (η /mPa·s), and relative viscosities (η_r) of disaccharide, D-(+)-maltose monohydrate in H₂O and aqueous solutions of (0.05, 0.15, and 0.3) m Na saccharin at $T = (298.15, 303.15, 308.15, \text{ and } 313.15) \text{ K}$

m (mol·kg ⁻¹)	η (T/K)	η_r						
	298.15	303.15	308.15	313.15	298.15	303.15	308.15	313.15
D-(+)-maltose monohydrate+H ₂ O								
0.0000	0.8900	0.7972	0.7191	0.6527	0.9898	0.9916	0.9906	0.9903
0.0405	0.9243	0.8279	0.7449	0.6757	1.0385	1.0386	1.0358	1.0352
0.0806	0.9594	0.8583	0.7736	0.7019	1.0780	1.0767	1.0758	1.0754
0.1205	0.9995	0.8928	0.8020	0.7273	1.1230	1.1200	1.1153	1.1142
0.1606	1.0377	0.9260	0.8331	0.7543	1.1660	1.1615	1.1585	1.1556
0.2005	1.0845	0.9664	0.8675	0.7870	1.2186	1.2122	1.2063	1.2057
D-(+)-maltose monohydrate+0.05 <i>m</i> Na saccharin								
0.0000	0.9071	0.8040	0.7187	0.6582	0.9907	0.9900	0.9906	0.9923
0.0399	0.9421	0.8328	0.7446	0.6814	1.0386	1.0358	1.0360	1.0353
0.0796	0.9795	0.8660	0.7735	0.7093	1.0798	1.0771	1.0762	1.0776
0.1199	1.0213	0.9026	0.8053	0.7380	1.1259	1.1226	1.1205	1.1212
0.1599	1.0644	0.9383	0.8393	0.7653	1.1734	1.1670	1.1677	1.1627
0.1998	1.1071	0.9754	0.8693	0.7945	1.2204	1.2132	1.2095	1.2071
D-(+)-maltose monohydrate+0.15 <i>m</i> Na saccharin								
0.0000	0.9309	0.8372	0.7455	0.6772	0.9952	0.9938	0.9908	0.9924
0.0405	0.9734	0.8734	0.7747	0.7030	1.0456	1.0433	1.0391	1.0381
0.0800	1.0135	0.9069	0.8042	0.7303	1.0887	1.0832	1.0787	1.0783
0.1199	1.0572	0.9457	0.8402	0.7589	1.1357	1.1296	1.1270	1.1207
0.1598	1.0995	0.9820	0.8698	0.7854	1.1811	1.1730	1.1667	1.1598
0.1998	1.1500	1.0266	0.9095	0.8209	1.2354	1.2263	1.2200	1.2121
D-(+)-maltose monohydrate+0.3 <i>m</i> Na saccharin								
0.0000	0.9738	0.8722	0.7817	0.7099	0.9969	0.9953	0.9944	0.9938
0.0401	1.0195	0.9112	0.8157	0.7383	1.0469	1.0447	1.0435	1.0399
0.0805	1.0645	0.9488	0.8477	0.7674	1.0932	1.0878	1.0843	1.0810
0.1208	1.1108	0.9892	0.8824	0.7991	1.1406	1.1341	1.1288	1.1256
0.1602	1.1600	1.0311	0.9203	0.8311	1.1912	1.1822	1.1773	1.1706
0.2004	1.2071	1.0743	0.9580	0.8632	1.2396	1.2317	1.2255	1.2158

Table 4: Viscosity B -coefficients, and dB/dT , of disaccharide, D-(+)-maltose monohydrate in water and aqueous solutions of (0.05, 0.15, and 0.3) m Na saccharin at $T = (298.15, 303.15, 308.15, \text{ and } 313.15) \text{ K}$

System	Parameters	(T/K)			
		298.15	303.15	308.15	313.15
D-(+)-maltose monohydrate+ water	B	1.120	1.080	1.059	1.053
	dB/dT	-0.0044			
D-(+)-maltose monohydrate+ 0.05 m Na saccharin	B	1.143	1.111	1.096	1.072
	dB/dT	-0.0046			
D-(+)-maltose monohydrate+ 0.15 m Na saccharin	B	1.185	1.144	1.129	1.078
	dB/dT	-0.0067			
D-(+)-maltose monohydrate+ 0.3 m Na saccharin	B	1.208	1.170	1.142	1.103
	dB/dT	-0.0068			

CONCLUSION

The study explores the use of a blend of D-(+)-maltose monohydrate and sodium saccharin as an alternative to sweeteners to improve taste and stability in sweetened compositions. The volumetric and viscometric properties of D-(+)-maltose monohydrate in water and aqueous sodium saccharin were measured at temperatures ranging from 298.15 K to 313.15 K. The thermodynamic parameters, such as V_ϕ , V_ϕ^0 , S_ϕ , E^∞ , $\Delta_{\text{trs}} V_\phi^0$, ASV, B , and dB/dT were calculated from the experimental data. The findings suggest that transfer occurs from water to aqueous sodium saccharin, with the transfer volume increasing as the concentration of the cosolute rises. Additionally, the sweetness of the studied disaccharide was preserved $(0.634\text{--}0.644)10^{-6} \text{ m}^3 \cdot \text{kg}^{-1}$ when blended with sodium saccharin. The solute (D-(+)-maltose monohydrate) can form structures in water and at various concentrations of aqueous sodium saccharin system, as shown by positive B -coefficient and negative dB/dT values.

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Nil

AUTHORS CONTRIBUTIONS

Prajakta Jondhale: Interpretation of data, and Drafting of the manuscript. Valmik Jondhale: Analysis of the results and final manuscript.

CONFLICT OF INTERESTS

The authors declare no conflict of interest among the author.

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