

Superconductivity and Its Applications: A Comparative Review of Materials, Technologies and Emerging Opportunities

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ABSTRACT

Background: Superconductivity is a remarkable quantum phenomenon characterized by the disappearance of electrical resistance and the expulsion of magnetic flux below critical operating conditions. Since its discovery, superconductivity has evolved from a laboratory phenomenon into a foundation for high-field magnets, medical imaging, particle accelerators, sensitive measurement systems and emerging quantum technologies.

Objective: This paper presents a structured review and comparative analysis of superconducting materials and their technological applications, with the literature review primarily restricted to scientific developments published before 2017. **Methodology:** A structured literature review was conducted using peer-reviewed publications from established physics and materials science journals indexed in major scientific databases. The selected studies were evaluated according to superconducting transition temperature, critical magnetic field, current-carrying capability, cooling requirements, material characteristics and application potential. **Results:** The analysis demonstrates substantial differences between conventional low-temperature superconductors and high-temperature superconductors. Conventional materials such as NbTi and Nb₃Sn remain important for high-field magnet systems because of their technological maturity, while cuprate-based superconductors offer higher transition temperatures and the possibility of operation using comparatively economical cooling systems. **Conclusion:** Superconductivity has already enabled several mature technologies, particularly MRI, accelerator magnets and ultra-sensitive sensors. However, widespread deployment remains constrained by cryogenic requirements, fabrication complexity and material cost. Future research should focus on higher-performance superconductors, improved conductor architectures, reduced cooling requirements and the integration of superconducting systems into energy and quantum technologies.

Keywords: Superconductivity, high-temperature superconductors, low-temperature superconductors, Josephson junctions, MRI, SQUID, magnetic levitation, quantum technology.

I. INTRODUCTION

Superconductivity is one of the most significant and extensively studied phenomena in condensed-matter physics. It was first observed by Heike Kamerlingh Onnes in 1911 during experiments on mercury at cryogenic temperatures, where the electrical resistance of the material was found to decrease abruptly to an experimentally undetectable level below a characteristic transition temperature. This discovery introduced a new state of matter with electrical properties fundamentally different from those of conventional conductors.

Another defining characteristic of superconductivity was subsequently identified through the Meissner effect, in which a superconducting material expels magnetic flux as it enters the superconducting state. The combination of zero electrical resistance and magnetic flux exclusion distinguishes superconductivity from ordinary metallic conduction and forms the basis for many of its scientific and technological applications [1], [2].

The development of superconducting materials has progressed through several important stages. Early practical applications were primarily based on conventional metallic superconductors, particularly niobium-titanium (NbTi) and niobium-tin (Nb₃Sn), which demonstrated suitable properties for the development of high-field magnets and other cryogenic systems. A major breakthrough occurred in 1986 with the discovery of high-temperature superconductivity in copper-oxide materials by Bednorz and Müller. These materials exhibited transition temperatures substantially higher than those of conventional superconductors and significantly expanded the scope of superconductivity research [3].

Over time, the development of superconducting materials has created opportunities for their application across several scientific, medical, industrial, and technological fields. Important application areas include magnetic resonance imaging, particle accelerators, magnetic levitation systems, superconducting quantum interference devices, electrical power transmission, fault-current limitation, nuclear-fusion magnets, superconducting electronics, and quantum information systems. The ability of superconductors to carry electrical current with extremely low energy loss and generate strong magnetic fields makes them particularly valuable in applications where conventional materials face limitations.

Despite significant progress, the widespread implementation of superconducting technologies remains constrained by challenges such as cryogenic cooling requirements, material brittleness, conductor fabrication complexity, and overall system cost. Consequently, continued research is focused on improving superconducting material performance, increasing critical temperatures and current densities, developing mechanically robust conductors, and reducing the cost and complexity of cooling systems.

This paper presents a comparative review of major superconducting materials and their technological applications. The analysis examines conventional and high-temperature superconductors with respect to their physical characteristics, operating requirements, advantages, limitations, and application potential. In accordance with the defined scope of this study, the literature review primarily emphasizes significant scientific developments and research published **before the end of 2016**.

II. LITERATURE REVIEW

A. Conventional Superconductivity

The microscopic understanding of conventional superconductivity was established through the Bardeen-Cooper-Schrieffer (BCS) theory. According to this theory, under appropriate conditions, electrons within a superconducting material can form correlated pairs known as Cooper pairs through interactions associated with lattice vibrations or phonons [4]. These paired electrons behave collectively and can move through the material without the conventional electrical resistance associated with normal metallic conduction.

The BCS framework successfully explained the superconducting behavior of many conventional materials and provided the theoretical foundation for understanding their transition into the superconducting state. However, the theory also suggested practical limitations in achieving extremely high transition temperatures through conventional electron-phonon coupling mechanisms. Consequently, conventional superconductors generally operate at relatively low temperatures and require cryogenic cooling for practical applications.

Important conventional superconducting materials include niobium-titanium (NbTi), niobium-tin (Nb₃Sn), lead (Pb), mercury (Hg), and magnesium diboride (MgB₂). Among these materials, NbTi has become particularly important for practical applications because of its mechanical flexibility, relatively easy fabrication into wires, and reliable performance in superconducting magnet systems. It has therefore been widely used in applications such as magnetic resonance imaging and scientific research magnets. Nb₃Sn, in contrast, is capable of operating at higher magnetic fields and temperatures than NbTi, making it suitable for advanced high-field applications. However, its brittle nature creates significant fabrication and mechanical handling challenges. Thus, the selection of a conventional superconductor depends on the required balance between critical temperature, magnetic-field capability, current-carrying capacity, mechanical properties, and manufacturing feasibility.

B. High-Temperature Superconductors

The discovery of superconductivity in copper-oxide compounds by Bednorz and Müller represented a major breakthrough in superconductivity research [3]. Subsequent investigations led to the identification of materials with superconducting transition temperatures exceeding the boiling point of liquid nitrogen, creating new opportunities for practical applications. Among these materials, yttrium barium copper oxide, generally represented as YBa₂Cu₃O_{7-δ} or YBCO, emerged as one of the most important high-temperature superconductors because of its high transition temperature and promising performance under strong magnetic fields.

High-temperature superconductors offer several advantages over conventional low-temperature superconductors, including higher transition temperatures, higher critical magnetic fields, and the potential to carry large electrical current densities. An important practical advantage is that some of these materials can operate using liquid-nitrogen-based cooling systems, which can be comparatively simpler and more economical than liquid-helium cooling. These characteristics have created opportunities for applications in high-field magnets, electrical power transmission, fault-current limiters, magnetic levitation systems, and advanced scientific equipment.

Despite these advantages, the practical implementation of high-temperature superconductors remains challenging. Many of these materials have ceramic structures and exhibit significant brittleness, making it difficult to fabricate them into flexible and mechanically robust conductors. Their anisotropic behavior and sensitivity to grain boundaries can also reduce current-carrying performance. Consequently, continued research in conductor fabrication, microstructural engineering, flux pinning, and mechanical reinforcement is necessary to improve their practical performance and support wider technological applications [5], [6].

C. Magnesium Diboride

The discovery of superconductivity in magnesium diboride (MgB₂) in 2001 generated considerable scientific and technological interest because the material combines a comparatively high superconducting transition temperature of approximately 39 K with a relatively simple chemical composition [7]. This transition temperature is significantly higher than that of many conventional metallic superconductors, while the material remains structurally less complex than copper-oxide high-temperature superconductors.

MgB₂ occupies an important position between conventional low-temperature superconductors and complex cuprate-based superconductors. Its comparatively simple composition, favorable superconducting properties, and potential for conductor fabrication have made it attractive for selected magnet, power cable, and electronic applications. In particular, MgB₂ can be considered for systems operating at intermediate cryogenic temperatures, where its performance may provide advantages over conventional superconductors.

However, its application potential depends on factors such as critical current density, magnetic-field performance, conductor processing, and cooling requirements. Continued research has therefore focused on improving its microstructure, flux-pinning characteristics, and current-carrying capability under practical operating conditions.

D. Iron-Based Superconductors

A further important class of superconducting materials emerged with the discovery of iron-based superconductors in 2008 [8]. This discovery demonstrated that high-temperature superconductivity was not restricted to copper-oxide materials and introduced a new family of compounds with distinct structural and electronic characteristics. The emergence of iron-based superconductors significantly expanded the scientific understanding of unconventional superconductivity and stimulated extensive research into their fundamental mechanisms and technological potential.

Research conducted before 2017 examined several important characteristics of these materials, including their crystal structures, magnetic properties, superconducting pairing mechanisms, critical magnetic fields, and potential applications in superconducting conductors. Many iron-based superconductors demonstrated promising high-field properties, making them scientifically attractive for applications where strong magnetic fields and high current-carrying performance are required.

Although their technological development remained less mature than established systems based on NbTi, Nb₃Sn, and YBCO, iron-based superconductors represented an important direction in superconductivity research. Their continued investigation may contribute to the development of new superconducting materials with improved performance, simplified fabrication, and broader application potential.

E. Superconducting Electronics

Superconducting electronics represents another important application area of superconductivity, particularly because of the unique properties associated with Josephson junctions. A Josephson junction generally consists of two superconducting regions separated by a thin insulating layer, normal-metal region, or other weak-link structure. The Josephson effect enables superconducting current and quantum phase-dependent phenomena to occur across this barrier, providing the foundation for several highly sensitive and advanced electronic devices.

This principle has enabled the development of superconducting quantum interference devices (SQUIDS), voltage standards, rapid single-flux-quantum circuits, and superconducting qubits. SQUID magnetometers are among the most sensitive instruments available for measuring extremely small magnetic fields and have applications in scientific research, geophysical exploration, nondestructive testing, and biomagnetic measurements [9].

Superconducting electronics has also become increasingly important in quantum information research. Superconducting qubits based on Josephson-junction circuits can be engineered and controlled to perform quantum operations, making them promising components for quantum computing systems. However, challenges related to cryogenic operation, environmental noise, coherence, fabrication consistency, and large-scale circuit integration remain important areas of research. Continued progress in superconducting materials and electronic-device engineering is therefore expected to play a significant role in the future development of high-performance sensors, quantum systems, and advanced superconducting electronics.

III. RESEARCH METHODOLOGY

This study adopts a **structured literature review and comparative analysis methodology** to examine the characteristics, performance, limitations, and technological applications of major classes of superconducting materials. The study is based on published scientific literature and does not involve original experimental measurements. The selected materials and technologies are systematically compared to identify their relative advantages, limitations, technological maturity, and potential for future applications.

A. Research Scope

The scope of the study includes major superconducting materials representing different stages of scientific and technological development. The analysis focuses on conventional superconductors, high-temperature superconductors, magnesium diboride (MgB₂), and iron-based superconductors. In addition to material characteristics, the study examines important technological applications of superconductivity, including high-field magnets, magnetic resonance imaging, particle accelerators, electrical power systems, superconducting sensors, magnetic levitation, and superconducting electronics. This broad scope enables a comparative understanding of how fundamental material properties influence practical application potential.

B. Literature Selection

The review primarily considers foundational and application-oriented scientific studies published before the end of 2016. Relevant literature was selected from peer-reviewed scientific publications based on its relevance to superconducting materials, underlying physical properties, technological applications, and engineering challenges. Priority was given to studies with significant scientific contributions and clear relevance to the comparative objectives of the present review.

The selection process also considered the **technological importance of the materials and the availability of measurable or comparable parameters**. Studies providing information on superconducting transition temperature, critical magnetic field, critical current density, cooling requirements, material characteristics, fabrication methods, and application performance were particularly relevant to the analysis. The selected literature was subsequently organized according to major material classes and technological application areas to support a systematic comparison.

C. Comparative Parameters

The superconducting materials were evaluated using a set of physical, engineering, and technological parameters. Critical temperature (T_c) was considered as a primary indicator of the temperature below which a material enters the superconducting state. Critical magnetic field was used to assess the ability of a superconductor to maintain superconductivity under strong magnetic-field conditions, while critical current density was considered to evaluate its capability to carry electrical current without losing its superconducting properties.

Additional parameters included cooling requirements, mechanical characteristics, and fabrication complexity, as these factors significantly influence the practical implementation of superconducting materials. The technological maturity of each material was also considered to distinguish between well-established superconductors used in commercial systems and emerging materials that remain primarily under research and development. Finally, application potential was evaluated by examining the suitability of different superconducting materials for magnets, power systems, sensors, electronic devices, and other advanced technologies. This multi-parameter comparison provides a systematic basis for identifying the relative strengths, limitations, and future prospects of the major superconducting material classes.

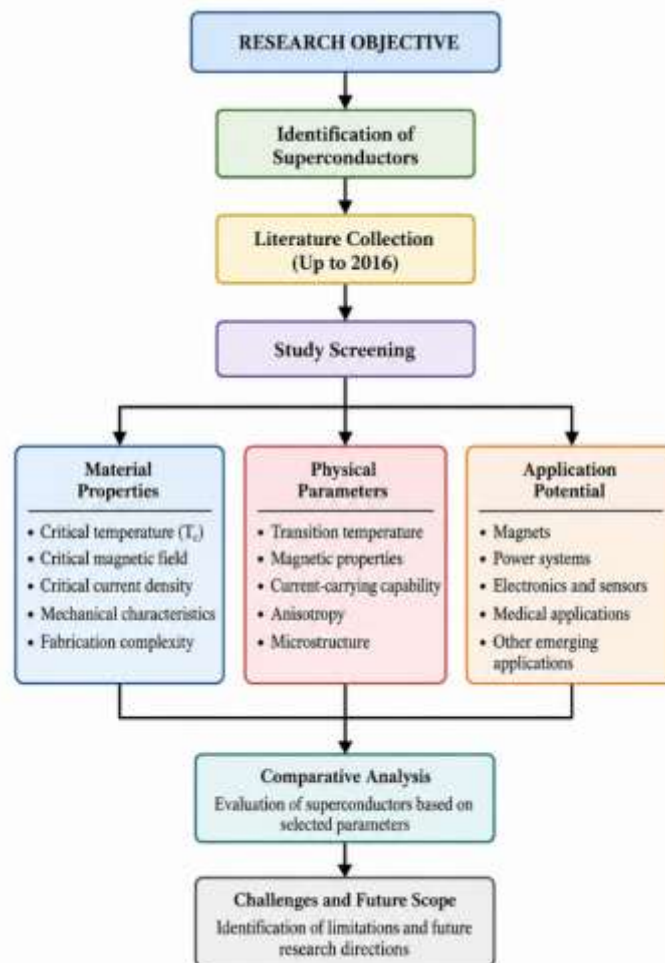


Figure 1. Research Methodology

IV. COMPARATIVE ANALYSIS OF SUPERCONDUCTING MATERIALS

Table I: Comparison of Major Superconducting Materials

Material	Approximate T _c	Type	Cooling Requirement	Major Strength	Major Limitation
NbTi	9.2 K	Conventional	Liquid helium	Ductile and technologically mature	Low transition temperature
Nb ₃ Sn	18 K	Conventional	Cryogenic	High-field capability	Brittle
MgB ₂	39 K	Conventional/intermediate	Cryogenic	Simple composition and higher T _c	Limited high-field performance
YBCO	~92 K	High-temperature	Liquid nitrogen possible	High T _c and strong field potential	Complex fabrication
BSCCO	Up to ~110 K	High-temperature	Liquid nitrogen possible	Very high T _c	Mechanical brittleness
Iron-based systems	Variable	High-temperature class	Cryogenic	High critical fields	Less technological maturity

The comparison indicates that superconducting materials cannot be evaluated solely on the basis of transition temperature. Mechanical properties, conductor fabrication, magnetic-field performance and cooling requirements are equally important.

Table II: Low-Temperature and High-Temperature Superconductors

Parameter	Low-Temperature Superconductors	High-Temperature Superconductors
Typical materials	NbTi, Nb ₃ Sn	YBCO, BSCCO
Transition temperature	Lower	Higher
Cooling	Usually liquid helium	Liquid nitrogen may be possible
Fabrication	Relatively mature	More complex
Mechanical flexibility	Generally better	Often brittle
Magnetic-field applications	Well established	High-field potential
Commercial maturity before 2017	High	Developing

V. MAJOR APPLICATIONS OF SUPERCONDUCTIVITY

A. Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) represents one of the most successful commercial applications of superconductivity. MRI systems require strong, stable, and highly uniform magnetic fields to produce detailed images of internal body structures. Superconducting magnets are particularly suitable for this purpose because they can generate high magnetic-field strengths while maintaining excellent field stability over extended periods. Compared with equivalent resistive magnets, superconducting magnet systems can provide high-field performance with reduced electrical losses and more compact configurations. Niobium-titanium (NbTi) has been widely used in MRI magnet systems because of its favorable superconducting properties, mechanical characteristics, and established conductor technology. The continued development of superconducting materials and cryogenic systems is expected to further improve the performance, efficiency, and accessibility of advanced medical imaging technologies.

B. Particle Accelerators

Large particle accelerators require powerful magnetic systems to guide, focus, and control the trajectories of charged particles. Superconducting magnets play a critical role in these facilities because they can generate strong magnetic fields with significantly lower electrical losses than conventional resistive magnets. Their ability to produce high magnetic fields also allows the construction of more compact magnet structures, which is particularly important in large-scale accelerator facilities. Established superconducting materials such as NbTi and Nb₃Sn have been widely investigated and applied for high-field magnet systems. The development of

improved superconducting conductors capable of operating under higher magnetic fields remains an important research area for future particle accelerators and high-energy physics experiments.

C. Magnetic Levitation

Superconductors can interact strongly with magnetic fields, enabling magnetic levitation and stable guidance mechanisms. These properties have generated considerable interest in their application to advanced transportation systems. Superconducting magnetic levitation can reduce or eliminate direct mechanical contact between moving and stationary components, thereby reducing friction and mechanical wear. This characteristic provides the potential for smooth operation and high-speed transportation. Superconducting maglev systems may also offer improved stability and load-carrying capability under appropriate operating conditions. However, the practical implementation of such systems depends on the development of reliable superconducting materials, efficient cryogenic cooling technologies, and economically viable large-scale infrastructure.

D. SQUID Sensors

Superconducting quantum interference devices, commonly known as SQUIDs, are among the most sensitive instruments available for the measurement of extremely small magnetic fields. These devices are based on Josephson junctions, where quantum interference effects enable highly sensitive detection of changes in magnetic flux. SQUID sensors have important applications in biomagnetic measurements, geological and geophysical exploration, non-destructive testing, and fundamental physics experiments. Their exceptional sensitivity makes them particularly useful in situations where conventional magnetic sensors cannot detect very weak signals. Despite their advantages, widespread deployment is influenced by challenges associated with cryogenic cooling, system complexity, and operational cost.

E. Power Systems

Superconductivity offers significant potential for improving the efficiency and performance of electrical power systems. Major application areas include superconducting power cables, transformers, fault-current limiters, generators, and superconducting magnetic energy-storage systems. Superconducting cables can potentially transmit large electrical currents with very low resistive losses, while superconducting fault-current limiters can provide rapid protection against excessive fault currents. Superconducting generators and transformers may also offer advantages in terms of power density and compactness. In addition, superconducting magnetic energy storage can provide rapid energy exchange and support power-system stability. However, the practical and economic viability of these technologies depends on whether the operational advantages and energy savings can justify the additional cost, complexity, and energy requirements associated with cryogenic cooling systems.

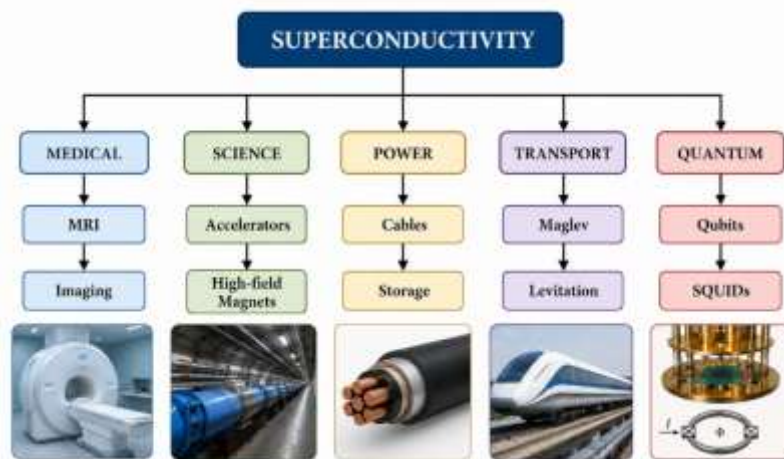


Figure 2. Major Application Areas of Superconductivity

VI. CHALLENGES AND FUTURE SCOPE

A. Cryogenic Requirements

One of the most significant barriers to the widespread adoption of superconducting technologies is the requirement for low operating temperatures. Conventional superconductors generally require cooling to cryogenic temperatures, often involving liquid helium or advanced refrigeration systems. Although high-temperature superconductors can operate at comparatively higher temperatures, they still require effective cooling to maintain superconducting performance. The cooling infrastructure adds complexity, energy consumption, and operational cost to superconducting systems. Future development should therefore focus on improving cryogenic efficiency, developing compact and reliable cooling systems, discovering superconducting materials with higher operating temperatures, and reducing the overall cost of cryogenic operation. Progress in these areas will be essential for expanding superconducting technologies beyond specialized scientific and industrial applications.

B. Material Fabrication

Material fabrication remains a major engineering challenge, particularly for high-temperature superconductors. Many of these materials are ceramic in nature and exhibit significant mechanical brittleness, which complicates their conversion into practical wires, tapes, and other conductor forms. Their performance can also be strongly affected by crystal orientation, defects, and grain boundaries, which may restrict the flow of superconducting current. Future research should therefore focus on improving wire-fabrication techniques, optimizing tape architecture, enhancing mechanical reinforcement, and developing effective grain-boundary engineering methods. Advances in these areas can improve conductor flexibility, current-carrying capacity, mechanical reliability, and suitability for large-scale technological applications.

C. Cost

The overall cost of a superconducting system extends beyond the cost of the superconducting material itself. Additional expenses are associated with cryogenic equipment, thermal insulation, system maintenance, monitoring, and control infrastructure. The economic feasibility of superconducting technology therefore depends strongly on the specific application and the performance advantages it can provide over conventional alternatives. In applications requiring extremely high magnetic fields, high current densities, exceptional measurement sensitivity, or compact system configurations, superconducting technologies may provide sufficient benefits to justify their higher initial and operational costs. Continued improvements in material processing, conductor manufacturing, cryogenic efficiency, and system design will be necessary to improve their economic competitiveness.

D. Power-System Integration

The integration of superconducting technologies into electrical power systems presents both opportunities and challenges. Superconducting cables, transformers, generators, fault-current limiters, and energy-storage systems must demonstrate clear technical or economic advantages over continuously improving conventional technologies. Their application may be particularly attractive in environments where very high current density is required, installation space is limited, strong magnetic fields are necessary, or specialized scientific and industrial infrastructure already supports cryogenic operation. Future research should focus on improving the reliability, efficiency, protection, and long-term operational performance of superconducting power devices. Successful integration will depend on demonstrating practical advantages under realistic operating conditions.

E. Quantum Technologies

Superconducting circuits became increasingly important in quantum information research before 2017, particularly because Josephson-junction-based devices allow the fabrication and controlled manipulation of artificial quantum systems. Superconducting qubits have emerged as promising components for quantum computing because they can be designed using established microfabrication techniques and integrated into complex electronic circuits. However, several technical challenges remain, including limited coherence times, control errors, environmental noise, and difficulties associated with scaling small quantum processors into larger architectures. Future research is therefore expected to focus on extending coherence times, improving qubit control and readout, developing effective quantum error-correction techniques, and creating scalable quantum architectures. Progress in these areas may enable superconducting technologies to play an increasingly important role in the development of practical quantum computing and advanced quantum information systems.



Figure 3. Future Development Pathway

Table III: Challenges and Future Research Priorities

Challenge	Current Limitation	Future Research Priority
Cooling	High operational complexity	Higher-temperature materials
Fabrication	Brittle ceramic materials	Improved conductor architecture
Cost	Expensive systems	Scalable manufacturing
Current density	Performance reduction in fields	Pinning and microstructure engineering
Grid integration	Cryogenic infrastructure	Efficient compact systems
Quantum coherence	Environmental noise	Improved device materials

VII. CONCLUSION AND FUTURE SCOPE

This paper presented a structured review and comparative analysis of superconducting materials and their technological applications, based primarily on literature available before the end of 2016.

The analysis shows that conventional superconductors such as NbTi and Nb₃Sn remain technologically important because of their mature fabrication methods and successful use in high-field magnet systems. High-temperature superconductors, particularly YBCO and BSCCO, provide significantly higher transition temperatures and create opportunities for applications that can utilize liquid-nitrogen cooling. MgB₂ represents an important intermediate material because of its comparatively high transition temperature and simpler composition, while iron-based superconductors broaden the scientific understanding of unconventional superconductivity.

The application analysis confirms that superconductivity has already achieved practical success in MRI systems, particle accelerators and ultra-sensitive magnetic measurement. Emerging opportunities in electrical power systems, magnetic levitation and quantum technologies could further expand its technological significance.

Future research should concentrate on the discovery and engineering of materials with higher transition temperatures and improved critical current densities. Equally important are advances in conductor fabrication, cryogenic technology and cost reduction. The integration of superconductors with quantum information systems and advanced energy infrastructure represents a particularly promising future direction.

In conclusion, superconductivity remains both a fundamental scientific challenge and a technologically important field. Continued progress in materials science, condensed-matter physics and cryogenic engineering will determine the extent to which superconducting technologies move from specialized applications toward wider commercial deployment.

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