Advances in Cryogenic Ceramics and Non-Metallic Materials for Engineering Solutions: A Scientometric Perspective

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Abstract. In recent years, cryogenic ceramics and non-metallic materials have emerged as a transformative research frontier, attracting growing attention for their ability to perform reliably under extreme low-temperature conditions. Defined by their dimensional stability, resistance to embrittlement, and superior adaptability, these materials are increasingly essential in aerospace, superconducting systems, biomedical preservation, and quantum technologies. The aim of this study is to provide a scientometric assessment of maps that research dynamics, thematic evolution, and collaboration patterns in the field. The scope encompasses ceramics, polymers, composites, and hybrid materials that offer advantages over traditional metals in cryogenic environments. Despite progress, significant gaps remain in scalable fabrication, sustainable processing, and the development of multifunctional high-entropy systems. Results highlight 2020 as the peak year of productivity, with leading institutions and researchers driving advancements. Overall, the findings demonstrate a shift from fundamental materials science to application-driven innovations, guiding future directions for sustainable and high-performance cryogenic solutions.

Keywords: Cryogenic Ceramics, Non-metallic Materials, Low-Temperature Applications, Scientometric Analysis, Advanced Composites, Thermal Stability

1 INTRODUCTION

1.1 From Sub-Zero Frontiers to Engineering Benchmarks

Scientific research on materials at cryogenic temperatures has shown tremendous progressions since its early laboratory-based limitations to the leading frontline of the

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solution to applied engineering (Zhang et al., 2025). Initial research in the field of cryogenic science concentrated mainly on the basic behavior of the materials

exposed to very low temperatures, usually lower than -150 °C. These were the first attempts to study phase transitions, mechanical behavior, and thermal characteristics of controlled laboratory conditions (Yang et al., 2025). This background played the role of leading to incremental introduction of cryogenic principles into the real-world engineering fields.

Aerospace engineering and scientific instrumentation has been one of the first and most significant fields of implementation since ultra-precise components are required to perform consistently even with changing and sometimes extreme cryogenic conditions (Lee et al., 2025). Traditional metal materials used in these environments were known to have mechanical strength, but there were problems with thermal misalignment and dimensional instability that led to the exploration of alternative materials. The result of this search was the adoption of ceramics and other non-metallic materials that proved to be more stable at cryogenic temperatures, thus closing the gap between microscopic material science standards and the macroscopic engineering standards (L. Zhang et al., 2025).

Materials and techniques have been pioneered that have played a role in this shift. Both Zerodur and ULE (Ultra Low Expansion glass) became important materials with low thermal expansion, and remarkable dimensional stability, required in the critical optical equipment. The materials have almost zero coefficients of thermal expansion, which means that the components retain their shape and orientation throughout a wide operating temperature, including cryogenic temperatures (Kinast et al., 2017). At the same time, new types of composite materials, in particular, silicon particle-reinforced aluminum alloys like AlSi40, greatly improved thermal stability by reducing the stress induced by coefficient of thermal expansion dissimilarities inherent in their constituents. The composites are customized versions of stiffness, thermal conductivity, and dimensional compatibility that is critical towards long-term optical device operation in cryogenic systems (Kinast et al., 2017).

Particularly to supplement material innovation, improvement of thermal treatments was a key factor in increasing the useful life of cryogenic materials (Li et al., 2025). Controlled heat treatments minimized the internal stresses developed during manufacturing and service and therefore improved the dimensional stability and inhibited plastic deformation during cyclic thermal loading. Studies of interferometry analysis and transmission electron microscopy have helped to understand the material stabilization processes underlying such increases, which also informed the design of materials and processing routes (Kinast et al., 2017).

As a bridge between research in the laboratory and engineering standards in the real world, these materials have been used extensively in large-scale, high precision projects (He et al., 2024). A prime example of the applicability of the cryogenic design is the James Webb Space Telescope (JWST). The optical system of the JWST includes 18 beryllium segments which are cooled to below 50 K in order to reduce thermal noise. The materials and engineering solutions that delve into this deserve the precedent work in the area of cryogenic ceramics and metal composites, and in this scenario, shape retention and alignment are important factors that assure the telescope of the imaging capacity it has never before had. In superconducting systems, in addition to space optics, the materials have been used, with thermal dimensional stability providing operational robustness. Likewise, the low expansion and stress reduction characteristics of sophisticated ceramics and composites are useful in structural parts with cryogenic regimes, a multi-disciplinary engineering influence with cryogenic material science (Zan et al., 2023).

1.2 Materials Beyond Metals: Ceramics, Polymers, and Composites in the Cryogenic Era

While metals have traditionally dominated engineering applications, particularly in cryogenic conditions, the last decades have demonstrated that non-metallic materials, including ceramics, polymers, and their composites—often outperform or complement metals in unique ways. Ceramics and glass-ceramics, e.g. as touched upon above, offer low thermal expansion and enhanced dimensional stability in cryogenic temperatures. These characteristics minimise deformation and failures caused by stress, which is important in a high precision application. The fact that they are intrinsically resistant to embrittlement and have great strength-to-weight ratios highlights their benefits over traditional metallic alloys in extremely cold conditions (Kinast et al., 2017).

Polymers and polymer-ceramic composites also took their place among the materials of interest in cryogenic applications, and that is largely because they possess such favorable thermomechanical characteristics and versatility. High performance polymers such as poly ether ether ketone (PEEK) are known to have high level of low temperature stability, coupled with good mechanical performance and embrittile resistance which are critical in components that undergo thermal cycling and mechanical loading. They can be used in various engineering industries, as when combined with ceramic fillers or metals as laminates, they also have the advantages of synergistic properties including increased toughness, dimensional control, and thermal insulation, which increases their usability (Alizadeh-Osgouei et al., 2019; Schwenger et al., 2024).

Hybrid composites have also improved their performance by allowing multi-functionality that is being adaptable to cold conditions. Fiber metal laminates (FMLs) which contain alternating layers of metals and ceramic-fiber reinforcements are used to provide an ideal combination of ductility, strength and thermal stability. These composites may be designed with a balance in mechanical properties through guided layering and orientations of the fibers, and finally, thermal behavior may be optimized. Likewise, the polymer-metallic composites, especially those that are made through methods such as cold spray additive manufacturing allow controlled microstructures and domain sizes, the direct effect of which on thermal and mechanical performance at cryogenic temperature (Schwenger et al., 2024; Costa et al., 2023).

Cryogenic adaptive responses are exhibited by functionally advanced composite systems, including those which make use of shape memory polymer composites (SMPCs). These materials take advantage of thermally induced shape memory to allow reversible mechanical deformations in order to either relieve thermal strain or to allow reconfigurable components. Current studies have concentrated on SMPs that respond to stimuli and contain magnetic, electroactive, or photoactive behavior, which is multifunctional and dynamically engineered and no longer relates to the response of a passive material to stimuli (Meng & Li, 2013; Behl et al., 2010).

Nevertheless, the development of cryogenic-compatible non-metallic materials has both challenges and opportunities. The final dimensional accuracy and mechanical integrity of these materials is critically dependent on manufacturing processes, such as machining and thermal treatments. An example is that machining of fiber-reinforced metal matrix composites (MMCs) must take into account temperature-dependent softening and chip growth processes to prevent microcracking or delamination, which may be amplified by cryogenic conditions. Controlled temperature machining has been demonstrated to be able to activate or inhibit specific deformation mechanisms, enhancing machinability and quality of parts (Zan et al., 2023). In a similar manner, the cooling policies have a direct influence on the tool-workpiece interface, which influences the surface roughness and distributions of residual stress (Domingo et al., 2022).

The high-entropy ceramics (HECs) are new classes of ceramics with promising properties such as low thermal conductivity, high strength, and toughening mechanisms that can be used in cryogenic applications. The compositional complexity and crystal chemistry of these multicomponent solid solutions provide unparalleled flexibility when tuning properties, and are enabling new engineered crystalline materials with improved performance metrics (Xiang et al., 2021).

1.3 Mapping Applications Across Scales and Sectors

Their varied and vital applications can be found in a multiplicity of scales and industries because the actual implementation of advanced cryogenic ceramics and non-metallic materials are spread throughout. Ceramics and composite that are dimensionally stable are essential in the aerospace field and in space exploration. Space telescopes, like the ones that are covered in the context of the JWST, rely on ultra-precise cryogenic mirrors that are based on the use of hi-tech ceramics and silicon particle-reinforced aluminum alloys. These materials retain their optical figure after repeated thermal cycling between room temperature to the cryogenic temperature, which guarantees the instruments of accuracy and instrument mission success. In addition to optical uses, these materials are also used structurally in propulsion systems that are cryogenic liquid fuel storage and thrust systems. Composite materials are light and have thermal insulation features, which reduce thermal losses and weights, enhance performance and efficiency in rockets and satellite subsystems (Liu et al., 2021; Costa et al., 2023).

Another key area of application of cryogenic material improvements is energy storage and the use of superconducting magnets. Ceramic and polymeric materials are also used as insulation and structural material of superconducting devices, in which the stability at liquid helium or liquid nitrogen temperatures is a requirement. The improvements in nanoporous adsorbents, metal-organic frameworks (MOF), and conductive polymer composites all contribute to the higher efficiency in storage and charge transportation under the cryogenic environment to enable the creation of energy-dense, lowloss conductive superconducting magnets and cryogenic storage devices (Wang et al., 2021; Hirscher et al., 2023; Shi et al., 2015).

The materials are also useful in biomedical preservation and quantum device integration. Polymers, hydrogels and polymer-ceramic nanocomposites offer essential capabilities including biocompatibility and controlled mechanical compliance between 0 C temperatures, making them useful in preserving tissues and biosensing. Developments have been carried out on high surface area conductive polymer hydrogels with rapid electrochemical responses to sensitive detecting in conditions of low-temperature operation. Additionally, nanophotonic and quantum photonic devices that depend on materials, which remain stable at cryogenic conditions to allow efficient manipulation of quantum states, use polymer composites and nanostructures to balance optical and thermal performances (Carlos D. S. Brites, 2012; (Dalton et al., 2023; Pan et al., 2012; Bashir et al., 2020).

1.4 Why Scientometrics Matters for Cryogenic Materials Research

Scientmetric and bibliometric analyses are potent instruments that could be used to explain the scenario in such a highly dynamic and interdisciplinary field like cryogenic materials. Sciometrics will provide insights into the players, institutions, and regions that lead the pack in the development of cryogenic ceramics and composites by quantitatively examining the trends in publications and citation networks, as well as collaborative activities of authors. Such a mapping, in addition to assisting in the identification of already established authorities, also helps in the identification of research clusters and new areas.

The interdisciplinary teamwork is particularly critical, because the combination of ceramics, polymers, and cryogenics engineering may imply a variety of skills of materials science, mechanical engineering, physics, and chemistry. Scientometric approaches serve well to unveil such cross-disciplinary connections and create awareness and synergistic research activities, which might otherwise be lacking (Xiang et al., 2021); (Liu et al., 2021).

In addition to mapping, scientometrics also reveals the gaps in knowledge and unexplored themes. As an illustration, it is possible to identify the necessity of the future research on sustainable manufacturing process, innovative high-entropy ceramics that optimize cryogenics, and improved multi-functional polymers with the help of citation and keyword trend analysis. These understandings can help researchers and financing organizations to focus their efforts strategically on the areas with the highest potential of innovations and limited knowledge base, speeding up the creation of technology and prioritizing the distribution of resources (Costa et al., 2023; Zan et al., 2023).

Strategically, scientometric findings inform decisions related to funding priorities, collaborative partnerships, and the direction of technology transfer initiatives. Data-driven insights from bibliometric studies ensure that research investments align with both scientific frontiers and practical engineering demands, facilitating the translation of academic advances into impactful cryogenic engineering solutions. This integrative approach bolsters the coherence between fundamental materials science progress and the specific challenges posed by cryogenic applications (Yuan et al., 2020).

To conclude, the history of cryogenic ceramics and non-metallic material development starting with the basic research in the laboratory to being an essential part of engineering can be viewed as the result of a multi-decade development of materials science, development of innovative composites, and optimization approaches to the formation of adaptive material structures. The large improvements in the cryogenic performance of ceramics, polymers and hybrid composites have expanded their reach to key technological sectors including aerospace, energy storage, biomedical use, and quantum device engineering. This domain is developed in a critical manner with the help of the scientific methodologies, which reveal the dynamics of research, the structure of collaboration, the new trends, and which finally lead to the coherent and efficient research strategies of the future breakthroughs.

2 METHODOLOGY

The methodology deals with scientometric analysis aiming at investigating the research field in cryogenic ceramics and non-metallic materials. It includes the monitoring of the publications trend of 2015 up to 2025, finding the influential authors and institutions and analyzing the evolution of the themes based on annual publications. The VOSviewer co-citation analysis reveals the main intellectual groups and the research partnerships. Citation networks and the Law of Bradford are also analyzed in order to identify the core and periphery journals in the field. By using this method, one can gain a full picture of the development of the field and its research trends.

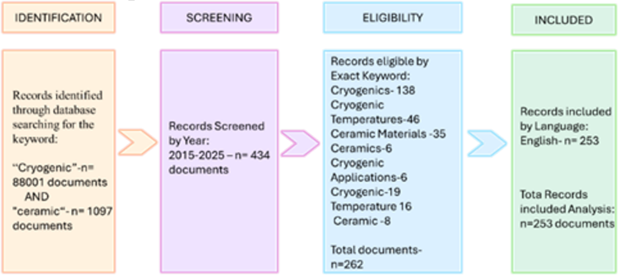

Fig. 1. PRISMA Flowchart

The PRISMA flowchart in figure 1 visually represents the systematic process of selecting relevant publications for the scientometric analysis. It outlines the stages of data retrieval, screening, eligibility assessment, and final inclusion of studies, ensuring a transparent and reproducible approach to data selection. This methodological tool helps track and justify the inclusion of specific research articles, guiding the analysis of publication trends, citation networks, and thematic evolution in cryogenic ceramics and non-metallic materials.

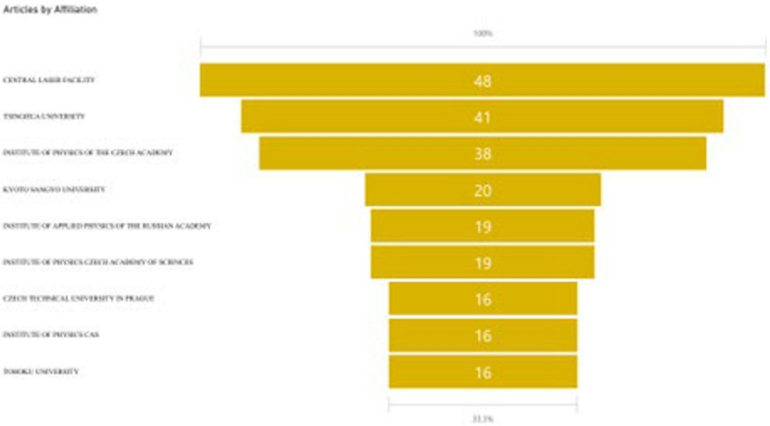

Fig. 2. Articles count by affiliation count

The scientometric distribution of publications by affiliation demonstrates the most active institutions, which give their contribution to the sphere as illustrated in the figure 2. Its main position is occupied by the Central Laser Facility (48 articles), then the Tsinghua University (41), and the Institute of Physics of the Czech Academy (38), as they are in the center of research development. At the mid-level, there are Kyoto Sangyo University (20) and Institute of Applied Physics of the Russian Academy (19) who are also heavily but specifically engaged. Less, but steady, contributions are made through institutions like Czech Technical University in Prague, Institute of Physics CAS, and Tohoku University, all having 16 articles each. Findings: The results indicate that Central Laser Facility and Tsinghua University are the most influential institutions when it comes to publication output.

Table 1. Scientometric indicators of authors highlighting leading contributors by h-index, g-index, citations, and publications.

Author	**h_index**	**g_index**	**m_index**	**Total Citations**	**Total Publications**
Lucianetti Antonio	7	11	0.63636364	129	11
Mocek Tomáš	7	11	0.63636364	137	15
Jambunathan	5	8	0.45454545	73	11

Venkatesan					
Xie Zhipeng	5	11	0.45454545	127	11
De Vido Mariastefania	4	8	0.36363636	157	8
Ertel Klaus G.	4	8	0.36363636	157	8

Table 1 shows author-level scientometric measures as h-index, g-index, m-index, total citations, total publications, which help in evaluating the research performance. Lucianetti Antonio and Mocek Tomaz have the highest h-index (7) and g-index (11), and they are backed by good citation rates (129 and 137 respectively). Xie Zhipeng also has a competitive g-index (11) and 127 citations indicating a consistent scholarly impact. The highest number of citations, 157 is recorded at De Vido Mariastefania and Ertel Klaus G., although both have h-indexes of moderate size (4). The diagram shows that other contributions with little publications like Gui Jingya and Wei Sai are emerging. Outcome: Mocek Tomasz and Lucianetti Antonio become top contributors whose productivity and contribution are equal.

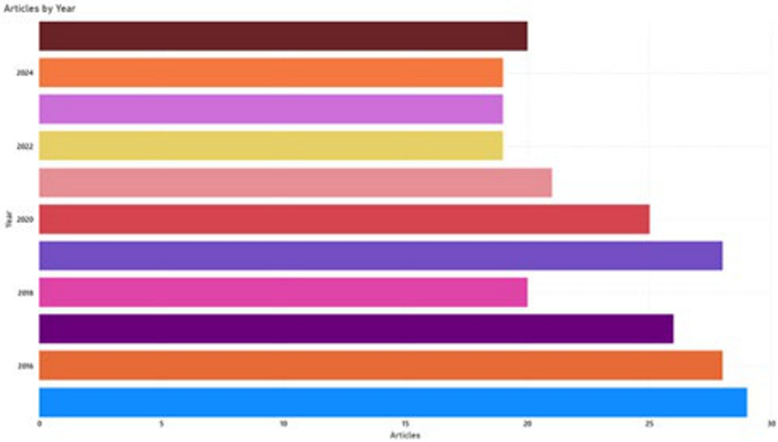

Fig. 3. Article production yearwise

The scientometric analysis of the 2015-2025 annual publications depicts that there is an upward trend in the research productivity (figure 3). In 20152016, the output is quite high (almost 30 articles), and the contributions to the journal have increased steadily in 20172018. An outstanding peak is reached in 2020, and it shows approximately 29 publications, which is the largest research output of the period. The steady decline is observed after 2020 with approximately 18-20 articles in the years 2022-2023 with an even smaller number of articles in 2025 (which probably results in the half-year data). The general trend shows that there is a peak in 2020 and thereafter years onwards show moderation though a steady downfall.

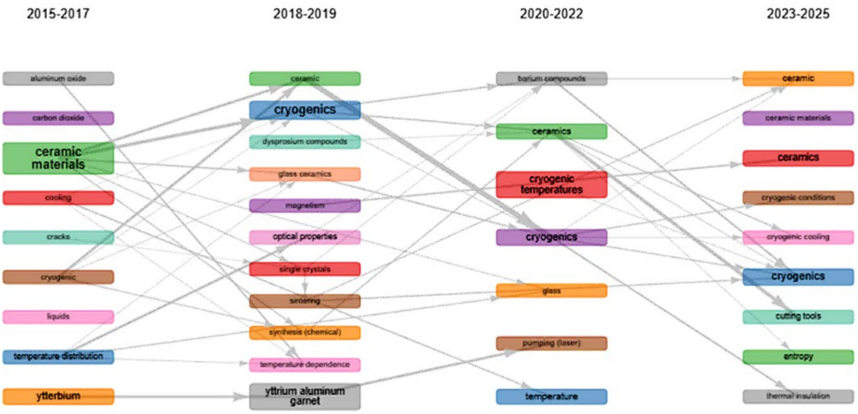

Fig. 4. Most used keywords

Thematically developed over the years in figure 4 indicates different developments in research. In 20152017, attention was paid to ceramic materials, ytterbium, and temperature distribution, which preconditioned thermal and material research. In 2018 2019, the themes changed to cryogenics, optical properties, and sintering, where the stress was put on material properties and processing. By 202022, the areas around which consolidation took place include cryogenic, ceramics, and glass, where the impact of thermal effects was connected to structural performance. The new applications in 2023–2025 include cutting tools, entropy, thermal insulation, and cryogenic cooling. The development is a shift in the basic material research to the more complex cryogenic applications with practical implications.

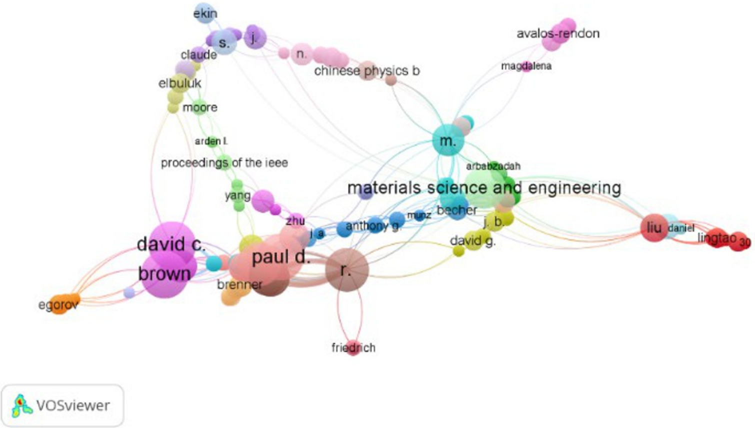

Fig. 5. Co-citation of the cited authors

The co-citation map, which has been made using VOSviewer in figure 5, shows the intellectual landscape as it clusters the authors who were cited into specific groups. The authors are represented as nodes and the frequency of citations as the size of the node and the co-citation strength between two authors as the links between the authors. Such more significant nodes as Paul D., David C. Brown, and Materials Science and Engineering indicate their central influence on the field. The colors are used to separate them into separate clusters, as follows: the blue-green cluster is the connection between M. Arbabzadeh and Materials Science and Engineering; the red cluster is connected to Liu and Inigata, indicating a powerful Asian research stream; the pink-purple nodes are related to Chinese Physics B, indicating a powerful influence on publication; and the brown cluster is related to Paul D. and R. with a core message of making a contribution to methodology. The inter-cluster relations are an interdisciplinary knowledge sharing, covering the material science, cryogenics, and applied engineering fields. The network map supports the existence of well organized author communities, where Paul D. and David C. Brown are the main hubs in the thematic clusters, leading to intellectual unity in the discipline.

Table 2. Bradford's Law distribution of core and peripheral journals.

Source	**Rank**	**Frequency**	**cumFrequency**	**Zone**
PROCEEDINGS OF SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING	1	26	26	Zone 1
CERAMICS INTERNATIONAL	2	14	64	Zone 1
OPTICAL MATERIALS EXPRESS	3	8	72	Zone 1
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY	4	5	77	Zone 1
JOURNAL OF THE AMERICAN CERAMIC SOCIETY	5	5	82	Zone 1

Table 2 shows the implementation of Bradford Law in the identification of core and peripheral sources in the area of the research. The most productive Zone 1 sources are Proceedings of SPIE The International Society for Optical Engineering with the highest frequency (26), Ceramics International (14), and Optical Materials Express (8). Other important publications in Zone 1 are IEEE Transactions on Applied Superconductivity and Journal of the American Ceramic Society. In Zone 2, there are moderate productive journals like Optics Express, Journal of Alloys and Compounds and Applied Physics Letters. The distribution of Bradford provides Proceedings of SPIE as the key centre source that contributes to the dissemination of knowledge.

3 CONCLUSION

The scientometric exploration of cryogenic ceramics and non-metallic materials underscores their growing significance in engineering applications, spanning aerospace, superconducting systems, biomedical preservation, and quantum technologies. The analysis confirms 2020 as the most productive year, with nearly 29 publications, reflecting heightened global interest. Core affiliations such as the Central Laser Facility and

Tsinghua University, along with prolific contributors like Mocek Tomáš and Lucianetti Antonio, have driven advancements in this domain. Journals including Proceedings of SPIE and Ceramics International emerge as central sources, shaping the knowledge base, while co-citation networks highlight the intellectual influence of Paul D. and David C. Brown as pivotal connectors.

Thematic evolution shows that there is a significant shift in the initial emphasis on ceramics and ytterbium into new areas of use in the field of cryogenic cooling, entropy, and thermal insulation, and that the research topics are consolidating and diversifying. This path presents interdisciplinary connections in materials science, applied physics, and engineering. In general, the paper offers evidence-based information that enhances the knowledge of the intellectual framework of the field and provides the future research opportunities on the topic of sustainable, high-performance cryogenic material solution. The future must look at sustainable manufacturing strategies, high-entropy ceramics and polymer multifunctional composite materials, especially in terms of scalability, energy saving, and ability to be integrated into the next generation cryogenic systems.

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