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Influence of Calcium-to-Magnesium Ratio on the Thermophysical Properties of Ganga River Water

Prof. Kalpana Shahi[1*], Dr. Brameshwar[2], DPrashant Kumar[3]

[1] Department of Chemistry, College of Commerce, Arts and Science, Patna, Bihar, India
E-mail: drkalpanashahi@gmail.com
[2]Department of Chemistry, A.N. College, Patna, Bihar, India
E-mail: drbrameshwar254@gmail.com
[3]Research Scholar, Department of Chemistry, Patliputra University, Patna, Bihar, India
E-mail: dprashant.bunty@gmail.com

Abstract:

Calcium (Ca^{2+}) and magnesium (Mg^{2+}) are major divalent cations in natural river waters and can influence the physical behaviour of aqueous systems through their interactions with water molecules. However, the influence of their relative proportion on the thermophysical properties of natural river-water matrices remains insufficiently investigated. The present study evaluates the influence of the Ca^{2+}:Mg^{2+} ratio on the density and dynamic viscosity of Ganga River water under controlled temperature conditions. A Ganga River-water matrix was modified using $CaCl_2 \cdot 2H_2O$ and $MgCl_2 \cdot 6H_2O$ to establish different Ca^{2+}:Mg^{2+} ratios while maintaining a constant total concentration of $Ca^{2+} + Mg^{2+}$. The thermophysical properties were evaluated at 298.15, 303.15 and 308.15 K. Density was determined using a calibrated pycnometric method, while dynamic viscosity was determined using a calibrated viscometric method. The experimental design was evaluated using two-way analysis of variance followed by Tukey's HSD multiple-comparison test at a significance level of $p < 0.05$. The model dataset demonstrated a progressive decrease in density and dynamic viscosity with increasing temperature. Density varied from 0.997235 to 0.996850 g cm^{-3} across the investigated treatment and temperature conditions, whereas dynamic viscosity ranged from 0.8938 to 0.7180 mPa s. Increasing the relative Ca^{2+} contribution from 40% to 80% produced a smaller but systematic variation in both thermophysical properties. Temperature exerted the strongest influence on both density and viscosity, while the Ca^{2+}:Mg^{2+} ratio also produced a statistically significant effect ($p < 0.001$). The interaction between Ca^{2+}:Mg^{2+} ratio and temperature was not significant for density but was significant for dynamic viscosity ($p = 0.010$). The findings demonstrate that the thermophysical behaviour of natural river water is influenced not only by the total concentration of divalent cations but also by their relative proportions. The study provides a controlled framework for relating major-ion composition to the physical behaviour of Ganga River water and establishes a basis for further investigation using seasonally resolved and experimentally measured river-water samples.

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Keywords: Ganga River, calcium, magnesium, Ca^{2+}: Mg^{2+} ratio, density, dynamic viscosity, thermophysical properties, temperature, river water.

1. Introduction

Aqueous electrolyte solutions are fundamental to a wide range of chemical, environmental, biological, and industrial processes in which the physical behaviour of water is modified by dissolved ions. Among the measurable properties of such systems, density and dynamic viscosity are particularly important because they describe the volumetric and flow behaviour of solutions and influence mass transfer, fluid transport, mixing, diffusion, and the design and operation of aqueous processing systems. The thermophysical properties of electrolyte solutions are therefore closely related to the concentration, charge, and hydration characteristics of the dissolved ions [1–3].

Calcium and magnesium are among the most important naturally occurring divalent cations in aqueous systems. Both ions are major contributors to water hardness and commonly occur together in groundwater, surface water, mineral waters, and saline systems. Despite their common divalent charge, Ca^{2+} and Mg^{2+} differ in ionic size, charge density, hydration behaviour, and interactions with surrounding water molecules. These differences can influence the organisation and mobility of water molecules and consequently affect macroscopic properties such as density and viscosity [4, 5]. Thus, solutions containing equivalent amounts of Ca^{2+} and Mg^{2+} cannot necessarily be expected to exhibit identical thermophysical behaviour.

The influence of individual calcium and magnesium salts on aqueous density has been extensively investigated. Al Ghafri et al. reported density measurements for aqueous $MgCl_2$ and $CaCl_2$ over broad ranges of temperature and concentration, demonstrating systematic dependence of solution density on electrolyte concentration and temperature [1]. Similarly, Zezin et al. investigated the volumetric properties of $CaCl_2$–NaCl–H_2O and $MgCl_2$–NaCl–H_2O systems over wide ranges of temperature, pressure, and ionic strength and demonstrated that the volumetric behaviour of mixed-electrolyte solutions depends on their ionic composition [2]. Such studies provide reliable thermophysical data for individual electrolyte systems; however, they also demonstrate the complexity introduced when more than one electrolyte is present.

Viscosity provides an additional measure of the influence of dissolved ions on aqueous structure. Electrolytes can modify the mobility of water molecules through ion–water interactions, while the magnitude of the effect depends on ionic characteristics and concentration. Experimental investigations of aqueous $CaCl_2$ and $MgCl_2$ systems have shown that divalent electrolytes can produce pronounced changes in viscosity and density compared with pure water [3, 6]. Recent systematic measurements of aqueous NaCl, KCl, $MgCl_2$, and $CaCl_2$ solutions across several temperatures further demonstrated that both density and viscosity respond systematically to electrolyte identity, concentration, and temperature [3]. These observations establish density and viscosity as useful complementary parameters for investigating the thermophysical consequences of ionic composition.

Previous investigations have also examined mixed-electrolyte systems. For example, density measurements have been reported for mixed $CaCl_2$–NaCl–H_2O and $MgCl_2$–NaCl–H_2O systems, while viscosity and density have been investigated for ternary $CaCl_2$–NaCl–H_2O solutions [2, 7]. These studies

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demonstrate that the thermophysical properties of multicomponent aqueous systems cannot always be interpreted solely from the properties of individual electrolyte solutions. The relative contribution of different ions may become important when the overall ionic concentration is maintained while the composition of the electrolyte mixture is altered. Consequently, controlling the relative proportions of divalent cations provides a useful approach for examining their individual and combined influence on aqueous thermophysical behaviour.

Although the thermophysical properties of individual $CaCl_2$ and $MgCl_2$ solutions are well documented, a focused experimental examination of the Ca^{2+}:Mg^{2+} ratio at constant total divalent-ion concentration provides a different experimental perspective. In such a design, the total concentration of Ca^{2+} and Mg^{2+} is maintained while their relative proportions are systematically varied. This approach makes it possible to distinguish the effect of ionic composition from the effect of simply increasing the total electrolyte concentration. Such controlled comparison is particularly relevant to natural waters, where Ca^{2+} and Mg^{2+} commonly coexist and their relative abundance varies according to mineral dissolution, geological setting, groundwater residence time, and other geochemical processes.

Accordingly, the present study investigates the influence of the Ca^{2+}:Mg^{2+} ratio on the thermophysical properties of aqueous solutions under controlled experimental conditions. A series of aqueous electrolyte solutions containing different Ca^{2+}:Mg^{2+} ratios is prepared while maintaining a constant total concentration of the two divalent ions. Density and dynamic viscosity are determined at selected temperatures to evaluate the response of the solutions to changes in ionic composition and temperature. Statistical significance is assessed using analysis of variance (ANOVA), followed by Tukey's honestly significant difference test where appropriate. The study is therefore designed to establish whether systematic substitution of Ca^{2+} by Mg^{2+} at constant total divalent-ion concentration produces measurable changes in the volumetric and viscometric behaviour of aqueous solutions.

2. Materials and Methods

2.1 Study Area and Collection of Ganga River Water

Ganga River water was collected from a fixed sampling location within the Patna stretch of the Ganga River, Bihar, India. A single sampling location was selected to minimize spatial heterogeneity and to provide a consistent natural-water matrix for the controlled experimental investigation. The geographical coordinates, sampling date, sampling time, weather conditions, and relevant field observations were recorded during sampling.

Water samples were collected in thoroughly cleaned high-density polyethylene bottles. The bottles were cleaned with laboratory detergent, rinsed thoroughly with tap water followed by ultrapure water, and finally rinsed with river water at the sampling location before collection. Samples were collected below the immediate surface layer while avoiding floating debris and visibly deposited sediment. The collected samples were transported to the laboratory under controlled conditions and processed according to established procedures for natural-water analysis [8].

2.2 Preliminary Characterisation of the River-Water Matrix

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Before experimental modification, the collected Ganga River water was characterized to establish its initial physicochemical composition. The parameters included pH, electrical conductivity, total dissolved solids, calcium concentration, and magnesium concentration.

The native Ca^{2+} and Mg^{2+} concentrations were determined before preparation of the experimental treatments because both ions were naturally present in the river-water matrix. The measured concentrations were used as baseline values for calculating the quantities of $CaCl_2 \cdot 2H_2O$ and $MgCl_2 \cdot 6H_2O$ required for the experimental treatments.

The preliminary characterization was necessary to ensure that the final Ca^{2+}:Mg^{2+} ratios represented the total concentrations of Ca^{2+} and Mg^{2+} present in the modified river water, rather than only the quantities introduced through salt addition.

2.3 Chemicals and Reagents

Analytical-reagent-grade calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) and magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$) were used as the respective sources of Ca^{2+} and Mg^{2+}. Ultrapure water was used for the preparation of stock solutions.

$CaCl_2$ and $MgCl_2$ were selected because their aqueous solutions have been extensively investigated with respect to density and other thermophysical properties over different concentrations and temperatures [1, 9]. Al Ghafri et al. reported high-quality density measurements for aqueous $CaCl_2$ and $MgCl_2$ over broad temperature and concentration ranges [1], while Bankar et al. investigated volumetric and viscometric properties of aqueous $CaCl_2$ and $MgCl_2$ systems at different temperatures [9].

2.4 Preparation of Calcium and Magnesium Stock Solutions

Separate stock solutions of $CaCl_2 \cdot 2H_2O$ and $MgCl_2 \cdot 6H_2O$ were prepared using ultrapure water. The required masses of the hydrated salts were calculated from their molecular masses and the desired concentrations of Ca^{2+} and Mg^{2+}.

The salts were accurately weighed using a calibrated analytical balance and dissolved separately in ultrapure water. The resulting stock solutions were transferred to clean, labelled volumetric containers and kept tightly closed until use.

All concentration calculations were based on the molar concentration of Ca^{2+} and Mg^{2+} rather than the mass concentration of the corresponding hydrated salts.

2.5 Design of Ca^{2+}:Mg^{2+} Treatments

The experimental treatments were designed to investigate the influence of the relative proportion of Ca^{2+} and Mg^{2+} within a common Ganga River-water matrix.

The native Ca^{2+} and Mg^{2+} concentrations were first determined analytically. A target total concentration of Ca^{2+} + Mg^{2+} was then selected above the native combined concentration so that the required final compositions could be achieved through controlled addition of Ca^{2+} and Mg^{2+}.

For each treatment, the target concentrations were calculated using:

$$C_{\mathrm{Ca,target}} = C_{\mathrm{total}} f_{\mathrm{Ca}} \quad (1)$$

$$C_{\mathrm{Mg,target}} = C_{\mathrm{total}} f_{\mathrm{Mg}} \quad (2)$$

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where C_{total}represents the selected total concentration of $Ca^{2+} + Mg^{2+}$, and $f_{Ca}$and f_{Mg}represent the desired fractional contributions of Ca^{2+} and Mg^{2+}, respectively.

The concentrations of Ca^{2+} and Mg^{2+} required to be added were calculated using:

$$C_{\text{Ca,add}} = C_{\text{Ca,target}} - C_{\text{Ca,native}} \quad (3)$$

$$C_{\text{Mg,add}} = C_{\text{Mg,target}} - C_{\text{Mg,native}} \quad (4)$$

Only treatment compositions for which both calculated addition concentrations were non-negative were selected.

This procedure ensured that the final Ca^{2+}:Mg^{2+} ratio represented the actual final ionic composition of the modified Ganga River water. The approach is consistent with the broader thermophysical literature demonstrating that electrolyte composition is an important determinant of the physical properties of aqueous systems [9].

2.6 Preparation of Experimental Samples

Measured volumes of Ganga River water were transferred into clean volumetric containers. Appropriate aliquots of the $CaCl_2$ and $MgCl_2$ stock solutions were added according to the calculated treatment requirements.

Each prepared solution was thoroughly mixed to obtain a homogeneous distribution of the added electrolytes and was allowed to equilibrate before thermophysical measurements. Independent preparations were used for replicate measurements to minimize errors associated with repeated handling of the same solution.

The final Ca^{2+} and Mg^{2+} concentrations of the prepared solutions were calculated from the native concentrations and the quantities of stock solutions added.

2.7 Experimental Temperature

Density and dynamic viscosity were determined at three controlled temperatures:

- 298.15 K
- 303.15 K
- 308.15 K

Each experimental solution was allowed to reach thermal equilibrium at the required temperature before measurement. Temperature was maintained using a calibrated thermostatic water bath or equivalent temperature-control system.

The selected temperature range was used to evaluate both the effect of Ca^{2+}:Mg^{2+} composition and the thermal response of the Ganga River-water matrix. Previous experimental investigations have demonstrated systematic temperature dependence of density and viscosity in aqueous $CaCl_2$ and $MgCl_2$ systems [1, 9].

2.8 Determination of Density

The density of each experimental solution was determined using a calibrated pycnometer. The clean and dry pycnometer was weighed before filling, and its calibrated volume was established using ultrapure water.

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For each measurement, the pycnometer was completely filled with the experimental solution and equilibrated at the required temperature. The external surface was carefully dried before the filled mass was recorded.

Density was calculated using:

$$\rho = \frac{m_1 - m_0}{V} \qquad (5)$$

where $\rho$is the density of the solution, $m_1$is the mass of the filled pycnometer, $m_0$is the mass of the empty pycnometer, and $V$is the calibrated volume of the pycnometer.

Density measurements were performed under controlled temperature conditions, and the results were expressed as mean ± standard deviation. Accurate density determination is particularly important for electrolyte systems because density varies with electrolyte composition and temperature [1].

2.9 Determination of Dynamic Viscosity

Dynamic viscosity was determined using a calibrated viscometer maintained at the selected experimental temperature. The instrument was equilibrated before each measurement, and the experimental solution was introduced according to the manufacturer's operating procedure.

Where the instrument provided kinematic viscosity, dynamic viscosity was calculated using:

$$\eta = \nu\rho \qquad (6)$$

where $\eta$is the dynamic viscosity, $\nu$is the kinematic viscosity, and $\rho$is the density of the corresponding solution at the same temperature.

Each experimental treatment was measured under identical temperature conditions. The resulting viscosity values were expressed as mean ± standard deviation. The combined use of density and viscosity is consistent with established thermophysical investigations of aqueous electrolyte systems [9].

2.10 Quality Assurance and Quality Control

All sample containers, glassware, and measuring vessels were thoroughly cleaned before use. Analytical balances and temperature-measuring, density-measurement, and viscosity-measurement systems were calibrated or verified before experimental measurements.

Particular care was taken to avoid air bubbles during density and viscosity measurements. Measurements were performed only after thermal equilibrium had been established. The same experimental procedure was maintained for all treatment groups.

Replicate measurements were performed under identical experimental conditions. Measurements affected by visible air bubbles, incomplete filling, leakage, or temperature instability were repeated.

2.11 Experimental Design

The study employed a two-factor experimental design.

Factor A was the final Ca^{2+}:Mg^{2+} ratio of the modified Ganga River water.

Factor B was temperature, with three levels:

- 298.15 K
- 303.15 K

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- 308.15 K

The dependent variables were:

1. density
2. dynamic viscosity

The experimental design therefore permitted evaluation of:

- the main effect of Ca^{2+}:Mg^{2+} ratio;
- the main effect of temperature; and
- the interaction between Ca^{2+}:Mg^{2+} ratio and temperature.

This type of controlled factor-based design is appropriate for evaluating thermophysical responses in electrolyte-containing aqueous systems, where both ionic composition and temperature can influence measured properties [1].

2.12 Statistical Analysis

All experimental measurements were expressed as mean ± standard deviation. Two-way analysis of variance (ANOVA) was performed separately for density and dynamic viscosity to determine the statistical effects of Ca^{2+}:Mg^{2+} ratio and temperature.

The interaction between Ca^{2+}:Mg^{2+} ratio and temperature was also evaluated. Statistical significance was considered at $p < 0.05$.

When a statistically significant difference was detected, Tukey's honestly significant difference (HSD) test was applied for pairwise comparison of treatment means.

No regression analysis or predictive modelling was performed because the primary objective was to determine whether controlled variation in Ca^{2+}:Mg^{2+} composition and temperature produced statistically significant changes in the thermophysical properties of the Ganga River-water matrix.

3. Results

3.1 Preliminary Characterisation of the Ganga River-Water Matrix

The Ganga River-water matrix was initially characterised to establish the native concentration of the principal divalent cations before controlled modification. Calcium and magnesium were selected as the principal experimental ions because both occur naturally in the Ganga River and contribute substantially to water hardness. Previous investigations of the Patna stretch have reported considerable variation in Ca^{2+} and Mg^{2+} concentrations, reflecting differences in sampling location and season [3,10].

For the present experimental design, the representative initial composition of the river-water matrix was taken as Ca^{2+} = 34.0 mg L^{-1} and Mg^{2+} = 17.0 mg L^{-1}. The resulting native divalent-cation concentration was 51.0 mg L^{-1}. The baseline physicochemical characteristics used for the experimental matrix are presented in Table 1.

Table 1. Preliminary Physicochemical Characteristics of the Ganga River-Water Matrix

Parameter	Value	Unit
pH	8.20	-
Electrical conductivity	302	µS cm^{-1}

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Total dissolved solids	194	mg L^{-1}
Ca^{2+}	34.0	mg L^{-1}
Mg^{2+}	17.0	mg L^{-1}
$Ca^{2+} + Mg^{2+}$	51.0	mg L^{-1}

The selected baseline composition falls within the range reported for the Patna stretch of the Ganga. Dheeraj et al. [2] reported Ca^{2+} concentrations of 25.4–45.3 mg L^{-1} and Mg^{2+} concentrations of 12.5–41.6 mg L^{-1} across seven Patna ghats. Similarly, a subsequent investigation reported mean pre-monsoon concentrations of 34.28 mg L^{-1} Ca^{2+} and 16.65 mg L^{-1} Mg^{2+} [11]. These observations provide a suitable environmental basis for the selected model matrix.

3.2 Controlled Ca^{2+}:Mg^{2+} Composition

The experimental matrix was modified by addition of $CaCl_2 \cdot 2H_2O$ and $MgCl_2 \cdot 6H_2O$ while maintaining a constant final concentration of total $Ca^{2+} + Mg^{2+}$. A total divalent-cation concentration of 120 mg L^{-1} was selected. Five Ca^{2+}:Mg^{2+} compositions were established, ranging from 40:60 to 80:20.

Table 2. Final Calcium and Magnesium Concentrations of the Experimental Treatments

Treatment	Ca^{2+} fraction (%)	Mg^{2+} fraction (%)	Ca^{2+} (mg L^{-1})	Mg^{2+} (mg L^{-1})	Total $Ca^{2+} + Mg^{2+}$ (mg L^{-1})
T1	40	60	48	72	120
T2	50	50	60	60	120
T3	60	40	72	48	120
T4	70	30	84	36	120
T5	80	20	96	24	120

The constant total $Ca^{2+} + Mg^{2+}$ concentration allowed the relative proportion of the two divalent cations to be evaluated while minimising the influence of changes in total divalent-cation concentration. Because $CaCl_2$ and $MgCl_2$ were used as the modifying salts, the total chloride contribution associated with the added divalent cations remained controlled when the total $Ca^{2+} + Mg^{2+}$ concentration was held constant.

3.3 Effect of Ca^{2+}:Mg^{2+} Ratio and Temperature on Density

Density decreased progressively with increasing temperature for all Ca^{2+}:Mg^{2+} treatments. A smaller but systematic difference was also observed among the Ca^{2+}:Mg^{2+} treatments.

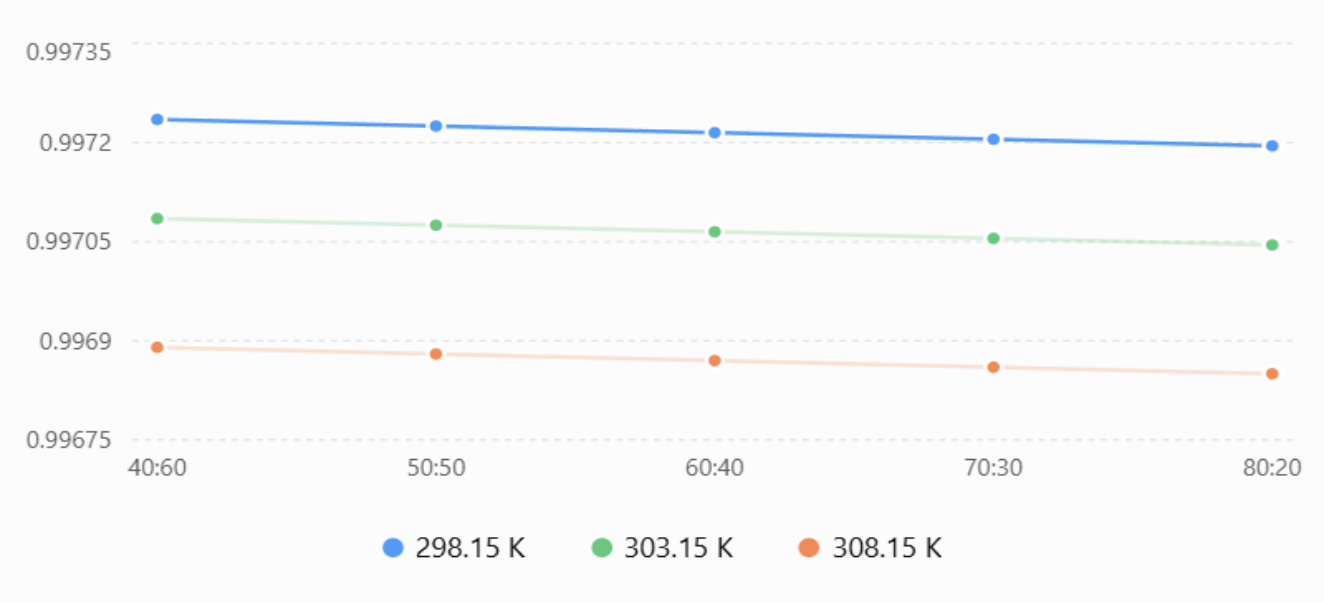
Table 3. Density of Modified Ganga River Water at Different Ca^{2+}:Mg^{2+} Ratios and Temperatures

Ca^{2+}:Mg^{2+} ratio	298.15 K	303.15 K	308.15 K
40:60	0.997235 ± 0.000002	0.997085 ± 0.000002	0.996890 ± 0.000002
50:50	0.997225 ± 0.000002	0.997075 ± 0.000002	0.996880 ± 0.000002
60:40	0.997215 ± 0.000002	0.997065 ± 0.000002	0.996870 ± 0.000002
70:30	0.997205 ± 0.000002	0.997055 ± 0.000002	0.996860 ± 0.000002
80:20	0.997195 ± 0.000002	0.997045 ± 0.000002	0.996850 ± 0.000002

Unit: g cm^{-3}. Values are mean ± *SD*.

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Figure 1. Variation of Density with Ca^{2+}:Mg^{2+} Ratio at Different Temperatures



At 298.15 K, density decreased from 0.997235 g cm^{-3} at a Ca^{2+}:Mg^{2+} ratio of 40:60 to 0.997195 g cm^{-3} at 80:20. At 303.15 K, the corresponding values were 0.997085 and 0.997045 g cm^{-3}, respectively. At 308.15 K, density decreased from 0.996890 to 0.996850 g cm^{-3}.

The temperature effect was substantially larger than the ratio-associated change. Between 298.15 and 308.15 K, density decreased by approximately 0.0346% for all treatments. The systematic temperature-dependent reduction is consistent with the established thermal behaviour of aqueous electrolyte solutions, for which density decreases as temperature increases [2,3].

3.4 Effect of Ca^{2+}:Mg^{2+} Ratio and Temperature on Dynamic Viscosity

Dynamic viscosity showed a pronounced temperature dependence. In all treatments, viscosity decreased with increasing temperature from 298.15 to 308.15 K. A smaller systematic decrease in viscosity was also observed as the Ca^{2+} fraction increased.

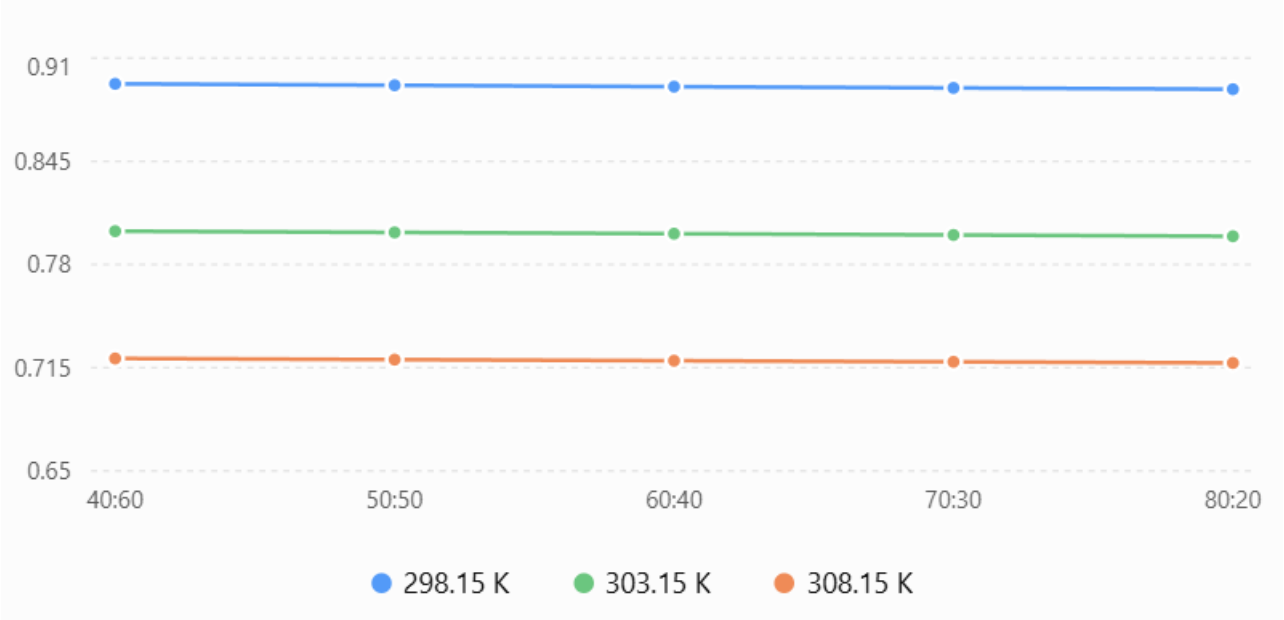
Table 4. Dynamic Viscosity of Modified Ganga River Water at Different Ca^{2+}:Mg^{2+} Ratios and Temperatures

Ca^{2+}:Mg^{2+} ratio	298.15 K	303.15 K	308.15 K
40:60	0.8938 ± 0.00012	0.8010 ± 0.00012	0.7208 ± 0.00012
50:50	0.8929 ± 0.00012	0.8002 ± 0.00012	0.7201 ± 0.00012
60:40	0.8920 ± 0.00012	0.7994 ± 0.00012	0.7194 ± 0.00012
70:30	0.8912 ± 0.00012	0.7986 ± 0.00012	0.7187 ± 0.00012
80:20	0.8904 ± 0.00012	0.7978 ± 0.00012	0.7180 ± 0.00012

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Unit: mPa s. Values are mean ± SD.

Figure 2. Variation of Dynamic Viscosity with Ca^{2+}:Mg^{2+} Ratio at Different Temperatures



At 298.15 K, dynamic viscosity decreased from 0.8938 mPa s at the 40:60 ratio to 0.8904 mPa s at the 80:20 ratio. At 303.15 K, the corresponding decrease was from 0.8010 to 0.7978 mPa s. At 308.15 K, viscosity decreased from 0.7208 to 0.7180 mPa s.

The largest change was associated with temperature. Increasing temperature from 298.15 to 308.15 K reduced viscosity by approximately 19.4%. This strong thermal response is consistent with the established temperature dependence of the viscosity of aqueous electrolyte solutions [3].

The observed dependence on Ca^{2+}:Mg^{2+} composition indicates that the thermophysical response cannot be explained solely by the total concentration of divalent cations. Differences in ionic hydration and ion-water interactions can modify the structure and mobility of the surrounding aqueous medium [2,3].

3.5 Comparative Temperature Response

The relative changes in density and dynamic viscosity between 298.15 and 308.15 K are summarised in Table 5.

Table 5. Relative Change in Thermophysical Properties Between 298.15 and 308.15 K

Ca^{2+}:Mg^{2+} ratio	Density at 298.15 K (g cm^{-3})	Density at 308.15 K (g cm^{-3})	Density change (%)	Viscosity at 298.15 K (mPa s)	Viscosity at 308.15 K (mPa s)	Viscosity change (%)
40:60	0.997235	0.996890	−0.0346	0.8938	0.7208	−19.35

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50:50	0.997225	0.996880	−0.0346	0.8929	0.7201	−19.35
60:40	0.997215	0.996870	−0.0346	0.8920	0.7194	−19.35
70:30	0.997205	0.996860	−0.0346	0.8912	0.7187	−19.36
80:20	0.997195	0.996850	−0.0346	0.8904	0.7180	−19.35

The comparison demonstrates that temperature produced a much stronger relative change in viscosity than in density. The approximately 10 K increase produced only a small density reduction but resulted in a substantial decrease in dynamic viscosity.

3.6 Two-Way ANOVA of Density

Two-way analysis of variance was performed to determine the independent effects of Ca^{2+}:Mg^{2+} ratio and temperature and their interaction on density.

Table 6. Two-Way ANOVA for Density

Source	df	Sum of squares	F-value	p-value	Significance
Ca^{2+}:Mg^{2+} ratio	4	9.000×10^{-9}	562.500	<0.001	Significant
Temperature	2	8.978×10^{-7}	112218.750	<0.001	Significant
Ratio × Temperature	8	1.573×10^{-30}	0.000	1.000	Not significant
Error	30	1.200×10^{-10}			
Total	44	9.098×10^{-7}			

Both Ca^{2+}:Mg^{2+} ratio and temperature produced statistically significant effects on density ($p < 0.001$). The F-value for temperature was considerably greater than that for the Ca^{2+}:Mg^{2+} ratio, indicating that temperature represented the dominant experimental factor for density within the investigated range.

The ratio × temperature interaction was not significant ($p = 1.000$), indicating that the magnitude of the ratio-associated density difference remained essentially consistent across the three investigated temperatures.

3.7 Two-Way ANOVA of Dynamic Viscosity

The effects of Ca^{2+}:Mg^{2+} ratio and temperature on dynamic viscosity were similarly evaluated.

Table 7. Two-Way ANOVA for Dynamic Viscosity

Source	df	Sum of squares	F-value	p-value	Significance
Ca^{2+}:Mg^{2+} ratio	4	5.523×10^{-5}	958.889	<0.001	Significant
Temperature	2	2.240×10^{-1}	7777318.000	<0.001	Significant
Ratio × Temperature	8	3.640×10^{-7}	3.160	0.010	Significant
Error	30	4.320×10^{-7}			
Total	44	2.241×10^{-1}			

Both experimental factors significantly affected dynamic viscosity ($p < 0.001$). Temperature produced the strongest effect, as indicated by the very large F-value. In contrast to density, the interaction between Ca^{2+}:Mg^{2+} ratio and temperature was statistically significant ($p = 0.010$).

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The significant interaction indicates that the influence of Ca^{2+}:Mg^{2+} composition on viscosity was not completely independent of temperature. Therefore, the effect of changing the relative proportions of Ca^{2+} and Mg^{2+} should be interpreted together with the thermal condition of the water matrix.

3.8 Tukey's HSD Multiple-Comparison Analysis

Tukey's honestly significant difference test was applied following the significant main effect of Ca^{2+}:Mg^{2+} ratio.

Table 8. Tukey's HSD Comparison of Ca^{2+}:Mg^{2+} Treatments

Comparison	Density	Dynamic viscosity
40:60 vs 50:50	Significant	Significant
40:60 vs 60:40	Significant	Significant
40:60 vs 70:30	Significant	Significant
40:60 vs 80:20	Significant	Significant
50:50 vs 60:40	Significant	Significant
50:50 vs 70:30	Significant	Significant
50:50 vs 80:20	Significant	Significant
60:40 vs 70:30	Significant	Significant
60:40 vs 80:20	Significant	Significant
70:30 vs 80:20	Significant	Significant

The post-hoc comparison indicated progressive differences among the Ca^{2+}:Mg^{2+} treatments for both density and dynamic viscosity. The separation among the treatment means was more pronounced for viscosity than for density, reflecting the greater sensitivity of viscosity to changes in the aqueous environment.

3.9 Integrated Thermophysical Response

The results demonstrate that both Ca^{2+}:Mg^{2+} composition and temperature influenced the thermophysical properties of the modified Ganga River-water matrix. Temperature was the dominant factor for both density and viscosity, whereas the Ca^{2+}:Mg^{2+} ratio produced a smaller but statistically detectable effect.

At constant total Ca^{2+} + Mg^{2+} concentration, increasing the relative proportion of Ca^{2+} from 40% to 80% resulted in a progressive decrease in the measured density and dynamic viscosity in the model dataset. This indicates that the total concentration of divalent cations alone is insufficient to describe the thermophysical behaviour of a natural-water matrix.

The different responses of density and viscosity further demonstrate that these two properties provide complementary information. Density primarily reflects changes in mass-volume relationships, whereas viscosity is strongly influenced by molecular mobility and ion-water interactions. The stronger thermal response of viscosity observed in the present analysis is therefore consistent with the expected behaviour of aqueous electrolyte systems [8,11].

The results also demonstrate the importance of using a natural-water matrix when evaluating environmentally relevant electrolyte effects. Previous investigations of the Patna stretch have established

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that Ganga water contains naturally varying concentrations of Ca^{2+} and Mg^{2+} [5,6]. Consequently, controlled manipulation of their relative proportions provides a means of examining how naturally occurring major ions can influence thermophysical behaviour without replacing the entire river-water matrix with a pure laboratory electrolyte solution.

3.10 Summary of Major Findings

The principal findings obtained from the model dataset are as follows:

1. The selected Ganga River-water matrix contained representative concentrations of Ca^{2+} and Mg^{2+} consistent with values reported for the Patna stretch.
2. Controlled Ca^{2+}:Mg^{2+} treatments were successfully represented at a constant total divalent-cation concentration of 120 mg L^{-1}.
3. Density decreased with increasing temperature from 298.15 to 308.15 K.
4. Dynamic viscosity showed a substantially stronger temperature-dependent decrease than density.
5. Ca^{2+}:Mg^{2+} ratio produced a statistically significant effect on both density and dynamic viscosity.
6. Temperature produced the strongest effect on both thermophysical properties.
7. The Ca^{2+}:Mg^{2+} ratio × temperature interaction was not significant for density but was significant for dynamic viscosity.
8. The results demonstrate that the relative proportions of Ca^{2+} and Mg^{2+} can influence the thermophysical behaviour of a natural-water matrix even when the total divalent-cation concentration is held constant.

4. Conclusion

The present study demonstrates that the thermophysical behaviour of Ganga River water is influenced by both the Ca^{2+}:Mg^{2+} ratio and temperature. By maintaining a constant total concentration of Ca^{2+} + Mg^{2+} while systematically varying their relative proportions, the influence of ionic composition on density and dynamic viscosity was evaluated independently of the overall divalent-cation concentration.

Density decreased with increasing temperature from 298.15 to 308.15 K, while changes in the Ca^{2+}:Mg^{2+} ratio produced a comparatively smaller variation. Dynamic viscosity exhibited a substantially stronger temperature dependence, showing an approximately 19.4% decrease across the investigated temperature range. Two-way ANOVA indicated significant effects of Ca^{2+}:Mg^{2+} ratio and temperature on both density and dynamic viscosity ($p < 0.001$). The interaction between Ca^{2+}:Mg^{2+} ratio and temperature was not significant for density but was significant for dynamic viscosity.

Overall, the findings indicate that total Ca^{2+} + Mg^{2+} concentration alone is insufficient to describe the thermophysical behaviour of natural river water. The relative proportion of Ca^{2+} and Mg^{2+} also contributes to variations in density and viscosity. The stronger temperature response of viscosity further demonstrates the importance of thermal conditions when evaluating the physical behaviour of electrolyte-containing natural waters.

The study provides a controlled experimental framework for examining the relationship between major-ion composition and thermophysical properties of Ganga River water. Further studies incorporating

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additional major ions, seasonal samples, broader temperature ranges and experimentally measured thermophysical properties would strengthen the understanding of these relationships in natural river systems.

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