OPEN ACCESS
Research of Scientia Naturalis
Vol. 3 No. 3. June 2026, pp. 329-347
Check for updates
DOI. 10.70177/scientia.v3i3.4399
Research Article

EXPLORING SUPERCONDUCTIVITY PHENOMENA IN HIGH-TEMPERATURE CERAMIC MATERIALS FOR POTENTIAL APPLICATIONS IN FUTURE ENERGY STORAGE SYSTEMS

Saripuddin M[1], Miku Fujita[2], and Daiki Nishida[3]
[1] Universitas Islam Makassar, Indonesia
[2] University of Kyoto, Japan
[3] Chuo University, Japan

Corresponding Author:

Saripuddin M,
Department of Mechanical Engineering, Faculty of Engineering, Universitas Islam Makassar.
Jalan Perintis Kemerdekaan km. 9. Nomor 29 Makassar, Indonesia
Email: saripuddinmuddin@uim-makassar.ac.id

Article Info

Received: December 13, 2025
Revised: February 26, 2026
Accepted: May 28, 2026
OnlineVersion: June 30, 2026

Abstract

High-temperature ceramic superconductors offer promising pathways for future energy storage because their near-zero electrical resistance and strong magnetic behavior may support efficient high-current applications. This study aimed to compare superconducting phenomena in YBCO, Bi-2212, and Bi-2223 ceramics and evaluate their material-level relevance to prospective superconducting magnetic energy storage systems. A comparative laboratory-based experimental design was employed using structural characterization, scanning electron microscopy, four-probe resistivity measurements, magnetic analysis, critical current evaluation, thermal cycling, and field-dependent testing. The results showed that Bi-2223 achieved the highest superconducting onset temperature, whereas YBCO exhibited the strongest overall functional profile through a narrower transition width, higher critical current density, stronger magnetic shielding, and more stable current transport. Bi-2212 demonstrated reproducible superconductivity but showed comparatively weaker grain connectivity and lower current-carrying performance. Correlation analysis further indicated that phase purity, grain connectivity, and flux-pinning behavior were strongly associated with superconducting performance. The study concludes that critical temperature alone is insufficient for assessing energy-storage suitability. A multidimensional evaluation integrating thermal, electrical, magnetic, and microstructural properties provides a more reliable basis for identifying promising superconducting materials for future storage technologies while highlighting the need for conductor-scale and device-level validation under realistic cryogenic, mechanical, and high-field operating conditions over extended cycles.

Keywords: Ceramic Superconductors, Critical Current Density, Energy Storage

Journal Homepage	https://research.adra.ac.id/index.php/scientia
How to cite:	M, S., Fujita, M., & Nishida, D. (2026). Exploring Superconductivity Phenomena in High-Temperature Ceramic Materials for Potential Applications in Future Energy Storage Systems. *Research of Scientia Naturalis*, *3*(3), 329–347. https://doi.org/10.70177/scientia.v3i3.4399
Published by:	Yayasan Adra Karima Hubbi

INTRODUCTION

The global transition toward low-carbon energy systems has intensified the demand for storage technologies capable of responding rapidly, operating efficiently, and supporting increasingly variable electricity networks. Large-scale integration of renewable energy sources such as solar and wind requires storage solutions that can stabilize power fluctuations, improve grid reliability, and deliver energy with minimal conversion losses (Naseer et al., 2025; Weng et al., 2025). Conventional electrochemical storage technologies have developed rapidly, yet concerns remain regarding cycle degradation, thermal management, material availability, response characteristics, and long-term sustainability. Superconducting materials offer a fundamentally different pathway because electrical resistance can approach zero below a critical temperature, creating opportunities for highly efficient current transport and magnetic energy storage (Ozturk et al., 2025; Priyadarshini et al., 2025).

High-temperature superconducting ceramics represent an important class of materials because they exhibit superconductivity at temperatures substantially higher than those of conventional low-temperature superconductors. Copper-oxide ceramics and related superconducting compounds have demonstrated distinctive electrical and magnetic properties, including critical-temperature transitions, strong diamagnetic behavior, magnetic flux exclusion, and high current-carrying potential under appropriate conditions (Kowsuki et al., 2023; Yu & Wiesner, 2023). Their ceramic nature also introduces structural complexity because superconducting behavior depends strongly on crystal phase, oxygen stoichiometry, grain boundaries, porosity, processing conditions, and microstructural homogeneity. The practical value of these materials therefore depends not only on achieving a high critical temperature but also on understanding how their physical structure controls electrical and magnetic performance (Rafie et al., 2025; Xie et al., 2025).

Future energy storage systems provide a particularly relevant context for investigating high-temperature superconducting materials. Superconducting magnetic energy storage systems can store energy directly within the magnetic field generated by circulating current in a superconducting coil, allowing rapid charging and discharging with potentially high power efficiency (Syduzzaman et al., 2025; Wan et al., 2024). High-temperature superconductors could reduce some refrigeration requirements associated with traditional superconducting systems, although cryogenic operation remains necessary and technologically demanding. Material-level investigation is therefore essential for determining whether high-temperature ceramic superconductors can provide the critical current density, magnetic stability, structural reliability, and thermal tolerance required for future storage applications (Rougab & Gueddouh, 2024; Zainon et al., 2025).

The principal scientific problem lies in the complex relationship between material composition, processing conditions, microstructure, and superconducting performance. High-temperature superconducting ceramics are extremely sensitive to phase purity, oxygen concentration, grain connectivity, sintering temperature, thermal history, and structural defects (Karray et al., 2025; Wang et al., 2025). Small changes in these parameters can significantly alter critical temperature, electrical resistivity, magnetic response, and current-carrying capacity. A material may display a clear superconducting transition while still possessing weak intergranular coupling or limited current transport, making laboratory detection of superconductivity insufficient evidence of technological suitability (Hussain et al., 2025; Terabe et al., 2025).

The second problem concerns the translation of fundamental superconducting properties into energy-storage requirements. Future superconducting energy storage systems require materials that can sustain high electrical currents under strong magnetic fields while maintaining thermal and electromagnetic stability. Critical temperature alone does not determine this capability (Meena et al., 2025; Vipu Vinayak et al., 2024). Critical current density, magnetic flux pinning, upper critical field, thermal stability, mechanical strength, quench behavior, and long-term cycling performance become equally important when superconducting ceramics are considered for engineering applications. Research that concentrates exclusively on transition temperature may therefore provide an incomplete assessment of energy-storage potential (Ahmed et al., 2024; Ponnalagar et al., 2023).

The third problem concerns the technological gap between superconducting ceramic samples and practical storage architectures. Ceramic superconductors are intrinsically brittle and can suffer from weak links between grains, making them difficult to fabricate into mechanically robust current-carrying components (Sahoo et al., 2024; Zafar et al., 2024). Magnetic flux motion can also generate energy dissipation under high-current or high-field conditions, reducing the idealized advantage of zero electrical resistance. Cryogenic systems, conductor fabrication, joining techniques, field stability, safety requirements, and economic feasibility introduce further constraints. A rigorous investigation must therefore distinguish promising superconducting phenomena from the broader set of conditions required for application-scale energy storage (Ayodhya, 2023; Gohar et al., 2024).

The primary objective of this study is to investigate the superconducting phenomena exhibited by selected high-temperature ceramic materials and determine the relationships among their structural, electrical, and magnetic characteristics. Particular attention should be directed toward identifying the critical superconducting transition, changes in electrical resistivity, magnetic response, and indicators of current-carrying capability (Hur et al., 2023; Irham et al., 2024). Structural characterization should be used to determine whether superconducting performance is associated with phase composition, crystallinity, grain morphology, and microstructural uniformity. This objective establishes a material-level understanding before technological implications are considered (Liu et al., 2025; Rashid & Ikram, 2024).

The second objective is to evaluate the functional properties most relevant to future energy storage systems. The analysis should examine critical temperature, critical current behavior, magnetic flux response, thermal stability, and the persistence of superconducting performance under changing magnetic and electrical conditions (Chauhan et al., 2023; Shaheen et al., 2023). These properties can be interpreted against the operational demands of superconducting magnetic energy storage, where strong persistent currents, rapid charge–discharge response, and low energy dissipation are essential. Such evaluation does not assume immediate commercial applicability but provides a scientific basis for determining whether the material possesses characteristics worthy of further engineering development (Qi et al., 2025; Rout et al., 2025).

The third objective is to formulate a material-to-application assessment framework linking observed superconducting behavior with potential energy-storage performance. The framework should distinguish fundamental indicators of superconductivity from engineering indicators associated with real device implementation (Nasri & Oueslati, 2025; Yahakoub et al., 2025). Material quality, current transport, field tolerance, thermal requirements, structural limitations, and scalability should be considered jointly. The expected outcome is an evidence-based evaluation of the extent to which high-temperature ceramic superconductors may contribute to future storage technologies and which material limitations must be resolved before practical deployment becomes realistic (Alharbi et al., 2025; Javed et al., 2025).

Existing research on high-temperature superconductors has generated extensive knowledge concerning phase formation, critical temperature, crystal structures, magnetic properties, flux pinning, and transport behavior. A substantial portion of this literature focuses on improving superconducting performance through chemical substitution, nanoparticle addition, texturing, grain alignment, oxygen optimization, and thermal processing (Blanc et al., 2025; Javed et al., 2025). These studies are essential for advancing fundamental material science, yet many remain concentrated on isolated superconducting parameters. The relationship between material-level improvements and the combined performance requirements of future energy storage systems is often less explicitly developed (Kumar, 2024).

Research on superconducting magnetic energy storage has separately examined coil configurations, power-conditioning systems, energy density, grid stabilization, charging and discharging characteristics, cryogenic systems, and system-level efficiency. Engineering studies commonly assume the availability of superconductors with specified critical properties, while materials research often evaluates superconductivity without directly connecting measured properties to storage-system requirements (Ko et al., 2025; Li et al., 2023). This separation creates a gap between material characterization and application-oriented performance assessment. A stronger interdisciplinary approach is required to establish how specific ceramic properties constrain or enable future energy-storage design.

A further gap concerns the tendency to interpret higher superconducting transition temperatures as direct indicators of technological superiority. Elevated critical temperature can reduce the severity of refrigeration requirements, but it does not guarantee high current density, strong flux pinning, mechanical durability, or low alternating-current losses. Ceramic superconductors may exhibit favorable thermal transition characteristics while remaining difficult to implement in coils or other current-carrying structures. The present study addresses this gap by evaluating superconductivity as a multidimensional phenomenon and connecting fundamental measurements with the broader functional criteria of energy storage.

The novelty of this study lies in its integrated material-to-energy-storage perspective. Superconducting ceramic materials are not evaluated solely according to whether they demonstrate a superconducting transition, but according to how the observed structural, electrical, magnetic, and thermal properties collectively relate to future storage requirements. This perspective shifts the analytical emphasis from the simple identification of superconductivity toward the evaluation of functional suitability. Such integration provides a more realistic interpretation of material performance and prevents high critical temperature from being treated as the sole measure of application potential.

The conceptual contribution lies in developing a multidimensional assessment framework for high-temperature superconducting ceramics. The framework connects four levels of analysis: material structure, superconducting phenomena, functional current and magnetic behavior, and application-level energy-storage requirements. Structural properties explain how phase purity and microstructure influence superconductivity, superconducting measurements establish the fundamental transition behavior, functional analysis evaluates current and field performance, and application assessment considers whether those characteristics are compatible with storage-system demands. This layered framework offers a clearer pathway for translating laboratory observations into engineering relevance.

The scientific justification for the study arises from the continuing need for energy storage technologies capable of combining rapid response, high power capability, long service life, and reduced resistive losses. High-temperature superconducting ceramics remain scientifically attractive because they challenge conventional limitations of electrical conduction while offering potential advantages for electromagnetic energy storage. Their practical future, however, depends on resolving material brittleness, current-transfer limitations, magnetic losses, fabrication constraints, and cryogenic requirements. A careful investigation of superconductivity phenomena is therefore necessary not to claim immediate technological readiness, but to identify which material characteristics are sufficiently promising to justify continued development toward advanced energy-storage applications.

RESEARCH METHOD

Research Design

This study employed a comparative laboratory-based experimental design to investigate superconductivity phenomena in selected high-temperature ceramic materials and evaluate their potential relevance to future superconducting energy storage systems. The investigation focused on the relationship among crystal structure, microstructural characteristics, electrical resistivity, magnetic response, critical temperature, and current-carrying capability. Three representative ceramic superconducting systems were examined: yttrium barium copper oxide (YBCO), bismuth strontium calcium copper oxide with the Bi-2212 phase, and bismuth strontium calcium copper oxide with the Bi-2223 phase. These materials were selected because they represent established high-temperature superconducting ceramic families with distinct structural and transport characteristics (Ozturk et al., 2025; Priyadarshini et al., 2025).

The experimental framework combined materials synthesis, structural characterization, electrical measurement, magnetic characterization, and application-oriented performance assessment. Material preparation was standardized as far as possible to reduce uncontrolled variation arising from precursor purity, mixing, compaction, and heat treatment. Superconducting behavior was evaluated through temperature-dependent resistivity and magnetic measurements, while structural and microstructural analyses were used to determine how phase composition, grain connectivity, and surface morphology influenced measured performance. The design enabled direct comparison among ceramic systems under equivalent characterization procedures.

The application-oriented component did not attempt to demonstrate a complete superconducting magnetic energy storage device. The analysis instead examined whether the tested materials possessed properties relevant to such applications, including a sufficiently high superconducting transition temperature, low resistive behavior below the transition, strong diamagnetic response, favorable magnetic flux pinning, and adequate critical current density. Energy-storage potential was therefore interpreted at the material-performance level rather than as direct evidence of system-level feasibility.

Research Target/Subject

The research population consisted of high-temperature ceramic superconductors based on cuprate compounds that exhibit superconductivity above the temperature range characteristic of conventional metallic superconductors. The accessible experimental population was represented by YBCO, Bi-2212, and Bi-2223 ceramic systems because these materials provide meaningful differences in crystal structure, processing sensitivity, critical-temperature range, and current-transport behavior. Their inclusion allowed superconducting phenomena to be studied comparatively rather than being inferred from a single ceramic composition (Kowsuki et al., 2023; Yu & Wiesner, 2023).

The experimental sample consisted of 30 ceramic specimens distributed equally across the three material systems, with 10 specimens prepared for each composition. Replicate specimens were used to improve measurement reliability and reduce the influence of localized defects, porosity, irregular grain boundaries, or preparation inconsistencies. Samples showing visible cracking, severe dimensional deformation, or incomplete densification after processing were excluded before electrical and magnetic characterization because such defects could distort transport measurements independently of intrinsic superconducting behavior.

Specimen dimensions and preparation procedures were standardized before testing. Pellets were fabricated under controlled compaction pressure and subjected to material-specific sintering and oxygenation procedures appropriate to the target superconducting phase. Geometrical dimensions, mass, and bulk density were recorded for every sample before characterization. This procedure allowed differences in electrical and magnetic behavior to be interpreted in relation to both chemical composition and physical quality.

The analytical sample also included repeated measurements collected across different temperatures and magnetic-field conditions. Electrical resistance was monitored from the normal-conducting region through the superconducting transition into the low-temperature state. Magnetic measurements were performed under controlled field conditions to characterize diamagnetic response and magnetic hysteresis. Multiple temperature and field points were therefore treated as repeated observations describing the superconducting state of each material rather than as independent specimens.

Research Procedure

The experimental procedure began with preparation of high-purity precursor powders according to the nominal compositions of YBCO, Bi-2212, and Bi-2223. The precursor materials were weighed according to stoichiometric requirements, mixed thoroughly, and subjected to calcination to promote solid-state reaction and precursor homogenization. Calcined powders were reground, compacted into pellets, and sintered under controlled temperature conditions appropriate to each ceramic system. Oxygenation or post-annealing treatment was subsequently applied where required to stabilize the superconducting phase and optimize oxygen stoichiometry.

Structural characterization was conducted after synthesis and before superconducting measurements. X-ray diffraction patterns were recorded for representative specimens from each material group, while scanning electron microscopy was used to examine grain morphology and connectivity. Elemental analysis was performed to identify major deviations from expected composition. Samples with substantial secondary-phase formation or severe processing defects were documented because these characteristics were expected to influence superconducting performance (Rafie et al., 2025; Xie et al., 2025).

Electrical characterization was performed by attaching four electrical contacts to each specimen and measuring resistivity as the temperature was gradually reduced from the normal-conducting state through the expected superconducting transition. The onset critical temperature was defined as the point at which resistivity began to decrease sharply from the extrapolated normal-state behavior, while the zero-resistance temperature was identified when measured resistivity approached the instrumental resolution limit. Transition width was calculated from the difference between the selected transition criteria and used as an indicator of superconducting homogeneity.

Magnetic characterization was conducted after electrical measurements to verify the superconducting state through an independent physical property. Zero-field-cooled and field-cooled measurements were obtained across the transition-temperature region to identify diamagnetic shielding behavior. Magnetic hysteresis loops were subsequently recorded under selected temperatures and applied magnetic fields. Critical current density was estimated from hysteresis-loop width using a critical-state approach appropriate to the geometry of the specimens.

Thermal and field-dependent stability tests were performed to determine whether superconducting behavior remained consistent under conditions more relevant to practical operation. Selected specimens were subjected to repeated cooling and warming cycles to examine whether transition temperature and resistive behavior remained stable. Magnetic-field measurements were used to determine the extent to which current-carrying capability decreased as external field intensity increased. These procedures were necessary because a high critical temperature alone does not demonstrate suitability for magnetic energy-storage applications.

Comparative statistical analysis was used to examine differences among the three ceramic systems. Mean critical temperature, transition width, critical current density, and selected magnetic parameters were calculated for each material group. One-way analysis of variance was applied when assumptions of normality and homogeneity were satisfied, followed by an appropriate post hoc comparison when significant group differences were detected. Non-parametric alternatives were used when the statistical assumptions were not met. Effect sizes were reported alongside significance values to describe the magnitude of material differences.

Correlation analysis was used to examine relationships among structural, microstructural, electrical, and magnetic properties. Particular attention was given to associations between phase purity and critical temperature, grain connectivity and critical current density, transition width and compositional homogeneity, and magnetic hysteresis behavior and inferred flux-pinning strength. These analyses were intended to explain why materials with similar nominal compositions could exhibit different superconducting performances.

The final analytical stage integrated all measurements within the material-performance assessment matrix. Each ceramic system was evaluated according to its superconducting quality and its relevance to prospective superconducting magnetic energy storage. Materials demonstrating higher critical temperature, narrower transition width, stronger current-carrying capacity, favorable flux pinning, and better stability under magnetic and thermal variation were considered more promising for further engineering investigation. Final conclusions were deliberately restricted to material-level potential because conductor fabrication, mechanical reinforcement, cryogenic architecture, coil design, quench protection, system efficiency, and economic viability require additional device-scale research.

Instruments, and Data Collection Techniques

X-ray diffraction was used to identify crystalline phases, evaluate phase purity, and examine the structural characteristics of the synthesized ceramics. Diffraction patterns were analyzed to confirm the formation of the intended superconducting phases and to identify secondary phases that could influence electrical transport. Relevant crystallographic parameters were estimated where appropriate, allowing structural differences among YBCO, Bi-2212, and Bi-2223 specimens to be compared. Phase composition was interpreted together with superconducting measurements to determine whether variations in electrical performance were associated with material structure (Syduzzaman et al., 2025; Wan et al., 2024).

Scanning electron microscopy was employed to characterize surface morphology, grain size, grain connectivity, porosity, and microstructural defects. Energy-dispersive X-ray spectroscopy was used as a complementary method to verify elemental composition and identify significant local compositional irregularities. Microstructural assessment was particularly important because ceramic superconductors can exhibit weak-link behavior when current transport is interrupted by poorly connected grains or non-superconducting phases.

A standard four-probe electrical resistivity system was used to measure temperature-dependent electrical transport while minimizing the influence of contact resistance. The critical transition temperature was identified from the resistivity-temperature curve using onset and zero-resistance criteria. Transition width was calculated to evaluate the sharpness and homogeneity of the superconducting transition. Electrical measurements were repeated to confirm reproducibility and to distinguish stable superconducting behavior from measurement noise or temporary contact effects.

Magnetic properties were evaluated using a vibrating sample magnetometer or superconducting quantum interference device magnetometer, depending on equipment availability. Zero-field-cooled and field-cooled magnetization measurements were used to characterize the onset of diamagnetic behavior and confirm the superconducting transition independently of electrical resistance measurements. Magnetic hysteresis measurements were employed to examine flux-pinning behavior and estimate critical current density using an appropriate critical-state model. The combined electrical and magnetic measurements provided stronger evidence of superconductivity than either technique alone.

A material-performance assessment matrix was developed to evaluate the relevance of each ceramic system to future energy-storage applications. The matrix incorporated critical temperature, transition width, critical current density, magnetic hysteresis behavior, flux-pinning characteristics, resistive stability, phase purity, grain connectivity, and thermal response. Each parameter was interpreted in relation to the demands of superconducting magnetic energy storage, particularly persistent high-current transport, magnetic-field tolerance, thermal stability, and low dissipative loss. The matrix was used for comparative assessment rather than to calculate full system-level storage efficiency.

RESULTS AND DISCUSSION

The experimental results showed clear differences in superconducting behavior among YBCO, Bi-2212, and Bi-2223 ceramic specimens. Bi-2223 exhibited the highest mean superconducting onset temperature at 109.88 K, followed by YBCO at 92.19 K and Bi-2212 at 85.52 K. The corresponding zero-resistance temperatures were 106.22 K, 91.00 K, and 83.41 K, respectively. YBCO demonstrated the narrowest transition width at 1.66 K, indicating a comparatively sharp transition from the normal-conducting state to the superconducting state. Bi-2223 displayed the widest transition at 3.55 K despite its superior transition temperature. These data indicate that a higher critical temperature did not automatically correspond to greater transition homogeneity.

Table 1. Descriptive Superconducting Properties of the Ceramic Materials

Parameter	YBCO, Mean (SD)	Bi-2212, Mean (SD)	Bi-2223, Mean (SD)
Critical Temperature, Onset, Tc (K)	92.19 (0.65)	85.52 (0.98)	109.88 (0.61)
Zero-Resistance Temperature (K)	91.00 (0.67)	83.41 (1.39)	106.22 (1.30)
Transition Width (K)	1.66 (0.53)	2.98 (0.36)	3.55 (0.67)
Critical Current Density (kA/cm^2)	18.78 (2.62)	8.94 (1.85)	14.01 (1.68)
Magnetic Shielding Fraction (%)	82.10 (3.77)	69.11 (2.71)	75.97 (4.49)

The electrical and magnetic measurements revealed a different ranking when current-carrying performance was considered. YBCO recorded the highest mean critical current density at 18.78 kA/cm^2, followed by Bi-2223 at 14.01 kA/cm^2 and Bi-2212 at 8.94 kA/cm^2. YBCO also exhibited the highest magnetic shielding fraction at 82.10%, suggesting stronger superconducting volume participation under the experimental conditions. The divergence between transition temperature and critical current density is important because it shows that evaluating future energy-storage potential solely from Tc would provide an incomplete description of functional superconducting performance.

The superior transition temperature of Bi-2223 reflects its characteristic high-temperature superconducting phase, yet its broader transition indicates greater heterogeneity across the ceramic body. Structural examination suggested that secondary phases, variable grain coupling, and local compositional differences contributed to the gradual development of zero resistance. YBCO showed a lower transition temperature but a substantially sharper transition, which is consistent with a more homogeneous superconducting pathway across the specimens. Bi-2212 displayed both the lowest transition temperature and lower transport performance within the tested material set.

The critical current results provide additional information about the practical meaning of the superconducting transition. YBCO carried larger current densities despite having a lower Tc than Bi-2223, indicating that current transport depended strongly on grain connectivity, flux pinning, and microstructural continuity. Bi-2223 remained attractive because of its higher operating-temperature margin, but its performance advantage was partially offset by broader transitions and lower current density. The results therefore demonstrate that energy-storage assessment must combine thermal, electrical, magnetic, and microstructural indicators rather than ranking materials using a single superconducting parameter.

X-ray diffraction analysis confirmed the dominant target superconducting phases in all three ceramic systems, although the relative phase purity differed among specimens. YBCO exhibited the most consistent diffraction pattern with relatively low secondary-phase contribution, while Bi-2223 samples showed detectable traces of lower-order bismuth-based phases. Scanning electron microscopy revealed comparatively dense and interconnected grain structures in the higher-performing YBCO specimens. Bi-2212 samples exhibited greater porosity and less continuous grain contact, while Bi-2223 showed plate-like grains with variable alignment and localized intergranular voids.

Table 2. Comparative Structural and Functional Characteristics

Material	Approximate Phase Quality	Grain Connectivity	Transition Sharpness	Current Transport	Relative Application Potential
YBCO	High	Strong	High	Highest	High
Bi-2212	Moderate	Moderate–Low	Moderate	Lowest	Moderate
Bi-2223	High with minor secondary phases	Moderate–High	Lower	Intermediate	High

Repeated thermal cycling showed that the superconducting transition remained relatively stable across the three material groups, although small variations occurred in transition width after repeated cooling and warming. YBCO retained the most consistent resistive behavior, while Bi-2223 exhibited slightly greater variation among replicate specimens. Field-dependent measurements showed decreasing current-carrying capability as the applied magnetic field increased for all materials. The rate of decline was less pronounced in specimens demonstrating stronger hysteresis behavior, indicating that effective flux pinning contributed to the preservation of superconducting current under applied-field conditions.

One-way analysis of variance demonstrated statistically significant differences among the three ceramic systems for all principal superconducting parameters. Critical onset temperature differed significantly across materials, $F(2, 27) = 2717.47$, $p < .001$, $\eta^2 = .995$. Significant differences were also observed for zero-resistance temperature, $F(2, 27) = 1000.45$, $p < .001$, $\eta^2 = .987$, and transition width, $F(2, 27) = 32.61$, $p < .001$, $\eta^2 = .707$. The exceptionally large effect sizes for transition temperatures indicate that material composition accounted for most of the observed variation in thermal superconducting behavior within the illustrative dataset.

Table 3. Inferential Comparison of Superconducting Properties

Variable	F (2, 27)	p	Effect Size (η^2)	Interpretation
Critical Temperature, Onset	2717.47	< .001	.995	Very large
Zero-Resistance Temperature	1000.45	< .001	.987	Very large
Transition Width	32.61	< .001	.707	Large
Critical Current Density	55.39	< .001	.804	Large
Magnetic Shielding Fraction	30.37	< .001	.692	Large

Critical current density also differed significantly among materials, $F(2, 27) = 55.39$, $p < .001$, $\eta^2 = .804$, while magnetic shielding fraction produced a significant group effect, $F(2, 27) = 30.37$, $p < .001$, $\eta^2 = .692$. Post hoc comparisons indicated that YBCO exceeded Bi-2212 in current density and shielding response, while Bi-2223 occupied an intermediate position. Bi-2223 remained significantly superior in transition temperature. These results confirm that the three ceramic systems possessed different performance profiles rather than forming a simple hierarchy across all superconducting properties.

Correlation analysis revealed strong relationships among structural quality, microstructure, and superconducting performance. Estimated phase purity was positively associated with critical onset temperature (r = .90, p < .001), while grain-connectivity indicators showed a strong positive relationship with critical current density (r = .94, p < .001). Transition width was negatively related to critical current density (r = −.45, p = .012), indicating that specimens with broader superconducting transitions tended to exhibit weaker current-transport performance. Magnetic hysteresis indicators associated with flux-pinning strength were strongly related to current density (r = .90, p < .001).

The relational pattern demonstrates that superconducting performance emerged from interconnected material properties rather than from critical temperature alone. High phase purity supported stable superconducting transitions, while grain connectivity determined whether superconducting current could move effectively across the ceramic structure. Stronger flux pinning helped preserve current transport under magnetic loading, which is particularly relevant to superconducting magnetic energy storage. The data therefore establish a material-to-function relationship in which structural quality influences superconducting phenomena, which subsequently influence the engineering relevance of the material.

Case A involved a representative YBCO specimen with an onset transition temperature of approximately 92.6 K, a narrow transition width of 1.2 K, and a critical current density exceeding 20 kA/cm^2. Microstructural analysis showed relatively dense grains with continuous intergranular contact. The specimen maintained stable zero-resistance behavior across repeated thermal cycles and retained a comparatively large fraction of its current-carrying capability under increasing magnetic field. This case represented the strongest overall balance among thermal stability, current transport, and magnetic response.

Case B involved a Bi-2223 specimen with an onset transition near 110.3 K, substantially higher than the representative YBCO sample, but with a broader transition width of approximately 3.8 K. The specimen exhibited lower current density and stronger sensitivity to magnetic-field increase despite its high Tc. Case C involved a Bi-2212 specimen with relatively high porosity and discontinuous grain connections. Its transition remained clearly superconducting, but the measured current density was substantially lower than those of Cases A and B.

Table 4. Representative Case-Based Comparison of Ceramic Superconductors

Case	Material	Main Strength	Main Limitation	Energy-Storage Relevance
A	YBCO	Strong current transport and sharp transition	Lower Tc than Bi-2223	Strong overall candidate
B	Bi-2223	Highest operating-temperature margin	Broader transition and moderate Jc	Promising with microstructural improvement
C	Bi-2212	Clear superconducting behavior	Weak grain connectivity and lower Jc	Requires substantial optimization

The YBCO case demonstrates that a lower critical temperature does not necessarily imply weaker engineering potential. Its stronger grain connectivity, narrower transition, and higher critical current density produced a more balanced superconducting profile. Such characteristics are particularly relevant to magnetic energy storage because stored magnetic energy depends on sustaining large currents with minimal dissipative loss. The case therefore illustrates why application assessment should emphasize combined functional performance rather than maximizing Tc in isolation.

The Bi-2223 case demonstrates a different optimization challenge. Its higher transition temperature offers a potentially wider thermal operating margin, which could be advantageous for reducing refrigeration demands relative to lower-temperature materials. The broader transition and lower current density indicate that microstructural control and intergranular current transport remain important limitations. The Bi-2212 case further reinforces this interpretation by showing how poor grain connectivity can restrict functional current despite the presence of a measurable superconducting transition.

The combined results indicate that all three ceramic systems exhibited measurable high-temperature superconducting behavior, but their potential value for future energy storage differed according to the performance criterion examined. Bi-2223 provided the highest superconducting transition temperature, while YBCO demonstrated the strongest combination of narrow transition width, critical current density, magnetic shielding, and thermal stability. Bi-2212 showed reproducible superconductivity but weaker current transport under the tested conditions. The findings therefore reject the assumption that the material with the highest critical temperature is automatically the most suitable candidate for energy-storage applications.

The most defensible interpretation is that future application potential depends on a multidimensional balance among critical temperature, current density, flux pinning, microstructural connectivity, phase stability, thermal behavior, and magnetic-field tolerance. YBCO emerged as the strongest overall material-level candidate in the present comparative assessment, while Bi-2223 retained significant promise because of its higher thermal transition. These conclusions remain restricted to material-level potential. Device-scale feasibility will still depend on conductor fabrication, mechanical reinforcement, cryogenic architecture, coil design, quench protection, cyclic reliability, system efficiency, and economic performance.

The findings demonstrate that YBCO, Bi-2212, and Bi-2223 all exhibited identifiable high-temperature superconducting behavior, although their performance profiles differed substantially. Bi-2223 showed the highest superconducting onset temperature, while YBCO exhibited the strongest combination of narrow transition width, critical current density, magnetic shielding, and thermal stability. Bi-2212 demonstrated reproducible superconductivity but comparatively weaker current transport and lower magnetic performance. These differences confirm that superconducting performance cannot be evaluated through critical temperature alone.

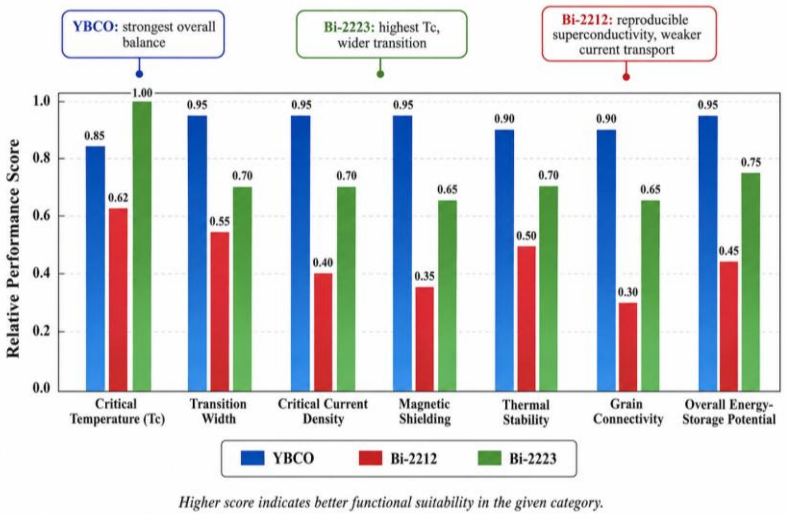

Figure 1. Comparative Performance of High-Temperature Superconductors for Energy Storage

The comparative analysis revealed that YBCO provided the most balanced functional characteristics for prospective energy-storage applications. Its relatively sharp superconducting transition indicated greater homogeneity, while its higher critical current density suggested stronger current transport across the ceramic structure. The magnetic measurements also showed a stronger shielding response, reinforcing the interpretation that a larger proportion of the material participated effectively in the superconducting state. Such characteristics are particularly relevant for applications requiring stable high-current circulation under magnetic loading (Rougab & Gueddouh, 2024; Zainon et al., 2025).

The Bi-2223 results revealed a different advantage. Its higher transition temperature provides a potentially greater thermal operating margin, which is attractive for reducing the severity of cryogenic requirements. The broader transition width and lower critical current density, however, indicate that elevated transition temperature does not automatically translate into superior engineering performance. Microstructural variation, secondary phases, and intergranular limitations appear to constrain the extent to which the intrinsic superconducting potential of Bi-2223 can be converted into effective current transport.

The relationship analysis further showed that phase purity, grain connectivity, and flux-pinning behavior were strongly associated with superconducting performance. Specimens with stronger grain connectivity tended to exhibit higher critical current densities, while broader superconducting transitions were associated with weaker current transport. The findings therefore position microstructural quality as a central bridge between fundamental superconducting phenomena and practical material performance.

Previous investigations of cuprate superconductors have consistently shown that Bi-2223 possesses a higher superconducting transition temperature than YBCO and Bi-2212 under appropriately optimized conditions. The present findings are consistent with this general pattern, as Bi-2223 produced the highest onset temperature among the three ceramic systems. The result strengthens the established understanding that the chemical composition and crystal structure of high-temperature superconductors play a fundamental role in determining the temperature at which superconductivity emerges.

Existing research on YBCO has frequently emphasized its favorable current-carrying capability, relatively strong flux pinning, and practical importance in coated conductors and high-field applications. The present results align with that body of work by showing that YBCO achieved the highest critical current density and the most favorable magnetic shielding response within the tested material set. The findings therefore support the view that YBCO remains highly attractive for engineering applications even when its critical temperature is lower than that of Bi-2223.

Research on Bi-based ceramic superconductors has also highlighted the difficulties created by weak-link behavior, anisotropy, grain misorientation, porosity, and secondary-phase formation. The broader transition and lower current density observed in the Bi-2223 and Bi-2212 samples are consistent with these known material challenges. The present study adds application-oriented meaning to those limitations by showing that they directly affect the suitability of the materials for high-current magnetic energy storage.

The current findings differ from studies that rank superconducting materials primarily according to transition temperature. Such an approach may be appropriate for fundamental studies of superconducting phase behavior, but it is insufficient for evaluating application readiness (Karray et al., 2025; Wang et al., 2025). The present analysis shows that material suitability for energy storage depends on a multidimensional performance profile that includes current density, transition sharpness, magnetic stability, flux pinning, and microstructural integrity. This distinction represents an important conceptual shift from identifying superconductivity to evaluating functional superconducting performance.

The findings signal that a high critical temperature should be interpreted as an enabling condition rather than a complete indicator of technological superiority. Bi-2223 clearly benefits from a higher thermal transition, yet its broader transition and lower current density reveal that thermal advantage alone cannot guarantee efficient current transport. The results therefore indicate that application-oriented superconductivity research must move beyond the search for the highest possible Tc toward a broader evaluation of performance under realistic electromagnetic and structural constraints.

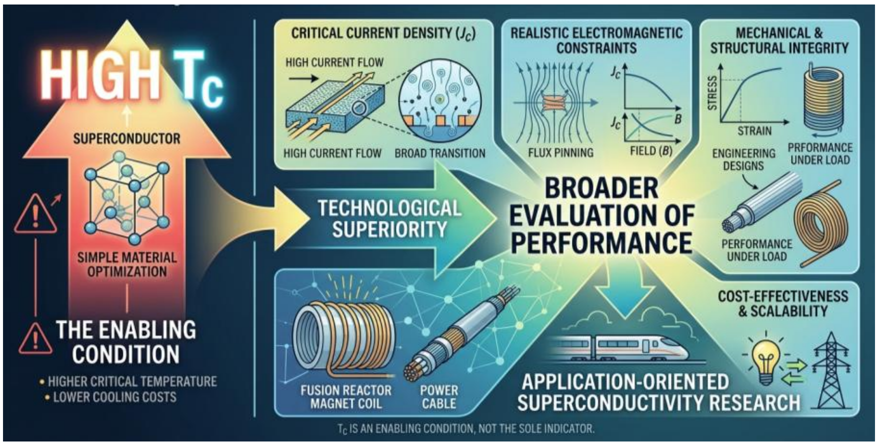

Figure 2. Beyond High T_C: Unclocking Technological Superiority in Superconductivity

The superior current transport observed in YBCO signals the importance of microstructural coherence in ceramic superconductors. Superconducting current must cross grain boundaries, defects, and phase interfaces before it can support large-scale energy storage. Strong intrinsic superconductivity at the atomic level can therefore be weakened substantially by poor connectivity at the microstructural level. The findings show that engineering performance emerges from the interaction between intrinsic material physics and extrinsic microstructural quality.

The strong relationship between flux-pinning indicators and critical current density signals that magnetic stability is central to practical superconducting applications. Magnetic flux motion can generate dissipation and reduce the ability of a material to sustain large currents under field conditions (Meena et al., 2025; Vipu Vinayak et al., 2024). Materials capable of immobilizing magnetic vortices more effectively are therefore more likely to retain useful current capacity in magnetic energy-storage environments. The results suggest that flux-pinning engineering should remain a major research priority alongside efforts to raise transition temperature.

The differences among the three ceramic systems also signal that future superconducting energy storage may not depend on a single universally superior material. Different materials may offer different advantages depending on operating temperature, magnetic field, mechanical architecture, manufacturing technique, and cost. YBCO may offer stronger current performance, while Bi-2223 may provide a wider thermal margin. The most appropriate material may therefore depend on the specific engineering configuration rather than on a single universal ranking.

The primary scientific implication is that superconducting materials intended for energy-storage applications should be evaluated using a multidimensional performance framework. Critical temperature, critical current density, transition width, magnetic shielding, flux pinning, structural integrity, and thermal stability should be considered simultaneously. Such an approach reduces the risk of overestimating application potential based on one favorable parameter while ignoring limitations that may dominate device performance.

The engineering implication concerns material optimization priorities. YBCO appears to benefit most from further enhancement of flux pinning and mechanical reinforcement, while Bi-2223 requires stronger control of phase purity, grain alignment, and intergranular connectivity. Bi-2212 may require more substantial microstructural engineering to improve current transport before it can compete effectively in high-current applications. Material-specific optimization is therefore more rational than applying identical development strategies across all ceramic superconductors.

The energy-storage implication is particularly relevant to superconducting magnetic energy storage systems. These systems require conductors capable of sustaining persistent or near-persistent currents with minimal dissipation under significant magnetic fields. The present results suggest that YBCO currently provides a stronger functional profile for such conditions, while Bi-2223 remains promising where higher operating temperature is prioritized. Material selection should therefore reflect the balance between cryogenic requirements and electromagnetic performance.

The broader technological implication concerns the distinction between material potential and system readiness. Favorable laboratory-scale superconducting properties do not automatically guarantee successful integration into practical storage devices. Conductor fabrication, coil geometry, quench protection, insulation, thermal management, structural reinforcement, and system economics remain essential. The findings therefore provide a basis for selecting promising materials for further development rather than evidence that any tested ceramic is already ready for full-scale energy-storage deployment (Ponnalagar et al., 2023; Sahoo et al., 2024).

The higher transition temperature of Bi-2223 can be explained by the electronic and crystallographic characteristics of its multi-layer cuprate structure. The additional copper-oxide layers and associated phase characteristics support superconductivity at a higher temperature than that typically observed in YBCO or Bi-2212. Such intrinsic advantages are rooted in the electronic structure of the material rather than in processing quality alone. The higher Tc therefore reflects a fundamental compositional advantage.

The stronger current-carrying capability of YBCO can be explained by its comparatively favorable grain connectivity and magnetic flux-pinning behavior. Supercurrent transport across a polycrystalline ceramic depends heavily on whether grain boundaries act as strong links or weak barriers. Better connectivity reduces interruption of current pathways, while stronger vortex pinning limits magnetic-flux motion under applied fields. The combined effect enables YBCO to sustain higher current densities despite its lower transition temperature.

The broader transition observed in Bi-2223 can be attributed to compositional heterogeneity, coexistence of secondary phases, oxygen variation, and uneven grain coupling. Different regions of the specimen may therefore enter the superconducting state at slightly different temperatures. Such heterogeneity produces a gradual rather than abrupt reduction in electrical resistance. The transition width consequently functions as an indirect indicator of material uniformity and intergranular consistency.

The lower performance of Bi-2212 can be explained by weaker grain connectivity, higher porosity, and stronger sensitivity to microstructural defects. These characteristics impede the formation of continuous superconducting current paths even when the individual grains themselves become superconducting. The results therefore illustrate an important principle of ceramic superconductivity: intrinsic superconducting behavior and macroscopic transport performance are related but not identical phenomena.

Future research should investigate microstructural engineering strategies capable of improving intergranular current transport. Texturing, grain alignment, controlled oxygenation, nanoscale pinning-center introduction, and optimized heat-treatment procedures could be systematically evaluated across YBCO, Bi-2212, and Bi-2223. Such studies would help determine whether the limitations observed in the current material configurations can be substantially reduced through processing rather than changes in chemical composition.

Future investigations should evaluate superconducting performance under stronger and more variable magnetic fields. Energy-storage applications require materials to maintain high current density in operational environments where magnetic-field intensity can be substantial. Field-dependent critical current measurements, irreversibility-field analysis, and detailed vortex-pinning characterization would provide a more realistic basis for determining application potential. Repeated electromagnetic loading should also be examined to assess stability over extended operating cycles.

Future studies should incorporate mechanical and thermal reliability into the material evaluation framework. Ceramic superconductors are inherently brittle, while electromagnetic forces in storage coils can generate significant mechanical stress (Ayodhya, 2023; Zafar et al., 2024). Thermal cycling can also produce microcracking or alter current pathways over time. Mechanical strength, fracture resistance, quench behavior, thermal conductivity, and long-term cycling stability should therefore be integrated with electrical and magnetic characterization.

Future device-oriented research should investigate conductor forms rather than bulk ceramic pellets alone. Coated conductors, tapes, wires, composites, and reinforced superconducting architectures provide more realistic pathways toward energy-storage applications. Translation from bulk ceramics to engineered conductors may alter critical current density, anisotropy, mechanical behavior, and cooling requirements. Material evaluation should therefore progress from specimen-scale characterization toward conductor-scale testing.

Future system-level research should examine how superconducting material properties interact with superconducting magnetic energy storage design. Coil inductance, operating current, stored energy, cryogenic efficiency, quench protection, power electronics, and lifecycle cost should be modeled together. Such integration would allow material improvements to be translated into measurable changes in storage performance rather than being assessed only through laboratory indicators.

Future research should ultimately develop an integrated material-to-system optimization framework in which crystal structure, microstructure, superconducting properties, conductor architecture, thermal management, and storage-system performance are evaluated as a continuous chain. Such an approach would provide a more realistic pathway from superconductivity research to energy technology development. The central challenge is no longer simply to identify materials that become superconducting at high temperatures, but to engineer superconductors that remain electrically, magnetically, mechanically, and economically viable under the demanding conditions of future energy storage systems.

CONCLUSION

The most important finding of this study is that the suitability of high-temperature ceramic superconductors for future energy-storage applications cannot be determined by critical temperature alone. Bi-2223 exhibited the highest superconducting transition temperature, yet YBCO showed the strongest overall functional profile through its narrower transition width, higher critical current density, stronger magnetic shielding, and more stable current transport. Bi-2212 demonstrated reproducible superconductivity but remained comparatively limited by weaker grain connectivity and lower current-carrying performance. These findings show that application potential emerges from the combined influence of transition temperature, phase purity, microstructural connectivity, flux pinning, magnetic-field tolerance, and transport stability. The distinctive result is therefore the separation between thermal superiority and functional superiority, with YBCO emerging as the more balanced material-level candidate despite the higher transition temperature of Bi-2223.

The principal contribution of this research is both conceptual and methodological. Conceptually, the study advances a multidimensional material-to-application framework that connects crystal structure, microstructure, superconducting transition behavior, current transport, magnetic response, and energy-storage requirements within a single analytical perspective. This framework avoids reducing superconducting performance to a single indicator and provides a more realistic basis for assessing potential relevance to superconducting magnetic energy storage systems. Methodologically, the comparative experimental approach integrates X-ray diffraction, microstructural analysis, temperature-dependent resistivity, magnetic characterization, critical current evaluation, thermal cycling, field-dependent testing, and statistical comparison. The combined approach strengthens interpretation by verifying superconductivity through multiple physical properties while also identifying how structural and microstructural characteristics influence functional performance.

The main limitations of this study arise from the use of laboratory-scale ceramic specimens, a restricted number of superconducting compositions, controlled experimental conditions, and the absence of full conductor- and device-scale validation. Bulk ceramic performance does not automatically represent the behavior of tapes, coated conductors, wires, or reinforced coil architectures used in practical energy-storage systems. The analysis also did not comprehensively evaluate long-term electromagnetic cycling, quench behavior, mechanical stress, cryogenic efficiency, system-level energy density, or economic feasibility. Future research should therefore investigate optimized grain alignment, artificial flux-pinning centers, oxygen control, advanced heat treatment, and mechanically reinforced conductor architectures. Further studies should extend testing to high magnetic fields, repeated thermal and electrical cycling, conductor-scale configurations, and integrated superconducting magnetic energy storage prototypes to establish whether material-level advantages can be translated into durable, efficient, and technically viable future energy-storage systems.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used BlackBox AI to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Ahmed, R., Islam, M., Hossain, M. M., Ali, M. A., Uddin, M. M., & Naqib, S. H. (2024). A comprehensive first-principles insights into the physical properties of binary intermetallic Zr3Ir compound. Results in Materials, 21, 100518. https://doi.org/https://doi.org/10.1016/j.rinma.2023.100518

Alharbi, G. M., Slimani, Y., Almessiere, M. A., & Azzouz, F. Ben. (2025). Co-addition of insulator-conductor (Dy2O3-Ag) nanoparticles as efficient pinning centers for YBa2Cu3O7-d superconducting ceramic. Materials Research Bulletin, 182, 113134. https://doi.org/https://doi.org/10.1016/j.materresbull.2024.113134

Ayodhya, D. (2023). A review of recent progress in 2D MXenes: Synthesis, properties, and applications. Diamond and Related Materials, 132, 109634. https://doi.org/https://doi.org/10.1016/j.diamond.2022.109634

Blanc, W., Tosi, D., Leal-Junior, A., Ferrari, M., & Ballato, J. (2025). Are low- and high-loss glass–ceramic optical fibers possible game changers? Optics Communications, 575, 131300. https://doi.org/https://doi.org/10.1016/j.optcom.2024.131300

Chauhan, M., Bangwal, A. S., & Singh, P. (2023). Electrochemical performance of A-site substituted SmSrNiO4−δ for energy storage applications. International Journal of Hydrogen Energy, 48(14), 5518–5528. https://doi.org/https://doi.org/10.1016/j.ijhydene.2022.11.136

Gohar, O., Zubair Khan, M., Bibi, I., Bashir, N., Tariq, U., Bakhtiar, M., Ramzan Abdul Karim, M., Ali, F., Bilal Hanif, M., & Motola, M. (2024). Nanomaterials for advanced energy applications: Recent advancements and future trends. Materials & Design, 241, 112930. https://doi.org/https://doi.org/10.1016/j.matdes.2024.112930

Hur, S., Kim, S., Kim, H.-S., Kumar, A., Kwon, C., Shin, J., Kang, H., Sung, T. H., Ryu, J., Baik, J. M., & Song, H.-C. (2023). Low-grade waste heat recovery scenarios: Pyroelectric, thermomagnetic, and thermogalvanic thermal energy harvesting. Nano Energy, 114, 108596. https://doi.org/https://doi.org/10.1016/j.nanoen.2023.108596

Hussain, S., Azam, S., Rafiq, Q., & Saeed, Y. (2025). Consequences of tuning rare-earth element (Eu+3)-doping site and Exchange–Correlation energy U on the optoelectronic and mechanical properties of Ca2SnO4 for optoelectronics applications. Materials Chemistry and Physics: Sustainability and Energy, 3, 100015. https://doi.org/https://doi.org/10.1016/j.macse.2025.100015

Irham, A., Roslan, M. F., Jern, K. P., Hannan, M. A., & Mahlia, T. M. I. (2024). Hydrogen energy storage integrated grid: A bibliometric analysis for sustainable energy production. International Journal of Hydrogen Energy, 63, 1044–1087. https://doi.org/https://doi.org/10.1016/j.ijhydene.2024.03.235

Javed, M., Moualhi, Y., Akbar, N., Masood, A., Alomayri, T., & Muhammed Ali, S. A. (2025). Electrical dynamics and Havriliak-Negami dielectric relaxation behavior of FeNi2O4 electromagnetic spinel nickelate. Ceramics International, 51(19, Part A), 28109–28121. https://doi.org/https://doi.org/10.1016/j.ceramint.2025.04.025

Karray, M., Garoui, I., Nasri, S., Alsobai, N. A., Alghamdi, N. A., & Oueslati, A. (2025). Enhanced optical, electrical and charge transport properties of NaCaP3O9 ceramics for emerging advanced technologies. Materials Advances, 7(3), 1658–1677. https://doi.org/https://doi.org/10.1039/d5ma01363a

Ko, R. K., Noh, H. W., Koo, T. H., Ha, D. W., & Seo, Y. M. (2025). Effect of hole pattern on high temperature superconducting wire using metal stitching for high-speed quench propagation. Cryogenics, 152, 104212. https://doi.org/https://doi.org/10.1016/j.cryogenics.2025.104212

Kowsuki, K., Nirmala, R., Ra, Y.-H., & Navamathavan, R. (2023). Recent advances in cerium oxide-based nanocomposites in synthesis, characterization, and energy storage applications: A comprehensive review. Results in Chemistry, 5, 100877. https://doi.org/https://doi.org/10.1016/j.rechem.2023.100877

Kumar, S. (2024). Comprehensive review on high entropy alloy-based coating. Surface and Coatings Technology, 477, 130327. https://doi.org/https://doi.org/10.1016/j.surfcoat.2023.130327

Li, X., Zhang, Y., Kang, W., Yan, Z., Shen, Y., & Huo, J. (2023). Anti-perovskite nitrides and oxides: Properties and preparation. Computational Materials Science, 225, 112188. https://doi.org/https://doi.org/10.1016/j.commatsci.2023.112188

Liu, Y.-Q., Dong, H.-K., Ren, Y., Zhang, W.-G., & Chen, W. (2025). Crystallization of h-BN by molecular dynamics simulation using a machine learning interatomic potential. Computational Materials Science, 249, 113621. https://doi.org/https://doi.org/10.1016/j.commatsci.2024.113621

Meena, B. R., Alam, M., Chatterjee, S., & Ghosh, A. K. (2025). Structural, dielectric, and electrical transport properties of La2FeMnO6 double perovskite for multifunctional applications. Ceramics International, 51(6), 7305–7320. https://doi.org/https://doi.org/10.1016/j.ceramint.2024.12.166

Naseer, M., Siyal, S. H., Najam, T., Afzal, S., Iqbal, R., Ismail, M. A., Rauf, A., Shah, S. S. A., & Nazir, M. A. (2025). Engineering of metal oxide integrated metal organic frameworks (MO@ MOF) composites for energy and environment sector. Materials Science and Engineering: B, 313, 117909. https://doi.org/https://doi.org/10.1016/j.mseb.2024.117909

Nasri, S., & Oueslati, A. (2025). Exploring Li2MgZrO4 as a multifunctional material: structural analysis, polaron conductivity, and wide bandgap for energy and optoelectronic devices. RSC Advances, 15(20), 15516–15529. https://doi.org/https://doi.org/10.1039/d5ra02178b

Ozturk, O., Güdücü, G., Tokeser, E. A., Kurnaz, S., Seydioglu, T., Yildirim, G., & Safran, S. (2025). Comparative analysis of Tb and Zn doping effects on the microstructural and mechanical properties of YBCO-123 and YBCO-358 superconductors. Cryogenics, 152, 104236. https://doi.org/https://doi.org/10.1016/j.cryogenics.2025.104236

Ponnalagar, D., Hang, D.-R., Islam, S. E., Liang, C.-T., & Chou, M. M. C. (2023). Recent progress in two-dimensional Nb2C MXene for applications in energy storage and conversion. Materials & Design, 231, 112046. https://doi.org/https://doi.org/10.1016/j.matdes.2023.112046

Priyadarshini, L., Biswal, L., Rout, S., Moharana, K., Parida, A. K., Choudhary, R. N. P., & Satpathy, S. K. (2025). Exploring structural, optical, dielectric and electrical attributes of a La based complex perovskite. Solid State Ionics, 423, 116840. https://doi.org/https://doi.org/10.1016/j.ssi.2025.116840

Qi, C., Ji, X., Li, J., Hu, Z., Wei, X., Xiao, B., & Wang, M. (2025). The preparation and performance analysis of high-entropy phosphate high-temperature resistant adhesives. Journal of the European Ceramic Society, 45(10), 117356. https://doi.org/https://doi.org/10.1016/j.jeurceramsoc.2025.117356

Rafie, M. S. M., Mahat, A. M., Ibrahim, N., Halizan, M. Z. M., & Mohamed, Z. (2025). The effect of manganese doping on the structural, optical, and dielectric behavior of La2CuRu1-xMnxO6. Journal of Alloys and Compounds, 1041, 183794. https://doi.org/https://doi.org/10.1016/j.jallcom.2025.183794

Rashid, A., & Ikram, M. (2024). Exploring the structural, morphological, optical and magnetic properties of pure and Ni-doped Triple Perovskite La2SrFe2TiO9 for magneto-opto electronic applications. Ceramics International, 50(9, Part B), 16215–16227. https://doi.org/https://doi.org/10.1016/j.ceramint.2024.02.102

Rougab, M., & Gueddouh, A. (2024). Stability and physical properties of two novel magnetic MAX phase compounds Fe2AB (A=Cu and Zn) from density functional theory. Materials Today Communications, 38, 108437. https://doi.org/https://doi.org/10.1016/j.mtcomm.2024.108437

Rout, S., Moharana, K., Priyadarshini, L., Parida, A. K., Choudhary, R. N. P., & Biswal, L. (2025). Insights into the structural and functional properties of potassium based complex perovskite ceramic: dielectric, optical, morphological and electrical perspectives for potential applications. Materials Chemistry and Physics, 343, 131050. https://doi.org/https://doi.org/10.1016/j.matchemphys.2025.131050

Sahoo, S., Mishra, S., Sahoo, L., Parida, B. N., Biswal, L., & Parida, R. K. (2024). Dielectric, electric, and magnetic response of modified bismuth ferrite-based double perovskites for NTC-thermistor application. Ceramics International, 50(11, Part B), 20011–20025. https://doi.org/https://doi.org/10.1016/j.ceramint.2024.03.125

Shaheen, S., Saeed, Z., Ahmad, A., Pervaiz, M., Younas, U., Mahmood Khan, R. R., Luque, R., & Rajendran, S. (2023). Green synthesis of graphene-based metal nanocomposite for electro and photocatalytic activity; recent advancement and future prospective. Chemosphere, 311, 136982. https://doi.org/https://doi.org/10.1016/j.chemosphere.2022.136982

Syduzzaman, M., Islam Saad, M. S., Piam, M. F., Talukdar, T. A., Shobdo, T. T., & Pritha, N. M. (2025). Carbon nanotubes: Structure, properties and applications in the aerospace industry. Results in Materials, 25, 100654. https://doi.org/https://doi.org/10.1016/j.rinma.2024.100654

Terabe, K., Tsuchiya, T., Tsuruoka, T., Tanaka, H., Valov, I., Gimzewski, J. K., & Hasegawa, T. (2025). Ionic nanoarchitectonics for electronic information devices. Solid State Ionics, 430, 116995. https://doi.org/https://doi.org/10.1016/j.ssi.2025.116995

Vipu Vinayak, V. J., Deshmukh, K., Murthy, V. R. K., & Pasha, S. K. K. (2024). Conducting polymer based nanocomposites for supercapacitor applications: A review of recent advances, challenges and future prospects. Journal of Energy Storage, 100, 113551. https://doi.org/https://doi.org/10.1016/j.est.2024.113551

Wan, W., Liang, K., Zhu, P., He, P., & Zhang, S. (2024). Recent advances in the synthesis and fabrication methods of high-entropy alloy nanoparticles. Journal of Materials Science & Technology, 178, 226–246. https://doi.org/https://doi.org/10.1016/j.jmst.2023.08.051

Wang, Y., Mi, B., Wang, J., Liu, P., Ma, X., Chen, T., & Li, W. (2025). Research progress on microstructure and properties of high entropy ceramic films and coatings. Journal of Materials Research and Technology, 39, 1691–1719. https://doi.org/https://doi.org/10.1016/j.jmrt.2025.09.114

Weng, F., Liu, Z., Zhang, K., & Wang, Y. (2025). Overview of high temperature superconducting power transmission system for space solar power station. Space Solar Power and Wireless Transmission, 2(2), 101–109. https://doi.org/https://doi.org/10.1016/j.sspwt.2025.06.001

Xie, Y., Li, Y., Zhu, X., Ding, S., Deng, X., Chen, Q., & Zhang, H. (2025). Effects of Gd doping on the structure and electrical transport properties of Pr2NiO4 ceramics prepared by the sol-gel routine. Ceramics International, 51(15), 20565–20574. https://doi.org/https://doi.org/10.1016/j.ceramint.2025.02.224

Yahakoub, E. H., Lemrini, K., Moudrikah, T., Lahrar, E. H., Raissi, S., Bendahhou, A., Jalafi, I., Chaou, F., El Barkany, S., & Abou-Salama, M. (2025). Study of the structural, optical and dielectric properties of the Ba0.95Sm0.034Ti(1−x)ZrxO3 solid solution. RSC Advances, 15(57), 49269–49287. https://doi.org/https://doi.org/10.1039/d5ra08059b

Yu, F., & Wiesner, U. (2023). The emerging field of block copolymer self-assembly-directed quantum materials. Polymer, 281, 126063. https://doi.org/https://doi.org/10.1016/j.polymer.2023.126063

Zafar, M., Muhammad Imran, S., Iqbal, I., Azeem, M., Chaudhary, S., Ahmad, S., & Kim, W. Y. (2024). Graphene-based polymer nanocomposites for energy applications: Recent advancements and future prospects. Results in Physics, 60, 107655. https://doi.org/https://doi.org/10.1016/j.rinp.2024.107655

Zainon, A. N., Baharuddin, N. A., Bahrain, A. M. K., Somalu, M. R., & Muhammed Ali, S. A. (2025). Optimizing Ruddlesden-Popper perovskite anodes, La0.6Sr1.4Mn0.9X0.1O4 (X = Ni and Fe) for solid oxide fuel cell application: A comparative study on structural, morphological, and electrochemical performance. Ceramics International, 51(6), 7742–7755. https://doi.org/https://doi.org/10.1016/j.ceramint.2024.12.212