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Substitutional Doping Ions in Sodium Bismuth Titanate Ceramics: A Systematic Literature Review

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ABSTRACT

Sodium bismuth titanate (NBT) has emerged as a promising material for energy storage and dielectric applications in advanced ceramics, particularly when modified through substitutional doping. This systematic literature review evaluates the impact of various substitutional dopants on the structural, electrical, and dielectric characteristics of NBT-based ceramics, addressing the urgent need for a comprehensive understanding of how compositional modifications can be leveraged to optimize material performance. A critical challenge lies in determining the most effective dopants and concentrations that can simultaneously enhance energy storage density, improve dielectric properties, and maintain thermal stability under demanding operating conditions. To address this, an extensive analysis of academic publications indexed in Scopus and Web of Science was conducted, focusing on studies published between 2022 and 2024. Following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, 29 relevant studies were identified and systematically examined. The findings were organized into three thematic areas: (1) phase transitions induced by dopants that enable superior energy storage performance, (2) microstructural tailoring to refine electrical conductivity and dielectric behavior, and (3) structural modifications that contribute to functional stability across wide temperature ranges. Evidence from these studies consistently indicates that both A-site and B-site substitutional doping particularly with rare earth and transition metal ions can significantly broaden the functional capabilities of NBT ceramics. In summary, this review emphasizes the innovative role of substitutional doping in advancing NBT-based ceramics and provides a valuable reference point for future research aimed at optimizing lead-free dielectric materials for high-performance capacitors and energy storage applications.

Keywords: Sodium bismuth titanate; (NBT); substitution; doping; energy storage; systematic literature review

INTRODUCTION

The advancement of dielectric materials has been crucial in contemporary materials science, particularly in the pursuit of more efficient and sustainable energy storage systems (Cui et al. 2017; Guillon 2021). Many researchers are interested in sodium bismuth titanate ($Na_{0.5}Bi_{0.5}TiO_3$ or NBT) due to its promising piezoelectric, ferroelectric, and dielectric properties (Polushina et al. 2020; Turki et al. 2019). In the general perovskite structure with the chemical formula ABO_3, the A-site is typically occupied by alkali or alkaline earth metal ions (such as Na^+, K^+, or Bi^{3+}), while the B-site is occupied by transition metal ions (such as Ti^{4+}), which are arranged in an octahedral framework coordinated with oxygen. NBT, as a perovskite-structured ceramic, is recognized for its potential application in actuators, sensors, capacitors etc. However, apart from its advantageous properties, it also exhibits certain shortcomings including dielectric losses, increased conductivity, and thermal instability, which limit its broader applications (Bhattacharyya et al. 2018). A promising approach to address these challenges is the modification of the NBT lattice through substitutional doping. This process involves the incorporation of foreign ions into the host lattice, which can profoundly modify the material's structural and electrical properties. NBT's substitutional doping enhances dielectric properties by altering the polarization mechanism, reducing dielectric losses, and improving stability under elevated temperatures and voltages.

The nature and extent of these enhancements depend on the type of dopant ions used. Dopants can be alkali metals, transition metals or rare earth elements; each affecting the NBT lattice in a unique way. For example, lanthanum (La) (Roy & Dutta 2024) and cerium (Ce) (Sundari et al. 2020) enhanced dielectric constant while reducing the loss tangent of the material. On the other hand, manganese (Mn) and iron (Fe) improve thermal stability and fatigue resistance of the materials. The doped NBT is influenced by the ionic radius and valence state of the dopant, to modify lattice stress. Adding dopant ions to NBT can also change the microstructure, including the grain size and shape, as well as phase transitions that directly impact the dielectric properties. The presence of dopant will affect the behavior of domain walls and the movement of charge carriers through the material, thereby altering the dielectric response. A thorough understanding of this variation is important for optimizing the doping process and tailoring the material's properties. The necessity to enhance NBT's dielectric properties and the broader goal, of developing lead-free (Pb-free) ceramics for eco-friendly applications motivate investigations into substitutional doping. As Pb-free alternative to the widely used perovskite ceramic material PZT (lead zirconate titanate, $Pb(Zr,Ti)O_3$), NBT aligns with global efforts to eliminate hazardous materials. The study of various dopants and their effects on NBT is important for advancing the field of dielectric materials and facilitating the development of next-generation electronic devices.

This article examines the substitutional doping in NBT, focusing on how different dopants influence the dielectric properties and the mechanism behind these effects. It highlights how doping can enhance dielectric performance of NBT and their relevance to Pb-free electronic materials, through a critical discussion of recent literature (Figures 1 and 2).

Figure 1 demonstrates that NBT provides better environmental performance than PZT with respect to climate change implications. NBT is a more sustainable option than PZT because it requires less electrical energy during fabrication thus lowering the carbon impact. It also does not produce lead oxide during high temperature processes. The energy requirements for laboratory manufacturing of NBT, PZT, and KNN (potassium sodium niobate, $K_{0.5}Na_{0.5}NbO_3$) ceramics differ from one another during processing activities such as batch weighing, ball milling, drying, calcining, and sintering as shown in Figure 2. NBT fabrication required substantially lower electrical energy consumption (66.67% less), due to shorter duration, during ball milling compared to PZT or KNN. NBT demonstrates an advantage for energy cost reduction in production cycles thus enabling sustainable manufacturing possibilities.

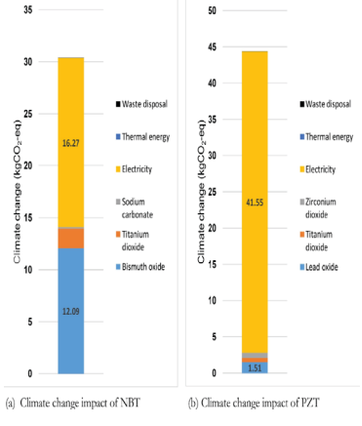

FIGURE 1. Comparison of the individual constituents of NBT and PZT piezoelectric ceramics in terms of climate change impact. Reproduced with permission from Ibn-Mohammed et al. 2018. Copyright 2018, Elsevier Ltd.

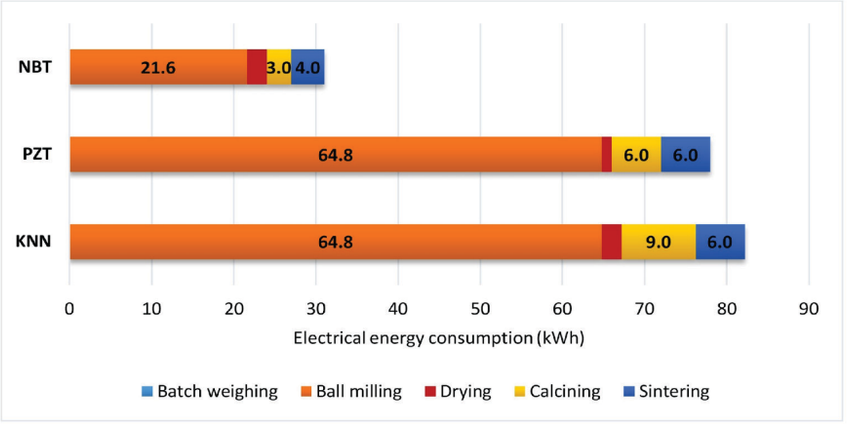

FIGURE 2. Comparative electrical energy usage for individual steps in the laboratory preparation of KNN, PZT, and NBT
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A-SITE AND B-SITE SUBSTITUTION

Substitutional doping in dielectric ceramics has been the subject of extensive research, particularly in NBT, because of its ability to modify functional properties. NBT, a lead-free ferroelectric material has been studied quite extensively for its possible applications in numbers of electrical devices. It has been established that substitution of ions in the NBT matrix can alter its structural, dielectric, and piezoelectric behavior. It thus leads to the development of a versatile material suitable for various advanced technological applications.

Doping NBT with rare-earth elements significantly affects its structural and dielectric properties. De Lira et al. (2024) highlighted the effects of doping NBT with rare-earth ions like Y^{3+}, Dy^{3+}, Yb^{3+}, and Er^{3+}. Their research shows that these dopants facilitate the formation of a rhombohedral phase with R3c symmetry, which makes NBT unique. When these ions were inserted into the NBT lattice, they caused lattice defects that could be seen in the spectra as Raman-active modes. These defects raised the dielectric permittivity and lowered the frequency dependence of the real permittivity. The impedance analysis indicated that rare-earth doping enhanced the grain boundaries resistance, hence augmenting the material's dielectric performance. Supporting these findings, Kumar et al. (2022), demonstrated that the incorporation of Ho^{3+} ions in NBT improved its dielectric properties across an extensive temperature range, making it suitable for high-temperature applications.

Transition metal doping has also been investigated for improving the electrical properties of NBT ceramics, especially with manganese. Nayak & Polai (2024) studied the influence of Mn^{3+} acceptor doping in the non-stoichiometric NBT system. Their studies showed that Mn^{3+} incorporation enhanced the conductivity of bulk oxide-ions and this was more pronounced when the doping was boosted to higher levels. The improved conductivity is because of electrostatic coupling between Mn^{3+} and Ti^{4+}, or between Mn^{3+} and O^{2-} in the NBT structure. This is consistent with the observations by Politova et al. (2021) who discovered that the incorporation of Mn into NBT ceramics increases the dielectric permittivity and the piezoelectric coefficients. Their findings show that Mn doping increases conductivity and modifies dielectric behavior, which makes it suitable for application in solid oxide fuel cells.

Incorporating complex ions into the B-site of NBT ceramics is one of the measures that has been identified to increase energy storage capacity. According to Fan et al. (2024) doping NBT with $(Al_{0.5}Nb_{0.5})^{4+}$ complex ions enhanced relaxor characteristic and high energy storage ability. This inclusion of ions led to a finer grain size and variation in transition temperature, helping to keep the high dielectric permittivity over wide temperature range. Zhang et al. (2024) also found that the substitution of Ti^{4+} with Zr^{4+} in NBT decreased grain size and increased breakdown strength, thus improving energy storage performance. These investigations suggest the importance of B-site doping for achieving high energy storage efficiency, making NBT-based ceramics promising candidates for advanced capacitor applications.

The effects of A-site doping in NBT have also been widely studied, particularly with rare-earth ions like Pr^{3+} and La^{3+}. A study by Villanueva-Vega et al. (2023) focused on the effects of Pr^{3+} incorporation in a $(Bi_{0.5}Na_{0.5})TiO_3$-$(Ba_{0.9}Ca_{0.1})TiO_3$ (BNT-BCT) solid solution, observing substantial decreases in grain size and enhancements in dielectric and piezoelectric properties. The maximum piezoelectric coefficient was observed when Pr^{3+} is 0.5

mol%. On the same note, Ruth (2023) showed that when bismuth magnesium zirconate (BMZ) was incorporated into NBT-MgZr ceramics there were changes in the vibrational modes hence improving the dielectric constant and residual polarization. These studies indicate that the change of dopant at A-site affects the dielectric and piezoelectric characteristics of NBT ceramics.

Considerable work has been done to understand the influence of various types of dopants and their concentrations on the electrical characteristics and microstructure of NBT ceramics. Koch et al. (2022) examined how viscosity of acceptor dopants influences the electrical conductivity of NBT. They found that different dopants interacted differently with oxygen vacancies, thereby affected the conductivity values. The non-linear relationship between dopant concentration and defect formation caused changes in the microstructure, which affected the electrical behavior. A study by Li et al. (2022), described that Sn-doped NBT ceramic has higher energy storage. The addition of SnO_2 improved dielectric constants and increased grain size, hence improved the energy storage density, also called recoverable energy density, (W_{rec}) and energy efficiency (η).

Therefore, it can be stated that the incorporation of dopant ions into NBT ceramics enhances their functional characteristics. Various types of ions including rare earth elements, transition metals, and complex ions have been incorporated at the A-site or B-site of the NBT ceramics lattice, which significantly enhanced the structural, dielectric, piezoelectric, and energy storage properties. De Lira et al. (2024), Nayak & Polai (2024), Fan et al. (2024) and others, have performed systematic studies on the role of ion substitution in altering the characteristics of NBT ceramics for application in electronics and energy storage devices.

In NBT ceramics, the structural and dielectric modifications caused by rare-earth dopants are particularly significant. For example, Ho^{3+} doped NBT-barium titanae (NBT-BT) ceramics exhibited a dual-phase monoclinic and tetragonal structure, W_{rec} of 1.88 J/cm³, η of 83% and a notable electrocaloric effects (Sekhar et al. 2023). Similarly Eu^{3+} doping in the $Na_{0.2}K_{0.3}Bi_{0.5}TiO_3$ (NKBT) ceramics yielded W_{rec} of 1.7 J/cm³ and η of 82% respectively (Sahu & Asthana 2024). Both studies demonstrate that rare-earth ions promote relaxor ferroelectric phases and boost energy storage performance.

IMPROVEMENTS THROUGH THE UTILISATION OF A-SITE AND B-SITE SUBSTITUTION

To tailor the physical and chemical properties of the NBT perovskite structure (Figure 3), substitutional doping at the A-site and B-site (Figure 4) has been widely employed. Wang et al. (2023a) synthesized $Bi(Mg_{0.5}Hf_{0.5})O_3$ (BMH), which enhanced the breakdown strength and energy storage performance of NBT ceramics achieving W_{rec} of 4.63 J/cm³ and η of 75.1%. Similarly, Li et al. (2023a) demonstrated that incorporating $BaTiO_3$ in $Bi_{0.5}Na_{0.5}TiO_3$-$Bi(Mg_{2/3}Nb_{1/3})O_3$ (NBT-BMN) ceramics yielded a dielectric W_{rec} of 1.02 J/cm³ while maintaining its temperature stability.

THERMAL STABILITY AND GRAIN REFINEMENT

Doping has been shown to significantly improve the thermal stability and microstructure of NBT ceramics. Ancy et al. (2023) achieved a stable W_{rec} of 0.655 J/cm³ at 150°C in $1\text{-}(x+y)(Bi_{0.5}Na_{0.5})TiO_3 - xBaTiO_3 - yBaZrO_3$ (BN-BT-BZ), demonstrating high temperature endurance. Similarly Aggarwal et al. (2023) incorporated $Ba_{0.85}Sr_{0.15}Zr_{0.1}Ti_{0.9}O_3$ (BSZT) into NBT which caused grain refinement and enhanced thermal stability, achieving an energy storage efficiency of about 85%.

RELAXOR FERROELECTRIC BEHAVIOR

Relaxor ferroelectric materials exhibit an unusual dielectric response as a function of temperature. For instance, Wang et al. (2022) incorporated $CaTiO_3$ into NBT ceramics, achieving a W_{rec} of 1.38 J/cm³ and η of 91.3 % with ultra-fast discharge rates. Using polarization engineering and grain alignment methods, Li et al. (2024) obtained a W_{rec} of 15.7 J/cm³ and an η of 95%. These findings highlight the potential of dopant-induced relaxor behavior in enhancing the energy storage properties of NBT-based ceramics.

COMPOSITIONAL DESIGN FOR MULTIFUNCTIONAL PROPERTIES

Advancements in compositional optimization continue to broaden the functional applications of NBT ceramics. Li et al (2024a) developed Nb-doped NBT-BT ceramics that attained a W_{rec} of 0.5 J/cm³, with improved piezoelectric characteristics. Additionally, they proposed a new grain alignment method for Mn^{2+}-doped NBT multilayer ceramic capacitors, achieving an energy density of 15.7 J/cm³. These studies underscore the critical relationship between compositional design and multifunctional performance.

INFLUENCE OF RARE-EARTH AND TRANSITION METAL ADDITIVES

Continued research on individual dopants could also enhance the understanding of their effects on NBT ceramics. Sahu et al. (2022) reported that NBT with high K^+-rich substitutions yielded W_{rec} of 0.5 J/cm³. Li et al. (2022) studied SnO_2-doped NBT-BT ceramics and achieved a maximum W_{rec} of 1.27 J/cm³ and minimum η of 79.15% by reducing remnant polarization. In addition, the incorporation of $Bi(Mg_{0.5}Ti_{0.5})O_3$ (BMT) has been shown to improve the relaxor behavior and energy storage properties (Fathabad et al. 2024).

TAILORING DIELECTRIC AND FERROELECTRIC BEHAVIOR

The use of special dopant like $Bi(Mg_{0.5}Sn_{0.5})O_3$ (BMS) in $Na_{0.5}Bi_{0.5}TiO_3$–$Sr_{0.85}Bi_{0.1}TiO_3$ (NBT-SBT) ceramics has proven effective in increasing polarization level and breakdown strength. Wang et al. (2023b) obtained W_{rec} of 7.5 J/cm³ and η of 85%, showing the importance of A-site and B-site dopant incorporation. Similarly, Li et al. (2023a) reported that $BaTiO_3$ incorporation enhanced both the ferroelectric and dielectric properties of NBT based ceramics.

Substitution doping in NBT based ceramics has thus become a significant approach for improving dielectric properties especially for applications in energy storage (Figure 5). This advancement aligns closely with the United Nations' Sustainable Development Goals (SDGs) by promoting sustainable and efficient energy solutions that contribute to climate action and affordable clean energy (United Nation, n.d.; Zainuddin et. al 2024). In systems with complex compositions, previous studies have investigated a diverse range of doping ions to improve various factors, including polarization, energy storage density, and dielectric stability.The incorporation of K^+ ions into NBT ceramics affects the relaxor properties and energy density performance (Sahu et al., 2023). By analyzing the hysteresis and switching current curves, they identified three distinct zones, each of which exhibits different dynamic behaviors affecting the polarization and domain-switching processes. These observations align with the findings of Li et al. (2024a), who showed that Mn^{2+} doping reduced the evaporation of alkali-earth cations thus improving the polarization and reducing dissipation loss in NBT ceramics.

Another study by Wang et al. (2022) demonstrated that doping NBT with $CaTiO_3$ led to a reduction in grain size, thereby enhancing the dielectric breakdown strength and favoring the relaxor characteristics. This approach resulted in energy storage density of about 1.38 J/cm³ and an efficiency of 91.3%. Comparatively, Sahu et al. (2023) reported the best energy density of 0.5 J/cm³ for K-doped NBT, underscoring that different dopants induce varied effects on the performance characteristics. These comparative analyses show that the dopants selection should be tailored to specific performance characteristics desired in the intended application.

Another promising opportunity for improving NBT ceramics involves the, incorporation of high entropy perovskite oxides an innovative approach. Li et al. (2023b) explored the idea of co-doping NBT with high entropy perovkite oxides and $NaNbO_3$ (NN), which produced dense microstructures with an average grain size of 5μm. This co-doping approach enhanced dielectric temperature stability and energy storage performance, achieving a recoverable energy density of 2.4×10^{-3} J/cm³ and a discharge efficiency of 71%. These outcomes are consistent with those of Wang et al. (2023a), who employed polarization and grain alignment engineering via a synergistic optimization method to achieve energy density of 15.7 J/cm³ with 95% plus efficiency. The enhancements noted in all these studies demonstrate that refined doping techniques offer significant potential for overcoming intrinsic weaknesses of NBT ceramics, such as A-site volatilization and Ti^{4+} reduction.

This relaxor behavior and its contribution to dielectric properties can be further explained through studies involving different doping elements. For instance, the transformation of relaxor phases in K^+-rich NBT ceramics, as discussed by Sahu et al (2023), exhibited pinched P–E loop behavior, suggesting a higher potential for energy storage applications. Similarly, the absence of remnant polarization observed by Wang et al (2022) led to improved energy efficiency, which is achieved by Ca^{2+} doping. The integration of multiple studies reveals a consistent trend: systematic doping not only improves relaxor behavior and energy stored density but also broadens the dielectric strength, that in return increases the overall capacitor performance.

RESEARCH QUESTION

1. How are the energy density, dielectric properties and thermal stability of NBT ceramics affected by substitutional doping with various ions under diverse operational conditions?
2. How do different doping methodologies enhance the performance of NBT ceramics? What are the practical implications of employing substitutional doped NBT ceramics in energy storage devices?

METHODOLOGY

The methodology outlined in this literature review adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. PRISMA is recognized globally as a gold standard for reporting systematic reviews, ensuring transparency and reproducibility by detailing the review process systematically (Page et al. 2021). By following the PRISMA framework in Figure 6, as similarly employed by Rus et al. (2023) and Ismail et al. (2025), we ensure comprehensive search, selection, and inclusion of relevant studies, thus enhancing the credibility and value of the review. Special attention is given to randomized studies to minimize bias and provide a robust evidence base for evaluations. The primary databases employed for this research were Scopus and Web of Science, chosen for their extensive and updated coverage. Scopus offers broad coverage across many disciplines, while Web of Science is more selective and indexes high-impact journals. However, as with any bibliographic database, limitations exist, including potential gaps in data completeness and record consistency.

IDENTIFICATION

The identification stage involves selecting keywords and related terms using dictionaries, thesauruses, encyclopedias, and prior literature. These terms were then used to formulate search strings tailored for Scopus and Web of Science databases (see Table 1). The initial database searches yielded a total of 121 potentialy relevant publications.

SCREENING

In the screening phase, the retrieved studies were evaluated for relevance to the research questions and alignment with the research focus, specifically focusing on ion substitution doping in Sodium Bismuth Titanate (NBT) dielectric ceramics. 74 publications were excluded leaving 47 papers for further assessment. Screening was conducted according to the predefined inclusion and exclusion criteria outlined in Table 2. Only journal articles published in English from 2022 to 2024 were considered. Publications such as book reviews, conference proceedings, older meta-analyses and meta-syntheses were excluded due to redundancy or lack of relevance. During this process, one additional study was excluded for redundancy, resulting in 46 eligible publications advancing to the next stage.

ELIGIBILITY

During the eligibility phase, the 46 articles carried forward from the screening stage were examined in greater detail to ensure compliance with the inclusion criteria and are relevance to the study objective. Titles and abstracts were carefully examined, resulting in the exclusion of 32 articles due to irrelevance, inconsistencies between the abstract and study aims or insufficient focus on substitutional doping in NBT ceramics. This left 14 articles ready for detailed review.

DATA ABSTRACTION AND ANALYSIS

The data abstraction phase utilized an integrative analysis approach, which allowed for the synthesis of various research designs and quantitative methods. The process began with a thorough examination of the 14 selected publications to extract relevant claims and pertaining to substitution doping in sodium bismuth titanate (NBT). This scrutiny helped in identifying key methodologies and results within the selected studies. Collaboration with subject-matter experts, Dr. ZZ, Dr. AA and Dr. NP in materials science physics, and Dr. NP in mechanical engineering, facilitated the development of grounded themes relevant to the study's context. We maintained a detailed log during the data analysis to record thoughts, inquiries, and perspectives critical for interpreting the data. Comparisons of findings were made to identify and resolve any discrepancies in theme development.

Throughout this process, domain validity was ensured by expert reviews that evaluated the clarity, significance, and appropriateness of each theme. Adjustments were made based on expert feedback to refine the themes for consistency and continuity across the manuscript.

QUALITY OF APPRAISAL

Following the guidelines established by Kitchenham (2012), once primary studies were selected, it is necessary to evaluate the quality of the research they provide and conduct a quantitative comparison of the findings. As shown in Table 3, this review adapts the quality assessment framework developed by Abouzahra et al. (2020) which includes six criteria for assessing the quality of studies in systematic literature reviews (SLRs). The evaluation of each criterion employs a three point scoring system, which are: Fully implemented criteria has a 'Yes' (Y) score of 1, while a 'Partly' (P) response gets a score of 0.5 if partially complied with, but with some deficiencies; the response gets a score

of 0 if the criteria is not implemented at all, indicated by 'No' (N). The quality assessment process employed in this study is depicted in Table 3, where three experts assess each criterion.

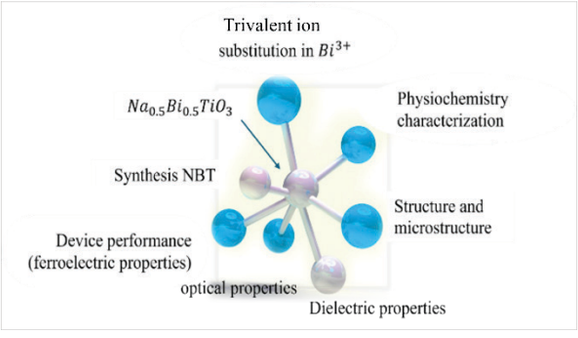

FIGURE 3. Structural and physico-chemical characterization of $Na_{0.5}Bi_{0.5}TiO_3$

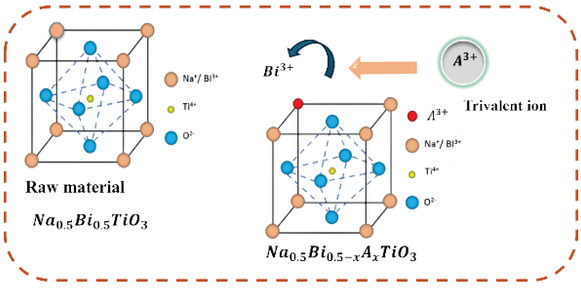

FIGURE 4. Substitution of Bi^{3+} with Trivalent Ions in $Na_{0.5}Bi_{0.5}TiO_3$

TABLE 1. The selection criterion for engine string in Scopus and WOS

Type of searching engine	Search engine string
Scopus	TITLE-ABS-KEY (("sodium bismuth titanate" OR nbt) AND (substitut* OR dop*) AND ("energy storage")) AND PUBYEAR > 2021 AND PUBYEAR < 2025 AND (EXCLUDE (SUBJAREA , «MATH")) AND (LIMIT-TO (LANGUAGE , «English")) AND (LIMIT-TO (DOCTYPE , «ar")) AND (LIMIT-TO (PUBSTAGE , «final"))) Date of Access: November 2024
WoS	TITLE-ABS-KEY (("sodium bismuth titanate" OR nbt) AND substitution OR doping) AND («energy storage») (("Sodium Bismuth Titanate" OR NBT) AND (Substitution) AND (Doping) AND ("energy storage")) (Topic) and 2024 or 2023 (Publication Years) and Article (Document Types) Date of Access: November 2024

TABLE 2. Other selection criterion for searching in Scopus and WOS

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2022 – 2024	< 2022
Literature type	Journal (Article)	Conference proceeding, book, review, meta-analysis, meta-synthesis
Publication Stage	Final	In Press

TABLE 3. Quality assessment (QA) process to assess the quality based on the mentioned criteria

Quality assessment	Expert 1	Expert 2	Expert 3	Total Marks
Is the purpose of the study clearly stated?	Y	Y	Y	3
Is the interest and the usefulness of the work clearly presented?	Y	Y	Y	3
Is the study methodology clearly established?	Y	Y	Y	3
Are the concepts of the approach clearly defined?	Y	Y	Y	3
Is the work compared and measured with other similar work?	Y	Y	Y	3

As shown in the table, the quality assessment process ensures a systematic and rigorous evaluation of the selected studies, and the following explanation provides further detailing of the steps taken:

1. Clarity of study objectives
   • Assesses the clarity and explicit statement of the study's aims and scope.

2. Relevance and significance ("So what" factor)
   • Evaluates research significance and potential contributions to the field.

3. Clarity of methodology
   • Reviews the appropriateness and detailed documentation of research methods.
   • Ensures replicability of the study.

4. Conceptual clarity and comprehensibility
   • Examines the clarity of theoretical concepts and definitions.
   • Assesses comprehensibility of the research approach.

5. Comparison with existing literature
   • Evaluates how findings relate to existing literature.
   • Positions the study within the broader academic context.

Each expert independently assesses each study using the scoring framework described earlier (Yes = 1, Partly = 0.5, No = 0). A cumulative score above 3.0 from the three experts was required for a study to pass this appraisal phase and ensured that only high-quality studies were included in the subsequent stages of analysis.

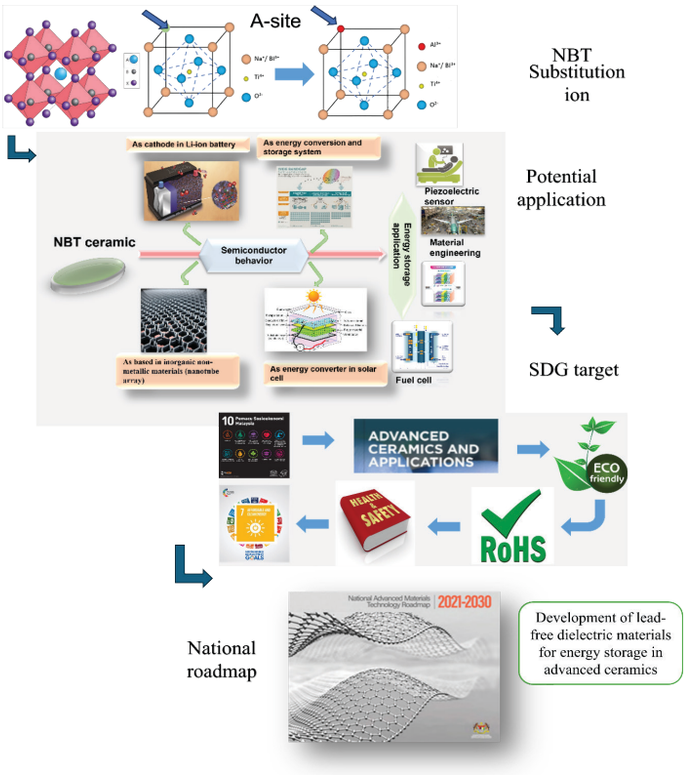

FIGURE 5. Future perspectives of NBT-based ceramics in energy storage and Sustainable Development Goals (SDG)

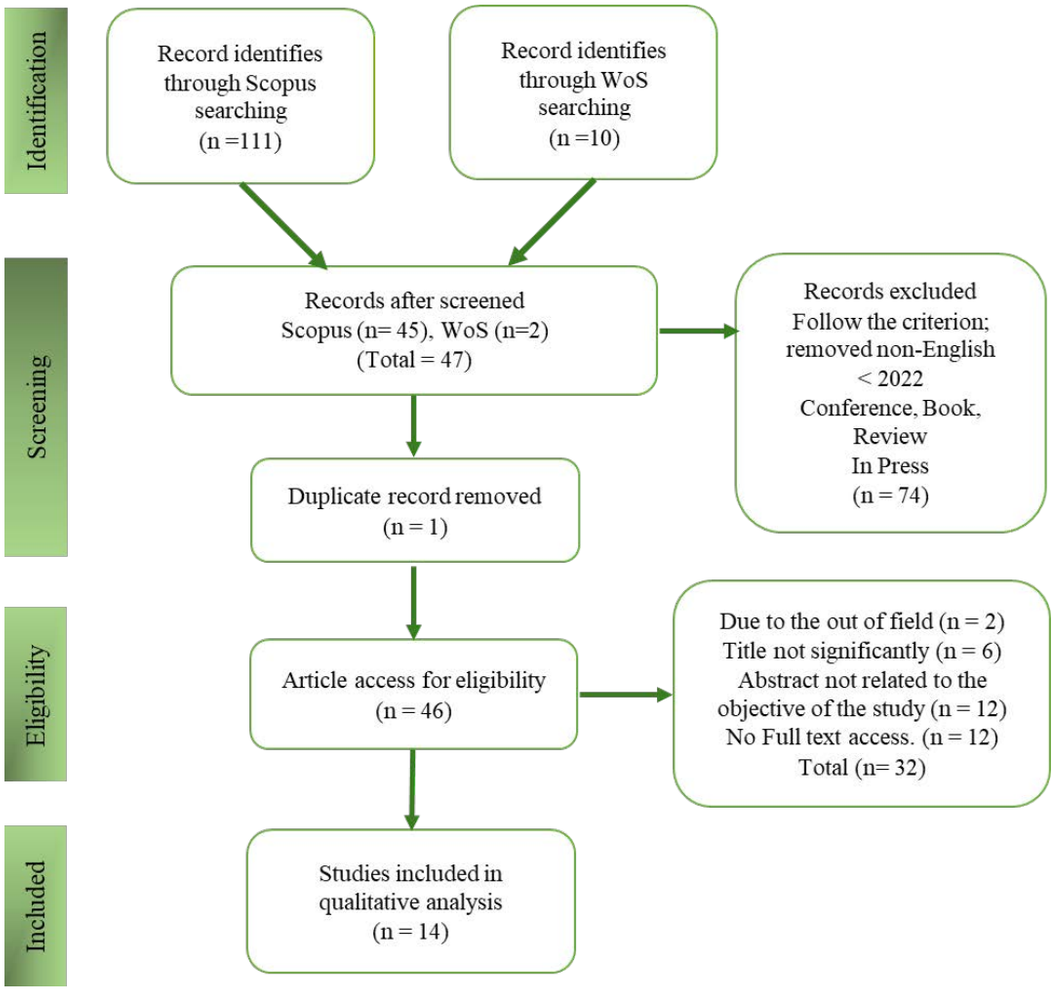

FIGURE 6. Flow diagram of the proposed searching study (Yan & Li 2023)

This review also addresses the role of doping in NBT to enhance its energy density. The findings indicate that the energy density of NBT increases with the addition of multiple dopant types compared to undoped or singly substituted NBT. For example, in the $Na_{0.5}Bi_{0.5-x}Ho_xTiO_3$ samples, with x values of 0.0, 0.5, 1, 2, and 3 mol%, the energy density was measured at only 0.68 J/cm³. The highest energy densities were typically observed under maximum applied electric fields during ferroelectric characterization and at elevated temperatures during evaluation. Articles outside the scope of this review, identified using key words such as medical, mathematics and pharmacy were excluded. Specific topics that were not selected include investigations into pyroelectric, fatigue-free, thin-film and polymer. Studies focusing on magnetic assessments without addressing energy storage or electrical properties were also omitted. In addition, cross-sectional studies and case reports were excluded if full text access was not available through the databases or when authors did not respond to requests made via ResearchGate or email.

RESULTS AND DISCUSSION

ENHANCING ENERGY STORAGE CHARACTERISTICS VIA ADVANCED MATERIALS SCIENCE

Significant progress has been achieved in the study of NBT ceramics, particularly in achieving high recoverable energy density, W_{rec} and energy efficiency, η. Several works highlight the ability to control the material properties by means of doping and structural modifications. Li et al. (2024a) added Mn^{2+} into NBT-based multilayer ceramic capacitors (MLCCs) to prevent Ti^{4+} reduction during sintering process. This adjustment minimized energy wastage and improved polarization, achieving a W_{rec} of 15.7 J/cm³ and η of 95%. The proportional breakdown strength, attributed to <111> grain orientation, increased by 42% thus proving the effectiveness of polarization engineering and grain alignment

In a similar manner, Wang et al. (2023b) utilized $Bi(Mg_{0.5}Sn_{0.5})O_3$ (BMS) doping in NBT-SBT ceramics through the viscous polymer process (VPP). Their technique resulted in a the recoverable or effective polarization, ΔP of 64.6 μC/cm², a breakdown strength (E_b) of 440 kV/cm, and a W_{rec} of 7.5 J/cm³ with fairly stable performance across the 20-120 °C range.

Difeo et al. (2023) observed a structural transition from rhombohedral-tetragonal coexistence to a pure tetragonal phase in NBT–BT ceramics with Nb doping. This compositional modification enhanced the energy storage properties, with a W_{rec} of 0.50 J/cm³ at room temperature, was recorded, highlighting the impact of compositional changes on energy density and piezoelectricity.

STRENGTH DECREASE AND RELAXOR PERFORMANCE IMPROVEMENTS

The dielectric breakdown strength, E_b and relaxor ferroelectric nature of the NBT based ceramics highly influence the energy storage density. Wang (2023) proposed a multi-scale insulation regulation strategy using Sm^{3+} and Mg^{2+}–Nb^{5+} dopants, which increased E_b to 480 kV/cm and W_{rec} to 7.3 J/cm³. This method also improved relaxor properties and thermal stability across a wide temperature range of 25 to 200 ºC by altering the formations of the secondary phases, and destructing the long range ferroelectric domains

Similarly, Sahu & Asthana (2024) synthesised $Na_{0.2}K_{0.3}Bi_{0.5}TiO_3$–Eu (NKBT–Eu) ceramics and attained W_{rec} of 1.7 J/cm³ at a higher E_b of 188 kV/cm. Their work also demonstrated thermal stability, with the dielectric constant ranging within ±20% across 120–500 °C; highlighting the benefits of rare-earth dopants in enhancing relaxor states.

Wang et al. (2022) introduced $CaTiO_3$ into NBT ceramics, which improved relaxor behavior and reduced grain size, achieving a W_{rec} of 1.38 J/cm³ and η of 91.3%. The material also featured an ultrafast discharge rate of 94 ns and a high current density of 1520 A/cm², properties suitable for pulse power application.

THERMAL PERFORMANCE AND ENERGY CONSERVATION ENHANCEMENTS

Thermal stability is essential for practical application of NBT based ceramics. Capacity and energy density one of a material or device, rechargeability, and power density after variation in temperature are other parameters of the key performance. In the $0.8Na_{0.5}Bi_{0.5}TiO_3$-$0.2Sm_{1/3}Sr_{1/2}(Mg_{1/3}Nb_{2/3})O_3$(0.8NBT-0.2SSMN) modified NBT ceramics, Wang (2023a) demonstrated a W_{rec} of (1.77 ± 0.08) mJ/cm³ and η of (82.9 ± 4.3) % across 25–200 °C, which was attributed to multi-scale insulation strategies. Likewise, in Er^{3+} & Dy^{3+} co doped NKBT ceramics, Sahu & Asthana (2024) focused on the thermal stability of ceramics regarding energy storage and dielectric properties under varying temperatures. This basically points to the fact that optimized structural stability and modification by dopants could be employed to achieve improved thermal performance and energy conservation in NBT ceramics.

COMBINED TECHNIQUES FOR HIGH CAPACITANCE ENERGY STORAGE DEVICES

Comprehensive engineering approaches including both compositional and structural modifications, have produced better energy storage. Li et al. (2024a) and Wang et al. (2023b) demonstrated that strategic grain alignment and doping can achieve high W_{rec} and η with robust operational stability under challenging conditions. These findings corroborate those of Difeo et al. (2023) and Wang (2023b) who stress the importance of doping strategies to limit the grain size, increase breakdown strength, and enhance relaxor ferroelectric properties.

DIELECTRIC PROPERTIES: STRUCTURAL MODIFICATIONS AND DIELECTRIC STABILITY

A systematic review of recent studies on NBT-based ceramics reveals how distinct doping strategies significantly enhance dielectric performance. Li et al. (2023b) demonstrated that co-doping with $Sr(Zr_{0.2}Sn_{0.2}Hf_{0.2}Ti_{0.2}Nb_{0.2})O_{3-x}$ (SZSHTN) and $NaNbO_3$ (NN) achieved temperature stability from -35.4 to 224.3°C, with energy density of 2.4 J/cm³ and discharge efficiency of 71%. Similarly, Ho^{3+} modification, investigated by Sekhar et al. (2023), produced monoclinic-tetragonal phase coexistence, yielding 1.88 J/cm³ energy density with 83% efficiency, while simultaneously reducing oxygen vacancies. Li et al. (2023) study on $BaTiO_3$ doping showed tetragonal-to-rhombohedral phase transition, resulting in 38.29 μC/cm² polarization and 80 kV/cm breakdown strength, with dielectric stability up to 200 °C. These findings collectively demonstrate that various doping approaches effectively enhance the structural and dielectric properties of NBT Each method offers specific advantages for high-temperature capacitor applications, where stability and reliability are critical. The systematic analysis confirms that targeted doping strategies successfully modify NBT properties through phase transitions and structural modifications, leading to improved dielectric stability and energy storage capabilities.

RELAXOR BEHAVIOR AND DOMAIN DYNAMICS

The doping nature of NBT modifiers play a role in enhancing relaxor characteristics, enabling ceramics to exhibit complexdielectric properties and improved energy performance. Sahu et al. (2023) examined K^+-rich substituted NBT compositions and identified three domains by applying scaling laws. These compositions displayed peculiar feature of relaxor phase transitions, expressed in terms of polarization, switching current and strain dependence. The study correlated polarization versus electric (P-E) loop morphology to energy storage capability, and found an optimal recoverable energy density of 0.5 J/cm^3 with a breakdown strength of 79 kV/cm in NKBT-30. From this investigation, it was possible to determine the connection between relaxor behavior and ferroelectric domain mechanisms and also gain understanding on how to improve dielectric performance.

Sekhar et al. (2023) also demonstrated relaxor ferroelectric characteristics in Ho^{3+} doped NBT-BT ceramics, in which such doping induced a dynamic condition for domain reversal. Lower oxygen vacancies and better phase stability improve dielectric properties at high temperature. Li et al. (2023) further explored the effect of co-doping in detail and confirmed that the domain flexibility was significantly improved, which was the main reason behind a stable dielectric response within a wide temperature range. These studies establish a clear connection between the dopant-induced relaxor state and enhanced dielectric stability in NBT ceramics. By tuning domain dynamics through doping strategies, the relaxor nature of NBT-based ceramics can be optimized, enabling superior dielectric and energy storage performance.

OPTIMIZED DIELECTRIC AND ENERGY STORAGE INTEGRATION

Dielectric and energy storage properties in NBT based ceramics depend on the polarization behavior, dielectric breakdown strength and thermal stability. Li et al. (2023a) incorporated $BaTiO_3$ (BT) into $Bi_{0.5}Na_{0.5}TiO_3$-$Bi(Mg_{2/3}Nb_{1/3})O_3$ (NBT-BMN) systems and achieved a recoverable energy density of 1.02 J/cm³ together with an efficiency of 62.91%. Enhanced dielectric and energy storage properties resulted from the phase transition that occurred due to BT doping. Sekhar et al. (2023) showed the ability of Ho^{3+} as a dopant to enhance electrocaloric features and luminescence, thus broadened the scope of the NBT ceramics for energy storage and electronics applications.

Li et al. (2023b) pointed out that while co-doping was beneficial for the relaxation and stabilization of the dielectric properties, as well as improved the energy storage capacity. These observations align with earlier work by Sahu et al. (2023) who demonstrated that the change in relaxor behavior, captured through scaling factor, contributed to improved energy storage density. Collectively, these studies underscore the potential of targeted doping strategies and composite formation in NBT systems. By integrating dielectric stability with enhanced energy storage performance, such approaches present a promising pathway for the development of high-capacitance, thermally stable materials tailored to industrial applications.

CLUSTER: THERMAL STABILITY IN MODIFIED NBT CERAMICS

Thermal stability is one of the most important properties that must be considered to achieve high performance in modified NBT ceramics. The thermal characteristics of NBT based ceramics strongly depend on compositional changes, which directly influence phase transitions, polarization dynamics, and relaxor characteristics. Ancy et al. (2023) investigated $(Bi_{0.5}Na_{0.5})TiO_3$-$BaTiO_3$-$BaZrO_3$ (BNT-BT-BZ) ternary ceramics and identified a morphotropic phase boundary (MPB) between tetragonal and rhombohedral phases. When Ba^{2+} and Zr^{4+} ions were introduced into NBT-BT, the grain size was minimized, and transformed the long-range ferroelectric order into a relaxor state. These structural modifications enhanced remnant polarization and coercive field parameters, delivering an energy storage density of 0.655 J/cm³ at 150 °C with η ranging between 74.85–97.38%. These finding highlight the potential of BNT-BT-BZ ceramics for stable energy storage in high temperature conditions

Aggarwal et al. (2023) also observed thermal scaling behavior in NBT-BSZT composites. The incorporation of $Ba_{0.85}Sr_{0.15}Zr_{0.1}Ti_{0.9}O_3$ (BSZT) lowered the Curie temperature and dielectric constants but improved thermal stability. At BSZT contents of x = 0.5 and 0.6, the ceramics achieved energy storage efficiencies of approximately 80% and 85% respectively. These results demonstrate that bifunctional NBT-BSZT ceramics are suitable for applications where performance is influenced bythermal conditions, especially in ferroelectric devices.

Fathabad et al. (2024) studied the impact of $Bi(Mg_{0.5}Ti_{0.5})O_3$ (BMT) doping on the dielectric and electrocaloric properties of NBT-BT ceramics. The incorporation of BMT improved relaxor behavior, reduced the BT maximum polarization value and altered the depolarization temperatures. These adjustments ensured ergodic relaxor behavior at

lower temperatures and emphasized the role of defect dipoles and BMT in suppressing anti ferroelectric transitions. The optimized NBT-5BT-10BMT composition demonstrated promising potential for energy storage, owing to its favorable kinetics and thermal flexibility.

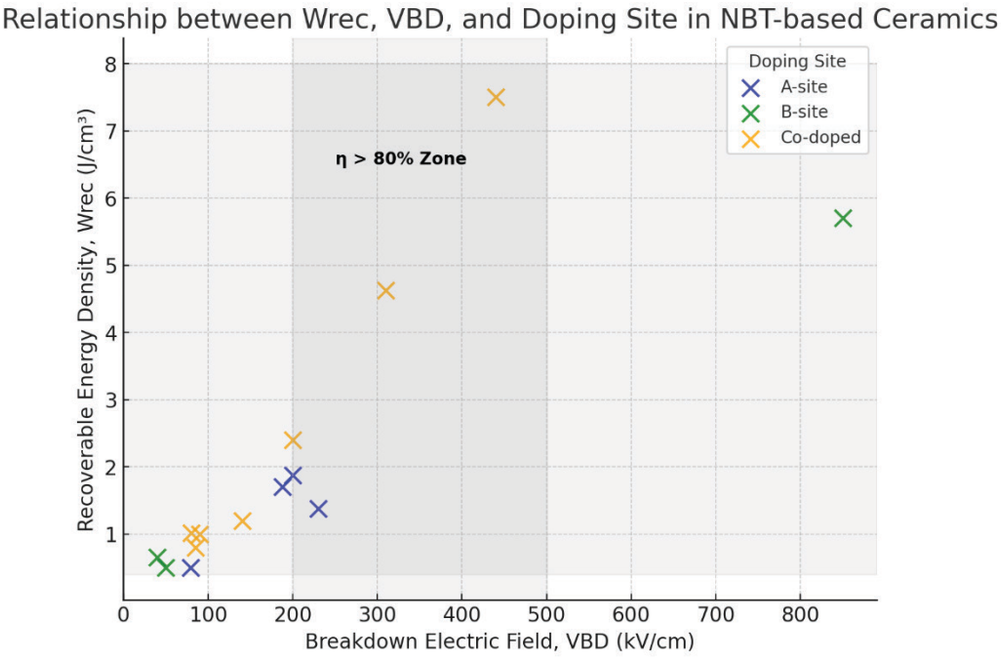

FIGURE 7. Relationship between recoverable energy density (W_{rec}) and breakdown electric field (VBD) for various doping sites in NBT-based ceramics. The shaded region indicates the high-efficiency zone (η > 80%).

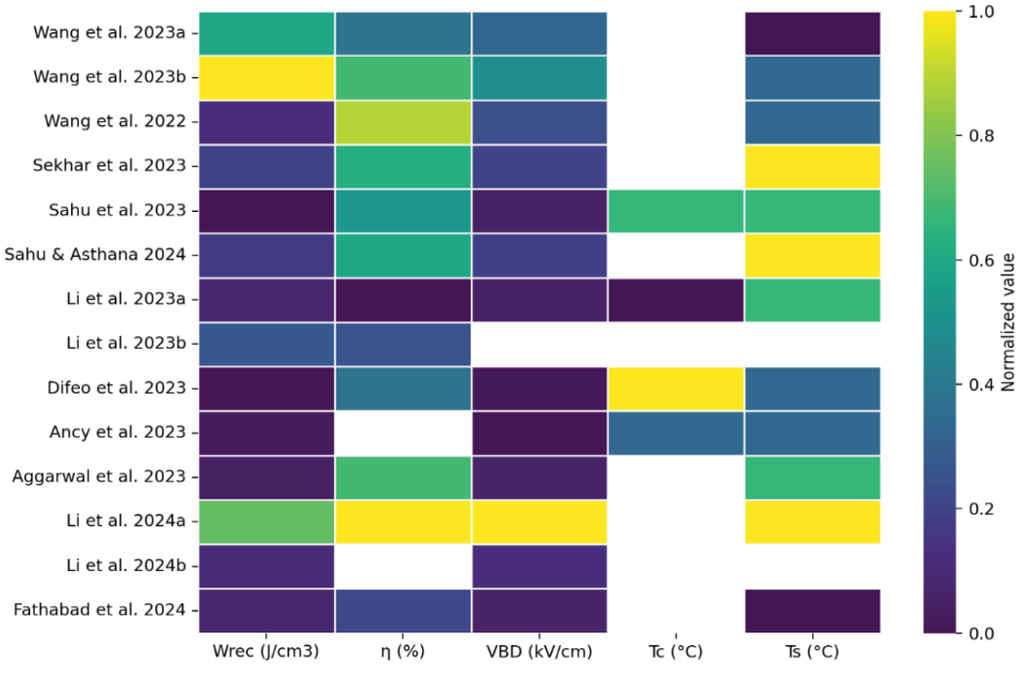

FIGURE 8. Comparison of normalized parameters (W_{rec}, η, VBD, Tc, and Ts) for various doped NBT-based ceramics reported in recent studies. The heatmap highlights performance variations across different compositions, showing that no single system achieves simultaneous optimization of all properties.

Figure 7 shows the relationship between recoverable energy density (Wrec) and breakdown electric field (VBD) for various doping systems in $Na_{0.5}Bi_{0.5}TiO_3$ (NBT)-based ceramics. The color represents the dominant doping site: A-site (blue), B-site (green), and co-doped (orange). The grey-shaded region indicates the high-efficiency zone (η > 80%). Most co-doped systems exhibit W_{rec} > 0.4 J/cm³ and VBD within 200–500 kV/cm, demonstrating the effectiveness of the co-doping strategy in enhancing the energy storage performance of NBT-based materials. While Figure 8 shows doping in NBT ceramics reveals a trade-off between W_{rec}, η%, and BDV. Optimal performance occurs at mid-BDV with mid-to-high W_{rec}, where reversible polarization is maximized without excessive conduction.A-site doping favors efficiency, while B-site doping mainly affects dielectric strength.

ELECTROCALORIC EFFECTS AND RELAXOR PROPERTIES

The electrocaloric effect (ECE) plays an important role in the thermal properties of NBT based ceramics and has applications in areas such as solid state cooling (Ma, 2022). Fathabad et al. (2024) reported that the incorporation of $Bi(Mg_{0.5}Ti_{0.5})O_3$ (BMT) into NBT-BT enhanced the relaxor characteristics of the material, as evidenced by dielectric spectroscopy The absence of a negative ECE was confirmed through direct calorimetric measurements based on Maxwell's relation. The authors explained that the hysteresis loops were formed by defect dipoles, where the pinning of the signal to the loop was attributed to defect effects rather than antiferroelectric behavior. This work demonstrated that the incorporation of BMT successfully improved both ECE and relaxor properties, and opening new opportunities forhigh-performance dielectrics with enhanced thermal characteristics.

Aggarwal et al. (2023) supported these results with respect to the thermal scaling of constrained hysteresis loops. Their analysis of loop areas helped identify BSZT content as one of the factors influencing energy storage efficiency in terms of under different thermal conditions. On the other hand, Ancy et al. (2023) strengthened the link between relaxor characteristics and thermal stability, showing that phase transformations in BNT-BT-BZ ceramics ensure stable performance across a wide temperature range.

INTEGRATED THERMAL ADAPTABILITY FOR ENERGY STORAGE APPLICATIONS

The studies involving structural adjustments combined with thermal property enhancements have significantly advancedthe development of NBT-based ceramics for energy storage applications. Ancy et al. (2023), Aggarwal et al. (2023) and Fathabad et al. (2024) focused on doping strategies to enhance thermal and dielectric stability. Through these Ba^{2+} and Zr^{4+} substitutions, BSZT composition modification and BMT doping, these studies showed the potential of well-designed NBT ceramics for efficient and reliable performance under thermal conditions. The observed phenomena suggest that phase stability, energy storage performance and electrocaloric effects are critical features for lead-free dielectric materials. Table 5 summarizes the selected studies retrieved from Scopus and WoS databases.

TABLE 5. Summary of selected research articles retrieved from Scopus and WoS (2022–2024) using the proposed search criteria.

Article objective	Sample equation	Calcination temperature, T_c/ duration Sintering temperature, T_s/ duration	Energy storage density (W_{rec}) energy efficiency (η); dielectric loss (ε''); breakdown voltage (V_{BD}); measurement temperature (T_m)	Reference
Improve energy storage performance with $Bi(Mg_{0.5}Hf_{0.5})O_3$ doping in NBT ceramics	$(1-x)\ Na_{0.5}Bi_{0.5}TiO_3–xBi(Mg_{0.5}Hf_{0.5})O_3$	T_s = 1100 °C/3 h	W_{rec} = 4.63 J/cm³; η = 75.1%; ε'' = moderate; V_{BD} = 310 kV/cm; T_m = 30–100 °C	Wang et al., 2023a
Enhance energy storage performance in NBT-SBT ceramics via a stepwise optimization route	$0.92(0.65Na_{0.5}Bi_{0.5}TiO_3)–0.35(Sr_{0.85}Bi_{0.1}TiO_3)–0.08Bi(Mg_{0.5}Sn_{0.5})O_3$	T_s = 1150 °C/2 h	W_{rec} = 7.5 J/cm³; η = 85%; ε'' = low; V_{BD} = 440 kV/cm; T_m = 20–120 °C	Wang et al. 2023b

continue...

... cont.

Optimize dielectric relaxor properties for energy storage performance	$0.8Bi_{0.5}Na_{0.5}TiO_3$–$0.2CaTiO_3$	T_s = 1150 °C	W_{rec} = 1.38 J/cm³; η = 91.3%; ε'' = low; V_{BD} = 230 kV/cm; T_m = ambient	Wang et al. 2022
Study energy storage, electrocaloric, and optical properties of NBT-BT with Ho modification	Ho-modified $Na_{0.5}Bi_{0.5}TiO_3$–$BaTiO_3$	T_s = 1250 °C/2 h	W_{rec} = 1.88 J/cm³; η = 83%; ε'' = moderate; V_{BD} = 200 (kV/cm); T_m = high temp (373 K)	Sekhar et al. 2023
Investigate relaxor and energy storage properties in NBT with K^+ doping	$Na_{0.5}Bi_{0.5}TiO_3$–K^+	T_c = 900 °C T_s = 1200 °C/2 h	W_{rec} = 0.5 J/cm³; η = ~80%; ε'' = moderate; V_{BD} = 79 kV/cm; T_m = ambient	Sahu et al. 2023
Improve energy storage performance and thermal stability in NKBT ceramics with Eu doping	$Na_{0.2}K_{0.3}Bi_{0.5}TiO_3$–Eu	T_s = 1250 °C/2 h	W_{rec} = 1.7 J/cm³, η = 82%, ε'' = low; V_{BD} = 188 kV/cm; T_m = 45–85°C	Sahu & Asthana 2024
Optimize relaxor dielectric properties with $BaTiO_3$ doping	$0.94Na_{0.5}Bi_{0.5}TiO_3$– $0.06Bi(Mg_2/3Nb_1/3)O_3$	T_c = 800 °C, T_s = 1200 °C/3 h	W_{rec} = 1.02 J/cm³; η = 62.91%; ε'' = moderate; V_{BD} = 80 kV/cm; T_m = 200 °C	Li et al. 2023a
Investigate the effect of NN co-doping and high-entropy perovskite oxide on the phase structure, microstructure, and dielectric properties of NBT-based lead-free ceramics.	$(1-x)(0.75Na_{0.5}Bi_{0.5}TiO_3)$ – $0.25Sr(Zr_{0.2}Sn_{0.2}Hf_{0.2}Ti_{0.2}Nb_{0.2})O_3$– $xNaNbO_3$	T_c = 850 °C/3h (first process); T_c = 1360 °C/6 h (second process); T_s = 1200–1250°C/2 hours	W_{rec} = 2.4 J/cm³; η = 71%	Li et al. 2023b
Optimize dielectric relaxor and energy storage properties through Nb doping	$0.94Bi_{0.5}Na_{0.5}TiO_3$– $0.06BaTiO_3$–xNb_2O_5	T_c = 950 °C, T_s = 1150 °C/2 h	W_{rec} = 0.5 J/cm³; η ~75%, ε'' = moderate; V_{BD} = 50 (kV/cm); T_m = ambient,	Difeo et al. 2023
Evaluate energy storage capability in BNBTZ ceramics at various temperatures	$1-(x + y)$ $(Bi_{0.5}Na_{0.5})TiO_3$– $xBaTiO_3$–$yBaZrO_3$	T_c = 850 °C, T_s = 1150 °C/3 h	W_{rec} = 0.655 J/cm³; η = 74.85–97.38%; ε'' = moderate; V_{BD} = 40 kV/cm; T_m = 150 °C	Ancy et al. 2023
Investigate thermal scaling and constrained hysteresis in NBT-BSZT system	(1-x) $Na_{0.5}Bi_{0.5}TiO_3$– (x) $Ba_{0.85}Sr_{0.15}Zr_{0.1}Ti_{0.9}O_3$	T_s = 1200 °C/2 h	W_{rec} = 0.8 J/cm³; η = ~85%; ε'' = moderate; V_{BD} = 85 kV/cm; T_m = ambient	Aggarwal et al. 2023
Optimize energy storage performance through grain alignment and Mn^{2+} doping	$(1-x)(0.65Na_{0.5}Bi_{0.5}TiO_3$– $0.35Sr_{0.7}Bi_{0.2}TiO_3$– $xMnO_2$	T_s = 1250 °C	W_{rec} = 5.7 J/cm³; η > 95% ε'' = low; V_{BD} = 850 kV/cm; T_m = ambient	Li et al. 2024a
	$0.92Na_{0.5}Bi_{0.5}TiO_3$– $0.08CaHfO_3$	T_s = 1100–1140 °C/2 h	W_{rec} =1.2 J/cm³; V_{BD} =140 kV/cm	Li et al. 2024b
Evaluate negative electrocaloric potential in NBT-BT with $Bi(Mg_{0.5}Ti_{0.5})O_3$	(1-x) $[0.95(Na_{0.5}Bi_{0.5})TiO_3$–$0.05BaTiO_3]$– (x) $Bi(Mg_{0.5}Ti_{0.5})O_3$	T_s = 1100 °C	W_{rec} = 1.0 J/cm³; η = ~70%; ε'' = moderate; V_{BD} = 90 kV/cm; T_m = ambient	Fathabad et al. 2024

CONCLUSION

The reviewed studies indicate that NBT-based ceramics can achieve significant performance improvements through precise compositional modifications. Strategic doping emerges as a crucial method for improving energy storage, electrical conductivity, and dielectric properties of NBT ceramics. These enhancements are particularly valuable in applications requiring high temperature stability and low dielectric losses.

It is evident from the studies that structural modifications of the oxide material are closely related to the functional characteristics of NBT ceramics. This includes variations in dopants and co-dopants, which significantly influence the overall energy conversion efficiency. The observed changes in dopant concentration and targeted doping strategies are extremely crucial because they make NBT-based ceramics electrically more stable and permit the use of in more complex electronics devices.

Recent publications indicate that substitutional doping in NBT has led to increased energy densities ranging from of 0.5 to 7.13 J/cm^3, depending on the dopant material and the doping method employed. Strategic doping whether at the A-site or B-site results in major structural reconfigurations such as phase shifting, minimization of oxygen vacancies, and controlled dielectric losses which together enhance efficiency and thermal stability. However, most of the solid oxide developments remain at Technology Readiness Levels (TRLs) 3 to 5, as defined by NASA's TRL scale (NASA 2025), and have not yet reached the industrial applications stage at TRL 8–9 levels.

The primary gap in the current literature lies in the challenge of enhancing breakdown strength and energy storage density without compromising permittivity and stability across different environments. Future studies should focus on optimizing the composition and microstructure of NBT-based materials. This includes exploring new dopants and composite structures, as well as fabrication and processing methodologies to achieve high permittivity dielectrics with high breakdown strength.

More importantly, different methods of doping, such as varying sintering temperatures, applying electric field pressures or employing different chemical integration techniques, significantly affect the resultant properties, even when using the same dopant materials. For example, Li^+ doping at comparatively low sintering temperatures can induce phase transformation into a higher symmetric structure, thereby improving energy density and dielectric characteristics compared to conventional doping technique. Furthermore, fundamental issues regarding the microstructural enhancement and the dielectric loss tan δ, reduction should be addressed to enhance the practical application of NBT ceramics. In the long term, there is a need for a more systematic approach in choosing materials and doping techniques toward the practical deployment of NBT in next-generation capacitive and sensor devices, as a step toward TRL 8–9.

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DECLARATION OF COMPETING INTEREST

None.

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