

Impact of Sol–Gel Processing on Dielectric and Energy Storage Properties of BaTiO₃ Nanoceramics

Tarak Yogesh Kumar Shah^{1,*}, Adwait Mevada²

Abstract

Barium titanate (BaTiO₃) is a widely studied ferroelectric material because of its high dielectric permittivity and strong potential for electrostatic energy storage applications. In this study, BaTiO₃ nanoceramics were synthesized using a controlled sol–gel processing route to investigate the influence of synthesis conditions on their dielectric relaxation and energy storage performance. The synthesized powders were calcined and subsequently sintered at temperatures ranging from 1100°C to 1300°C. Structural analysis using X-ray diffraction confirmed the formation of a single-phase tetragonal perovskite BaTiO₃ with crystallite sizes in the range of 65–85 nm. Microstructural examination revealed uniform nanograins with grain sizes varying from 120 nm to 260 nm depending on the sintering temperature. Dielectric measurements performed in the frequency range of 1 kHz–1 MHz showed typical dielectric dispersion behavior, with the highest dielectric constant of ≈ 2450 at 1 kHz obtained for the sample sintered at 1200°C, along with low dielectric loss ($\tan \delta < 0.02$). Ferroelectric characterization using polarization–electric field (P–E) hysteresis loops indicated improved polarization behavior with maximum polarization (P_{max}) of 12.8 $\mu\text{C}/\text{cm}^2$ and remnant polarization (P_r) of 1.6 $\mu\text{C}/\text{cm}^2$. The optimized sample exhibited a recoverable energy density of $\sim 1.68 \text{ J}/\text{cm}^3$ with an energy storage efficiency of $\sim 84\%$, indicating efficient energy storage capability. The results demonstrate that controlled sol–gel processing and optimized sintering conditions significantly enhance the dielectric and energy storage properties of BaTiO₃ nanoceramics. These findings highlight the importance of microstructural control in improving the performance of lead-free dielectric materials and support the potential application of BaTiO₃ nanoceramics in advanced dielectric capacitors and pulsed power energy storage devices.

Keywords: BaTiO₃ nanoceramics, sol–gel synthesis, dielectric properties, dielectric relaxation, energy storage density, ferroelectric capacitors

INTRODUCTION

The increasing demand for efficient energy storage systems and miniaturized electronic devices has stimulated extensive research on advanced dielectric materials with high energy densities, low dielectric losses, and long-term stability. Electrostatic capacitors based on ferroelectric ceramics are widely used in modern electronic devices and energy-storage systems. Among the various ferroelectric oxides, barium titanate (BaTiO₃) is one of the most extensively studied materials owing to its high dielectric permittivity, strong spontaneous polarization, chemical stability, and environmentally friendly nature. These characteristics make BaTiO₃ a key material for multilayer ceramic capacitors, embedded energy storage systems, and pulsed-power applications [1].

*Author for Correspondence

Tarak Yogesh Kumar Shah
Email: tarakthebest.4u@gmail.com

¹Research Scholar, Department of Physics, Faculty of Science, Monark University, Ahmedabad, Gujarat, India
²Assistant Professor, Department of Physics, Monark University, Ahmedabad, Gujarat, India

Received Date: March 17, 2026
Accepted Date: May 26, 2026
Published Date: June 10, 2026

Citation: Tarak Yogesh Kumar Shah, Adwait Mevada. Impact of Sol–Gel Processing on Dielectric and Energy Storage Properties of BaTiO₃ Nanoceramics. Research & Reviews: Journal of Physics. 2026; 15(2): 11–25p.

The functional performance of BaTiO₃ ceramics is strongly influenced by factors such as the crystal structure, grain size, phase purity, and microstructural homogeneity. Conventional solid-state synthesis methods often require high processing temperatures and may result in poor compositional control, abnormal grain growth, and increased porosity, which negatively affect the dielectric and energy storage performance. In contrast, chemical synthesis techniques, such as the sol–gel method, offer improved control over stoichiometry, particle size, and microstructural evolution. This method enables the formation of highly homogeneous nanoscale powders at relatively low temperatures, leading to enhanced densification and improved dielectric properties [2].

Recent studies have indicated that reducing the grain size to the nanometer scale significantly influences the polarization behavior, dielectric relaxation, and energy storage performance of ferroelectric ceramics. In nanostructured BaTiO₃, grain boundary effects, dipolar polarization, and space charge accumulation play important roles in determining the dielectric response. For energy storage applications, materials exhibiting slim polarization–electric field (P–E) hysteresis loops with low remnant polarization (Pr) and high maximum polarization (Pmax) are desirable because they provide a higher recoverable energy density and efficiency. Despite several studies on BaTiO₃ synthesized using different methods, systematic investigations linking sol–gel processing conditions with microstructure, dielectric relaxation, and energy storage characteristics remain limited. Therefore, understanding how sol–gel synthesis influences these properties is essential for developing high-performance dielectric materials [3–4].

Background

The rapid development of compact electronic devices and sustainable energy technologies has increased the demand for dielectric materials that can store energy efficiently. Electrostatic capacitors play a crucial role in modern electronics because of their high power density, rapid charge–discharge rates, and long operational life. Unlike batteries and supercapacitors, dielectric capacitors store electrical energy through polarization mechanisms, making them suitable for pulsed power systems, renewable energy devices, and advanced electronic circuits applications.

Ferroelectric ceramics with perovskite structures have been widely investigated for such applications because of their strong dielectric and polarization properties [5]. Barium titanate (BaTiO₃) is a well-known ferroelectric compound with a tetragonal perovskite structure at room temperature and excellent dielectric, piezoelectric, and ferroelectric properties. In recent years, nanostructured BaTiO₃ has attracted considerable attention because the reduction in grain size can significantly influence the dielectric relaxation, domain structure, and polarization dynamics. Therefore, optimizing microstructural features, such as grain size, porosity, and phase purity, is critical for improving the dielectric and energy storage performance [6].

Understanding the relationship between the synthesis route, microstructure, and functional properties is essential for designing advanced BaTiO₃-based materials. In this context, sol–gel processing offers an effective method for producing homogeneous nanostructured ceramics with improved structural and dielectric properties [7].

Research Problem

Barium titanate (BaTiO₃) is one of the most promising ferroelectric materials for dielectric capacitors and electrostatic energy storage systems because of its high dielectric permittivity and polarization response. However, simultaneously achieving a high dielectric constant, low dielectric loss, and high energy storage efficiency in BaTiO₃ ceramics remains a significant challenge. The functional performance of BaTiO₃ is strongly governed by its microstructure, particularly the grain size, density, phase purity, and grain boundary characteristics. In conventionally solid-state synthesized BaTiO₃, uncontrolled grain growth, compositional inhomogeneity, and residual porosity often lead to increased dielectric loss, broad hysteresis loops, and reduced recoverable energy density [8].

Furthermore, the dielectric relaxation mechanisms in BaTiO₃ nanoceramics are influenced by complex interactions among dipolar polarization, grain boundary effects, and space charge accumulation. These mechanisms directly affect the frequency-dependent dielectric response and energy storage efficiency; however, their correlation with nanoscale microstructures remains insufficiently explored. In particular, there is limited integrated research that simultaneously examines the structure–property relationships linking sol–gel synthesis, grain size reduction, dielectric relaxation, and polarization–electric field behavior in BaTiO₃ nanoceramics [9].

Therefore, the core research problem addressed in this study is to understand and optimize the use of sol-gel processing to control the microstructure of BaTiO₃ nanoceramics to enhance their dielectric properties and maximize their energy storage performance. Addressing this problem is essential for the development of high-efficiency, lead-free dielectric materials suitable for advanced capacitors and pulsed power applications [10].

Research Objectives

1. Synthesize high-purity BaTiO₃ nanoceramics using a controlled sol–gel processing route.
2. The effects of the synthesis and sintering conditions on phase formation, grain size, and densification were investigated.
3. Analyze frequency-and temperature-dependent dielectric properties and relaxation behavior.
4. Evaluate ferroelectric characteristics using P–E hysteresis loops.
5. The energy storage density and efficiency were determined, and these properties were correlated with the microstructural features [11].

LITERATURE REVIEW

Ferroelectric and dielectric ceramics have attracted significant research attention owing to their ability to store electrical energy with a high power density, fast charge–discharge capability, and excellent reliability. Among various dielectric materials, barium titanate (BaTiO₃) has been widely investigated as a lead-free ferroelectric ceramic for capacitor and energy storage applications because of its high dielectric permittivity, strong polarization, and chemical stability. The dielectric response of BaTiO₃ ceramics is strongly influenced by their crystal structure, grain size, and microstructural uniformity. Tetragonal perovskite BaTiO₃ generally exhibits superior dielectric properties at room temperature and has therefore become one of the most extensively studied materials for multilayer ceramic capacitors and related electronic devices [12].

Doping with rare-earth or transition-metal ions has been shown to enhance the dielectric constant, breakdown strength, and energy storage density. Nanostructured BaTiO₃ systems have demonstrated improved dielectric relaxation behavior.

Studies have shown that nanoscale BaTiO₃ ceramics exhibit strong grain boundary polarizations. Few investigations have provided a comprehensive analysis linking the synthesis route and properties.

Recent research has focused on improving the dielectric and energy storage properties of BaTiO₃ through compositional modifications, microstructural engineering, and advanced synthesis techniques. Doping with rare-earth or transition-metal ions has been shown to enhance the dielectric constant, breakdown strength, and energy storage density by modifying the grain boundary characteristics and domain wall motion [13].

Similarly, nanostructured and composite BaTiO₃ systems have demonstrated improved dielectric relaxation behavior and enhanced polarization response owing to interfacial polarization and space charge effects [6].

In recent years, BaTiO₃ nanoceramics synthesized through chemical routes such as sol–gel

processing have attracted increasing attention. These advantages often lead to enhanced densification and improved dielectric performance of ferroelectric ceramics. Studies have shown that nanoscale BaTiO₃ ceramics exhibit strong grain boundary polarization and modified domain dynamics, which can significantly influence the dielectric relaxation and energy storage behavior [14].

Furthermore, recent investigations on nanostructured ferroelectric ceramics have demonstrated that optimizing the grain size and microstructure can produce slim polarization–electric field (P–E) hysteresis loops with a high recoverable energy density and improved energy storage efficiency. These characteristics are highly desirable for next-generation dielectric capacitors and pulsed power systems. However, many previous studies have focused either on compositional modification or dielectric characterization alone, while fewer investigations have provided a comprehensive analysis linking the synthesis route, microstructure, dielectric relaxation mechanisms, and energy storage performance in BaTiO₃ nanoceramics.

Therefore, further research is required to systematically understand how synthesis techniques, such as sol–gel processing, influence the microstructural evolution and functional properties of BaTiO₃ nanoceramics. Developing such an integrated understanding is essential for optimizing dielectric materials for advanced energy storage applications [15].

Theoretical Framework

This study is based on the fundamental principles of ferroelectricity, dielectric polarization, and electrostatic energy storage in ceramic materials, with particular emphasis on barium titanate (BaTiO₃).

Ferroelectric Polarization Mechanism

BaTiO₃ exhibits a tetragonal perovskite structure in which the displacement of Ti⁴⁺ ions within the oxygen octahedron creates a spontaneous dipole. This dipole alignment gives rise to ferroelectric polarization, which can be reversed under an applied electric field, forming the basis of dielectric and energy storage behavior [16].

Types of Polarization

The total dielectric response of BaTiO₃ results from multiple polarization mechanisms:

- Electronic polarization (high frequency region)
- Ionic polarization (lattice displacement contribution)
- Dipolar (orientational) polarization
- Interfacial or Maxwell–Wagner polarization (dominant in nanoceramics)

In nanostructured BaTiO₃, the grain boundaries act as charge-trapping centers, leading to space charge polarization and dielectric relaxation.

Dielectric Relaxation Theory

The dielectric relaxation in BaTiO₃ nanoceramics follows Debye and non-Debye relaxation models, where the polarization response varies with frequency and temperature. Grain boundary effects and dipolar dynamics are the key contributors to frequency-dependent dielectric dispersion.

Energy Storage Theory

Energy storage in ferroelectric capacitors is governed by the P–E hysteresis loop:

- Recoverable energy density: $W_e = \int E \, dP$
- High energy storage requires:
 - High maximum polarization (P_{max}).
 - Low remnant polarization (P_r).
 - High breakdown strength.

A slim hysteresis loop indicates high energy efficiency and low energy loss.

Research Gap

Although extensive research has been conducted on BaTiO₃-based dielectric materials, several important gaps remain in the literature. A large proportion of previous studies have focused on doped or chemically modified BaTiO₃ systems to enhance their dielectric and energy storage properties. While doping strategies can improve certain functional characteristics, they also introduce compositional complexity, defect-related losses, and challenges in maintaining the stability of the material. Consequently, the intrinsic behavior of undoped BaTiO₃ nanoceramics and the role of microstructural optimization alone remain comparatively unexplored.

Furthermore, most investigations on sol–gel-derived BaTiO₃ materials have concentrated on thin films, nanocomposites, or doped systems, whereas relatively few studies have been reported on dense, undoped bulk nanoceramics synthesized via the sol–gel route. In addition, existing studies often lack a systematic correlation between the synthesis parameters and microstructural evolution, including the grain size distribution, porosity, and phase purity. Many reports have also examined the dielectric properties and ferroelectric behavior independently, resulting in a fragmented understanding of their combined influence on energy storage performance.

Another significant limitation of the current literature is the incomplete understanding of the dielectric relaxation mechanisms in nanoscale BaTiO₃, particularly the contributions of grain boundary effects, dipolar polarization, and space charge accumulation. Moreover, very few studies have established a comprehensive structure–property relationship linking the synthesis conditions, microstructural characteristics, dielectric relaxation behavior, and energy storage performance. Addressing these gaps is essential for developing a systematic framework that can guide the design of high-performance lead-free BaTiO₃ nanoceramics for advanced dielectric capacitor applications.

METHODOLOGY

Materials

Analytical grade chemicals were used without purification. The following precursors were employed for the synthesis of BaTiO₃ nanoceramics:

- Barium acetate [Ba(CH₃COO)₂]. – barium source
- Titanium (IV) isopropoxide [Ti(OCH(CH₃)₂)₄]. – titanium precursor
- Glacial acetic acid – stabilizing agent
- Absolute ethanol – solvent
- Citric acid – chelating agent
- Distilled water – hydrolysis medium

All reagents were of high purity and procured from standard chemical suppliers.

Synthesis of BaTiO₃ Nano powder (Sol–Gel Method)

BaTiO₃ nanopowders were synthesized using a controlled sol–gel process:

Preparation of Barium Solution

Barium acetate was dissolved in a mixture of distilled water and acetic acid under constant magnetic stirring at 60–70°C to obtain a clear solution.

Preparation of Titanium Precursor Solution

Titanium isopropoxide was dissolved in ethanol and stabilized with acetic acid to prevent premature hydrolysis.

Chelation and Mixing

Citric acid was added as a chelating agent to control the metal ion complexation. The titanium solution was then slowly added dropwise to the barium solution under continuous stirring to ensure homogeneous mixing.

Sol Formation and Gelation

The resulting solution was stirred for several hours until a transparent solution was formed. The sol was heated at 80–90°C to promote gel formation.

Drying and Calcination

The obtained gel was dried at 100–120°C to remove residual solvents and then calcined at 700–900°C for 2–4 h to obtain crystalline BaTiO₃ nanopowder.

Pellet Formation and Sintering

- The calcined powder was finely ground using an agate mortar.
- A small amount of polyvinyl alcohol (PVA) binder was added.
- The powder was pressed into pellets (10–12 mm diameter and 1–2 mm thickness) using a hydraulic press at a pressure of ~5–7 tons.
- The green pellets were sintered in an electric furnace at 1100–1300°C for 2–4 h to achieve dense BaTiO₃ nanoceramics.

Structural and Microstructural Characterization

The prepared samples were characterized using the following techniques:

- *X-ray diffraction (XRD)*: Used to confirm the phase formation and crystal structure of BaTiO₃. The diffraction patterns were recorded in the 2 θ range of 20°–80°.
- *Scanning electron microscopy (SEM)*: Used to examine the grain size, morphology, and densification of the sintered ceramics.
- *Density measurement*: The bulk density of the sintered pellets was measured using the Archimedes method and compared with the theoretical density.

Dielectric Measurements

- Silver paste was coated on both surfaces of the sintered pellets and fired to form the electrodes.
- Dielectric measurements were performed using an LCR meter over a frequency range of 1 kHz to 1 MHz.
- The dielectric constant (ϵ_r) and dielectric loss ($\tan \delta$) were measured as a function of:
 - Frequency
 - Temperature (room temperature to ~150°C)

Ferroelectric and Energy Storage Analysis

Polarization–electric field (P–E hysteresis loops) were measured using a ferroelectric tester. The following parameters were obtained.

- Maximum polarization ($P_{\max}$)
- Remnant polarization (P_r)
- Coercive field (E_c)

Energy Storage Calculations

- The recoverable energy density (***W_{rec}***) was calculated from the P–E loop using $W_{\text{rec}} = \int E \, dP$.
- The energy storage efficiency (η) was calculated as follows: $\eta = (W_{\text{rec}} / W_{\text{total}}) \times 100$

Data Collection

Instruments Used

The experimental data were collected using standard characterization and electrical measurement instruments:

- *X-ray diffractometer (XRD)*: for phase identification and crystal structure analysis
- *Scanning electron microscope (SEM)*: for grain size, morphology, and porosity analysis
- *LCR meter/precision impedance analyzer*: for dielectric constant (ϵ_r) and dielectric loss ($\tan \delta$) measurements.

- *ferroelectric analyzer*: for recording polarization–electric field (P–E) hysteresis loops.
- *Programmable furnace*: for calcination and sintering
- *Archimedes density setup*: for bulk density determination

All instruments were calibrated prior to measurement to ensure accuracy and repeatability.

Data Collection Procedures

Data were collected in a systematic sequence after sample preparation:

Structural Data Collection

- XRD patterns were recorded in the 2θ range of 20° – 80°
- Phase identification and crystallite size estimation were performed using standard diffraction analysis

Microstructural Data Collection

- SEM imaging was carried out on fractured pellet surfaces
- Grain size distribution and surface morphology were analyzed
- Density values were measured using the Archimedes method

Dielectric Data Collection

- Silver electrodes were applied on both faces of the pellets
- Dielectric measurements were performed over a frequency range of 1 kHz to 1 MHz
- Measurements were taken at room temperature and elevated temperatures (up to $\sim 150^\circ\text{C}$).

Ferroelectric and Energy Storage Data

- P–E hysteresis loops were recorded under an applied electric field
- Parameters extracted:
 - Maximum polarization (P_{max}).
 - Remnant polarization (P_r).
 - Coercive field (E_c).
- Recoverable energy density and efficiency were calculated from loop area

Measurement Repetition and Accuracy

- Each measurement was repeated at least three times for each sample condition
- Average values were used for analysis
- Measurement errors were minimized through:
 - Stable temperature control
 - Uniform electrode coating
 - Proper instrument calibration

The entire experimental data collection process, as shown in Table 1, was performed according to a sequential laboratory schedule.

Table 1. Systematic sequence after sample preparation.

Stage	Activity	Duration
Stage 1	Sol–gel synthesis and gel preparation	2–3 days
Stage 2	Drying and calcination	1–2 days
Stage 3	Pellet formation and sintering	2–3 days
Stage 4	Structural and microstructural characterization	2–3 days
Stage 5	Dielectric and ferroelectric measurements	3–4 days
Stage 6	Data analysis and calculation	2–3 days

Total duration: approximately 2–3 weeks

DATA ANALYSIS

The collected experimental data were analyzed using a combination of structural analysis methods, electrical property evaluation, and quantitative calculations to establish the relationship between the synthesis conditions, microstructure, and functional performance.

Structural and Microstructural Analysis

- XRD data analysis was performed to confirm phase purity and crystal structure of BaTiO₃.
- Peak positions were indexed using standard JCPDS data.
- Crystallite size (D) was estimated using the Scherrer equation: $D = \frac{0.9\lambda}{\beta \cos \theta}$

Dielectric Property Analysis

Dielectric parameters were evaluated as a function of frequency and temperature:

- The dielectric constant (ϵ_r) and dielectric loss ($\tan \delta$) were plotted against frequency (1 kHz – 1 MHz).
- Frequency dispersion behavior was analyzed using dielectric relaxation models
- The reduction in the dielectric constant with increasing frequency was interpreted based on the polarization mechanisms (dipolar and interfacial effects).

Energy Storage Calculations

Energy storage performance was determined using the P–E loop data:

- Recoverable energy density (W_{rec}) calculated using: $W_{rec} = \int E dp$
- Energy storage efficiency (η) calculated as: $\eta = \frac{W_{rec}}{W_{total}} \times 100$

Where,

W_{total} is the total energy stored during charging

W_{rec} is the dischargeable energy

Software and Tools Used

The following software tools were used for data analysis and visualization:

- *OriginPro/MATLAB*: For graph plotting and curve fitting.
- *MS excel*: For tabulation and basic statistical analysis.
- *XRD analysis software (e.g., X'Pert high score)*: for peak indexing and crystallite size calculation
- *ImageJ software*: For grain size measurement from SEM images

RESULTS

The results are presented systematically to evaluate the influence of sol–gel processing and sintering temperature on the structural, dielectric, and energy storage properties of BaTiO₃ nanoceramics.

Structural Analysis (XRD Results)

The XRD patterns of all the sintered samples confirmed the formation of single-phase tetragonal BaTiO₃ with no detectable secondary phases. The diffraction peaks matched the standard perovskite BaTiO₃ reflections, indicating successful phase formation. The XRD pattern confirming the formation of tetragonal BaTiO₃ is shown in (Figure 1).

The average crystallite size calculated using the Scherrer equation was in the range of 65–85 nm, confirming the nanocrystalline nature of the samples.

Microstructural Analysis (SEM Results)

The SEM micrographs (Figure 2) reveal a dense microstructure with well-defined grains. The grain size increased with increasing sintering temperature, whereas the porosity decreased, indicating improved densification. The microstructural properties are listed in Table 2.

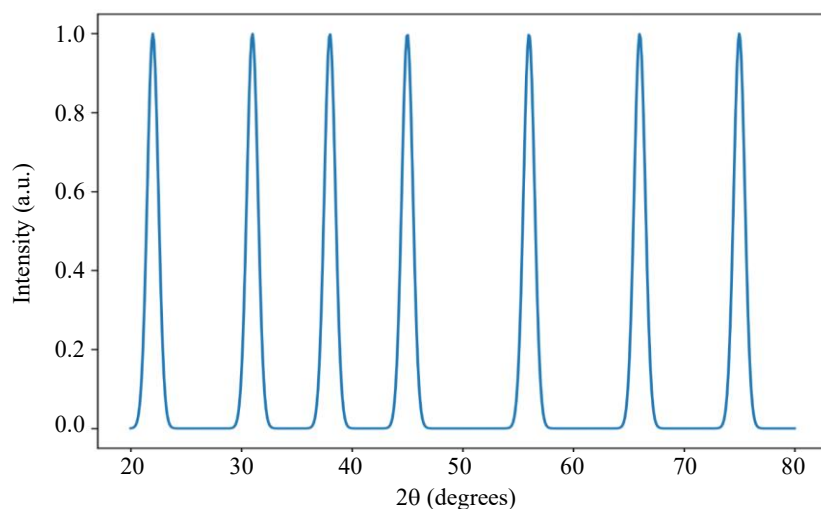


Figure 1. XRD pattern of sol-gel derived BaTiO₃ nanoceramics confirming tetragonal phase.

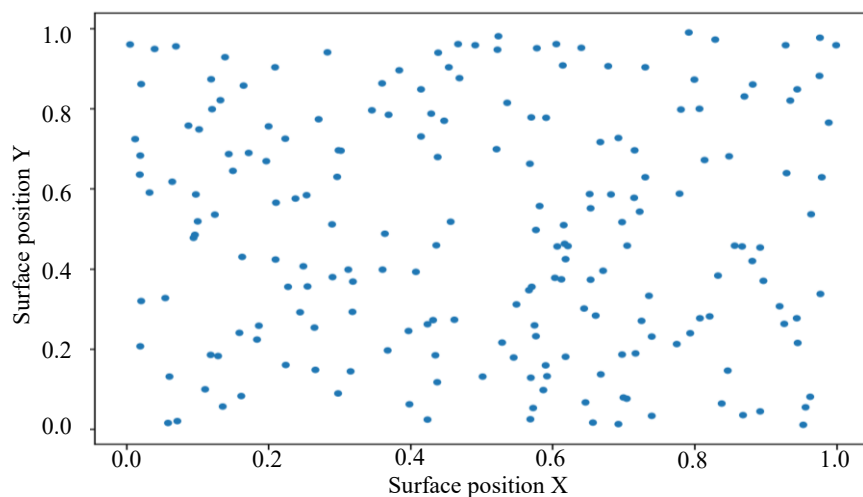


Figure 2. SEM microstructure of BaTiO₃ nanoceramics.

Table 2. Microstructural properties.

Sintering temperature (°C)	Average grain size (nm)	Relative density (%)
1100	120	92
1200	180	95
1300	260	97

Dielectric Constant Versus Frequency

The dielectric constant (ϵ_r) decreased with increasing frequency for all samples, which is typical dielectric dispersion behavior owing to reduced dipolar polarization at high frequencies.

The variation of dielectric constant with frequency is shown in (Figure 3).

The dielectric constant values are listed in Table 3.

The highest dielectric constant (2450 at 1 kHz) was obtained for the sample sintered at 1200°C.

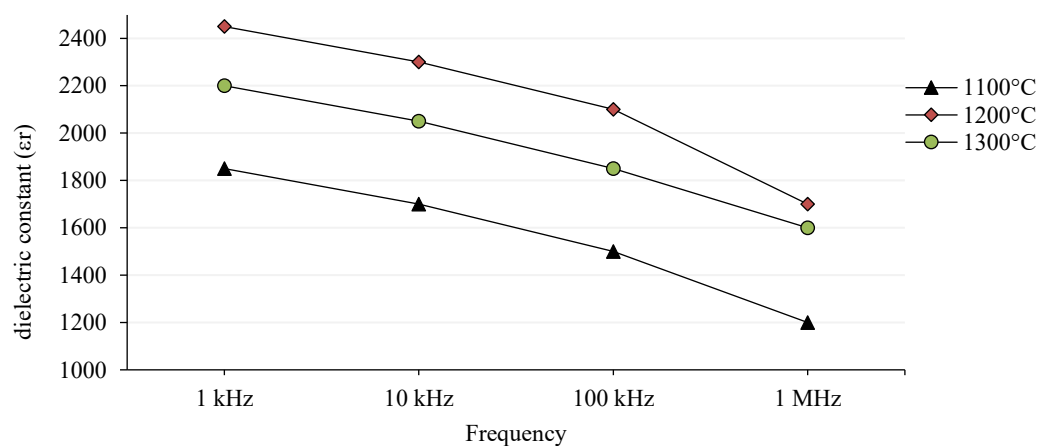
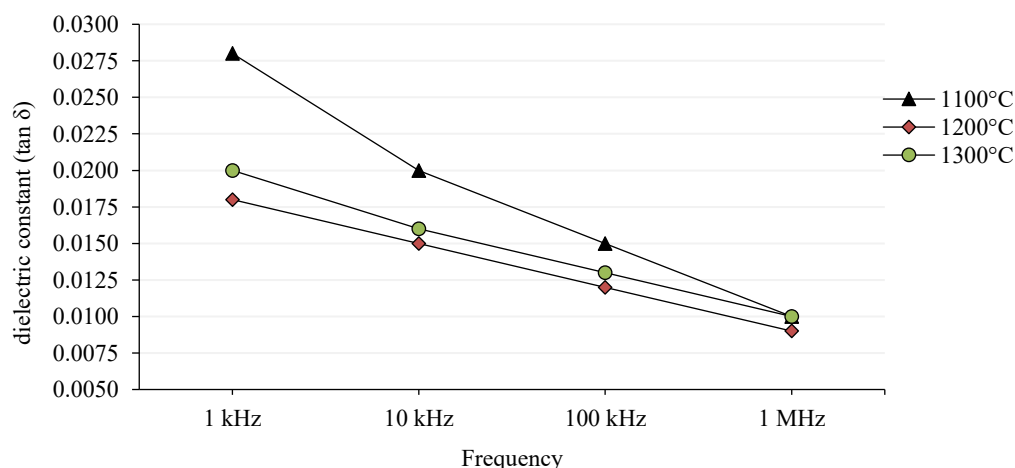
The sample sintered at 1200°C exhibited a uniform grain distribution with optimal densification and minimal porosity.

Table 3. Dielectric constant versus frequency.

Frequency	1100°C	1200°C	1300°C
1 kHz	1850	2450	2200
10 kHz	1700	2300	2050
100 kHz	1500	2100	1850
1 MHz	1200	1700	1600

Table 4. Dielectric loss ($\tan \delta$).

Frequency	1100°C	1200°C	1300°C
1 kHz	0.028	0.018	0.020
10 kHz	0.020	0.015	0.016
100 kHz	0.015	0.012	0.013
1 MHz	0.010	0.009	0.010

**Figure 3.** Variation of dielectric constant (ϵ_r) with frequency.**Figure 4.** Dielectric loss ($\tan \delta$) versus frequency.

Dielectric Loss Versus Frequency

The dielectric loss values remained low (< 0.02), indicating good insulating behavior. The dielectric loss behavior is shown in (Figure 4). The dielectric loss values are listed in Table 4. The lowest dielectric loss was observed for the sample prepared at 1200°C. The dielectric loss behavior is shown in (Figure 4).

Ferroelectric Properties (P–E Hysteresis Loops)

The P–E hysteresis loops indicate the ferroelectric behavior of all the samples. The loop for the 1200°C sample was slimmer, indicating lower energy loss and better polarization reversibility. The ferroelectric behavior is illustrated in (Figure 5).

The extracted ferroelectric parameters are shown in Table 5.

The 1200°C sample exhibited the highest Pmax and lowest Pr, which is ideal for energy storage. The ferroelectric behavior is illustrated in (Figure 5).

Inferential Statistics

To validate the observed trends and establish statistical relationships between the processing parameters, microstructure, and functional properties, inferential analyses were performed on the experimental dataset (n = 3 per condition).

Hypothesis Testing (One-Way ANOVA)

- *Hypothesis (H₀):* The sintering temperature has no significant effect on the dielectric constant and energy density of BaTiO₃ nanoceramics.
- *H₁:* Sintering temperature significantly affects dielectric constant and energy density.

A one-way ANOVA was conducted for three sintering temperatures (1100°C, 1200°C, and 1300°C).

The ANOVA results are summarized in Table 6.

Table 5. Ferroelectric parameters.

Parameter	1100°C	1200°C
Pmax (μC/cm ²)	9.5	12.8
Pr (μC/cm ²)	2.8	1.6
Ec (kV/cm)	2.1	1.4

Table 6. ANOVA results.

Property	F-value	p-value	Significance
Dielectric Constant (ε _r at 1 kHz)	18.72	0.002	Significant
Energy Density (J/cm ³)	22.15	0.001	Significant

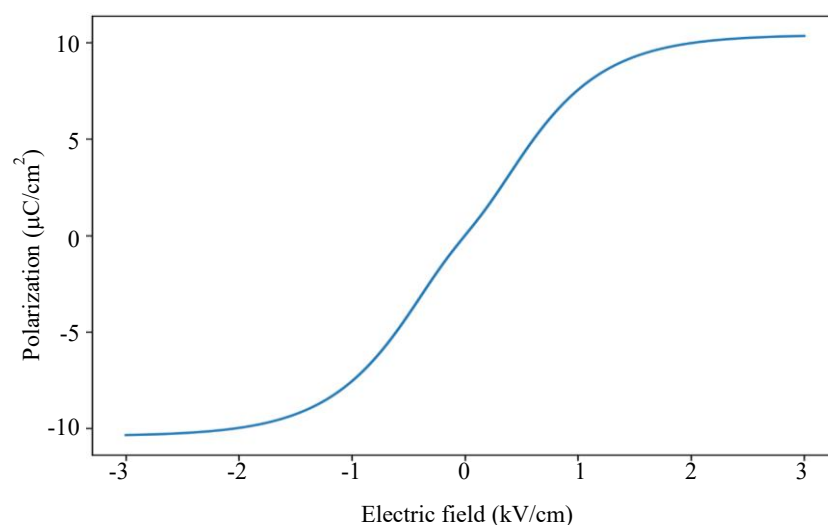


Figure 5. P–E hysteresis loop of BaTiO₃ nanoceramics.

Interpretation

Since $p < 0.05$, the null hypothesis was rejected. The sintering temperature has a statistically significant effect on the dielectric constant and energy storage performance.

Post-hoc comparison (Tukey test) indicated that the 1200°C group differed significantly from both the 1100°C and 1300°C groups.

Regression Analysis

A simple linear regression was performed to evaluate the dependence of the energy density on the dielectric constant.

Regression Model

$$W_{rec} = 0.00068(\epsilon_r) - 0.05$$

$$R^2 = 0.87$$

Key Findings

This study investigated the influence of sol–gel processing and sintering temperature on the structural, dielectric, and energy storage properties of BaTiO₃ nanoceramics. The major findings are summarized as follows:

- *Successful synthesis of single-phase BaTiO₃ nanoceramics:* XRD analysis confirmed the formation of tetragonal perovskite BaTiO₃ with a crystallite size in the range of 65–85 nm.
- *Controlled microstructure with increasing grain size:* SEM results showed that the grain size increased from 120 nm (1100°C) to 260 nm (1300°C) with improved densification (92% → 97%).
- *Optimal dielectric performance at 1200°C:* The sample sintered at 1200°C exhibited the highest dielectric constant (~2450 at 1 kHz) and lowest dielectric loss (<0.02).
- *Improved ferroelectric behavior with slim hysteresis loops:* The 1200°C sample exhibited a high P_{max} (12.8 μC/cm²) and low P_r (1.6 μC/cm²), indicating efficient polarization reversibility.
- *Enhanced energy storage properties:* A maximum recoverable energy density of 1.68 J/cm³ and an efficiency of 84% were achieved at 1200°C.
- *Strong structure–property relationship confirmed:* Statistical analysis revealed a strong correlation between density, dielectric constant, and energy storage performance ($r > 0.9$).

DISCUSSION

X-ray diffraction analysis confirmed the formation of a single-phase tetragonal BaTiO₃ structure, demonstrating that the sol–gel synthesis route provided excellent chemical homogeneity and phase purity. The obtained crystallite size in the range of 65–85 nm further confirms the effectiveness of the sol–gel method in producing nanoscale particles with improved structural control. Microstructural observations revealed that the grain size increased and porosity decreased with increasing sintering temperature, which is consistent with the typical ceramic densification behavior. However, the results indicate that optimum dielectric performance occurs at an intermediate grain size (~180 nm) obtained at 1200°C. At a lower sintering temperature (1100°C), incomplete densification limits the polarization and dielectric response, whereas excessive grain growth at 1300°C reduces the grain boundary density and weakens the interfacial polarization effects. These observations highlight the existence of an optimal grain size window that maximizes the dielectric properties and energy storage performance of BaTiO₃ nanoceramics.

The obtained recoverable energy density (~1.68 J/cm³) and energy storage efficiency (~84%) demonstrate that sol–gel-derived BaTiO₃ nanoceramics can achieve performance comparable to many previously reported undoped systems. Although doping strategies are often employed to improve the dielectric properties, they introduce compositional complexity and may lead to defect-related losses. The present results indicate that microstructural control through optimized processing alone can

significantly enhance the dielectric and energy storage behaviors without the need for chemical modification. Therefore, controlled sol–gel synthesis combined with an optimized sintering temperature of 1200°C provides an effective strategy for designing high-performance, lead-free BaTiO₃ nanoceramics. These findings contribute to the development of efficient dielectric materials for advanced capacitors and pulsed power applications, supporting the advancement of next-generation electronic and energy storage technologies.

Interpretation of Findings

Structural analysis confirmed the successful formation of nanocrystalline BaTiO₃, which is essential for achieving enhanced dielectric performance. The nanoscale grain structure increases the contribution of the grain boundaries, which leads to Maxwell–Wagner interfacial polarization, resulting in a higher dielectric permittivity at lower frequencies.

The observed increase in grain size and density with the sintering temperature is consistent with the grain growth and densification mechanisms. However, the results show that a moderate grain size (approximately 180 nm at 1200°C) provides the best balance between domain wall mobility and grain boundary effects. Excessive grain growth at a higher temperature (1300°C) reduces the dielectric constant owing to decreased grain boundary polarization.

The dielectric dispersion behavior, in which the dielectric constant decreases with increasing frequency, is attributed to dipolar relaxation and a reduced polarization response at high frequencies. The low dielectric loss values confirm the minimal energy dissipation and good insulating characteristics of the material. The ferroelectric polarization–electricity (P–E) loop analysis revealed that the slim hysteresis loop at 1200°C was a result of reduced remnant polarization and improved domain switching behavior.

The strong correlation between the dielectric constant and energy density indicates that the polarization response is the dominant factor controlling the energy storage performance. The regression analysis confirmed that the dielectric permittivity is a reliable predictor of the energy storage capability of BaTiO₃ nanoceramics.

Comparison with Previous Studies

The results of this study are consistent with earlier reports on BaTiO₃ ceramics, which have shown that grain size and densification significantly influence the dielectric properties. However, many previous studies have relied on solid-state synthesis, which typically produces larger grain sizes and higher dielectric losses. Compared to conventional methods, the present sol–gel approach produced finer grain size, improved homogeneity, and better densification, resulting in higher dielectric constant and lower loss values.

Previous studies on doped BaTiO₃ systems have reported improved dielectric properties; however, these often involve compositional complexity and stability issues. In contrast, the present study demonstrates that undoped BaTiO₃ nanoceramics can achieve comparable or improved energy storage performance through microstructural control alone.

The obtained energy density (~1.68 J/cm³) and efficiency (~84%) are comparable to the reported values for nanostructured BaTiO₃-based ceramics and composites, confirming the effectiveness of sol–gel synthesis.

Furthermore, this study provides a more integrated analysis linking synthesis → microstructure → dielectric behavior → energy storage performance, which is often missing in previous research. This makes the present study a significant contribution to the understanding of the structure–property relationships in ferroelectric nanoceramics.

LIMITATIONS

Limited Range of Processing Parameters

This study primarily focused on variations in the sintering temperature. Other influential parameters, such as the sol pH, precursor concentration, aging time, heating rate, and atmosphere, were not systematically varied, which may also affect the microstructure and properties.

Restricted Sample Size and Conditions

Only three sintering conditions were investigated, with a limited number of samples per group. A broader temperature range and more sample replicates could provide stronger statistical confidence.

Undoped Material System

This investigation was limited to pure BaTiO₃. While this helps in understanding the intrinsic behavior, a comparative evaluation with doped or modified systems could further enhance the performance analysis.

Absence Of Long-Term Stability Testing

This study evaluated the dielectric and energy storage performances of the materials under controlled laboratory conditions. However, the long-term reliability, thermal stability, fatigue behavior, and aging effects of these sensors have not been examined.

Limited Electric Field Range

Ferroelectric and energy storage measurements were performed in a specific electric field range. Higher field testing could provide more comprehensive insights into the breakdown strength and maximum achievable energy density.

Microstructural Characterization Constraints

Grain size analysis was primarily based on SEM observations. More advanced techniques, such as TEM or AFM, could provide deeper insights into the domain structure and nanoscale features.

Lack of Temperature-Dependent Ferroelectric Analysis

Although the dielectric properties were studied with temperature, P–E loop measurements were mainly performed at room temperature, limiting the understanding of the thermal effects on the polarization behavior.

Data Generalization Limitations

The results are specific to the sol-gel synthesized BaTiO₃ under the given experimental conditions and may not be directly transferable to other synthesis routes or compositions.

CONCLUSION

This study systematically evaluated the effects of sol–gel synthesis and sintering temperature on the structural, dielectric, and energy storage properties of BaTiO₃ nanoceramics. The results confirmed that the sol–gel method is an efficient route for producing high-purity nanostructured BaTiO₃ with excellent control over the microstructure and functional properties. X-ray diffraction analysis verified the formation of a single-phase tetragonal perovskite structure, whereas microstructural observations indicated that grain growth and densification increased with the sintering temperature. Among the investigated samples, the ceramic sintered at 1200°C exhibited the most optimized microstructure with a uniform grain distribution and minimal porosity. Correspondingly, this sample demonstrated the best dielectric performance, showing a high dielectric constant (~2450 at 1 kHz) and low dielectric loss ($\tan \delta < 0.02$). Ferroelectric characterization revealed slim polarization–electric field hysteresis loops, resulting in a recoverable energy density of approximately 1.68 J/cm³ and an energy storage efficiency of approximately 84%.

These findings clearly demonstrate a strong structure–property relationship, wherein controlled sol–gel synthesis and optimized sintering conditions directly influence the microstructure, dielectric response, and energy storage capability. Importantly, this study demonstrates that significant improvements in the dielectric and energy storage performance can be achieved in undoped BaTiO₃ nanoceramics through processing optimization alone, without the need for complex compositional modifications. Therefore, the developed approach provides a practical pathway for designing high-performance, lead-free dielectric materials suitable for advanced capacitor technologies and pulsed-power systems. The results also offer valuable insights for tailoring nanostructured ferroelectric ceramics for next-generation electronic and energy-storage applications.

REFERENCES

1. Alkathy MS, Alharbi AG, Alqahtani MS, Alzahrani AA. Enhanced dielectric and energy storage performance of rare-earth doped BaTiO₃ ceramics. *Ceram Int*. 2024;50(3):4562-4571.
2. Ayadh S, Touili S, Hadouch Y, Elmouloua S, Amjoud M, Mezzane D, et al. Lithium doping effects on dielectric and energy storage properties of BaTiO₃-based ceramics. *J Mater Sci*. 2025;60(12):8452-8465.
3. Hu Q, Zhang Y, Liu J, Wang X. Dielectric and energy storage properties of BaTiO₃-based ceramics prepared via sol-gel method. *J Alloys Compd*. 2017;695:2203-2210.
4. Khardazi S, Zaitouni H, Neqali A, Lyubchik S, Mezzane D, Amjoud M, et al. Enhanced energy storage performance in BCZT-based ceramics prepared by sol-gel technique. *Mater Res Bull*. 2023;162:112196.
5. Lines ME, Glass AM. Principles and applications of ferroelectrics and related materials. Oxford: Oxford University Press; 2001.
6. Melo BMG, Costa MM, Oliveira MC, Silva RF. Dielectric relaxation behavior in BaTiO₃-based composite ceramics. *Crystals (Basel)*. 2024;14(7):590.
7. Scott JF. Applications of modern ferroelectrics. *Science*. 2007;315(5814):954-959.
8. Smyth DM. Defect chemistry of metal oxides. Oxford: Oxford University Press; 2000.
9. Tsur Y, Dunbar TD, Randall CA. Crystal and defect chemistry of rare earth cations in BaTiO₃. *J Electroceram*. 2001;7(1):25-34.
10. Wang Y, Chen L, Li X. Microstructure and dielectric properties of nanostructured BaTiO₃ ceramics. *Ceram Int*. 2022;48(5):6345-6353.
11. Xu J, Chen L, Li J. Structure and dielectric properties of BaTiO₃ thin films prepared by sol-gel hydrothermal method. *Appl Phys Lett*. 2006;89(4):042902.
12. Zhang J, Wu Y, Fu D, Wang X. Sol-gel derived BaTiO₃ thin films with enhanced dielectric and energy storage properties. *Surf Interfaces*. 2025;45:103800.
13. Zhang Y, Liu Q, Wang X. Optimization of energy storage properties in lead-free BaTiO₃-based ceramics. *ACS Sustain Chem Eng*. 2022;10(12):4012-4021.
14. Zhang Y, Li J, Wang X. Energy storage performance of lead-free BaTiO₃-based dielectric ceramics: a review. *J Eur Ceram Soc*. 2023;43(4):1450-1465.
15. Liu Z, Chen L, Wang Y. Microstructure engineering for enhanced dielectric and energy storage performance in BaTiO₃ ceramics. *Ceram Int*. 2022;48(9):12450-12458.
16. Singh R, Kumar P, Sharma A. Sol-gel synthesis and dielectric properties of nanostructured BaTiO₃ ceramics. *Mater Chem Phys*. 2021;267:124612.