Review

Advancements in Flexible Ceramic Fibers for High-Temperature Applications: A Comprehensive Review

Zijian Xu [1,2], Ying Lyu [1,2], Chao Hou [1,2], Yanqi Han [1,2], Yunzhao Bai [1,2], YongAn Huang [1,2,*] and Kan Li [1,2,*]

[1] State Key Laboratory of Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, China; xuzijian2000@hust.edu.cn (Z.X.); ly9123@hust.edu.cn (Y.L.); houchao@hust.edu.cn (C.H.); M202470741@hust.edu.cn (Y.H.); yunzhaobai@qq.com (Y.B.)

[2] Institute for Advanced Electronics Manufacturing, Huazhong University of Science and Technology, Wuhan 430074, China

* Corresponding author. E-mail: yahuang@hust.edu.cn (Y.H.); kanli@hust.edu.cn (K.L.)

Received: 26 January 2025; Accepted: 7 April 2025; Available online: 14 April 2025

ABSTRACT: Flexible ceramic fibers (FCFs) have emerged as a highly promising material for high-temperature applications, effectively combining the excellent thermal stability of ceramic materials with the robust mechanical properties of flexible fibers. This review provides a comprehensive overview of recent advances in multifunctional FCF devices, focusing on innovative methods across material selection, structural design, and fabrication techniques to enhance their functional properties. These improvements, *i.e.*, mechanical strength, thermal conductivity, and oxidation resistance, make FCFs particularly suitable for a wide range of applications, including energy storage, sensing, and high-temperature filtration. Notably, advancements in fabrication techniques have enabled the creation of novel FCF devices for thermal insulation and high-temperature sensing, such as stretchable ceramic membranes and printable ceramic fiber papers. The review concludes by discussing the future potential of FCFs, especially in multifunctional applications in high-temperature environments, where they can serve as essential components of advanced technologies. This work highlights the versatility and potential of FCFs as a transformative material for next-generation high-temperature applications.

Keywords: Flexible ceramic fibers; High-temperature; Multifunctionalization

1. Introduction

Ceramics, a class of inorganic non-metallic materials, have been integral to human civilization since the advent of pottery and porcelain [1]. These materials are known for their high melting points, hardness, wear resistance, and chemical stability, making them essential in various fields such as energy production [2], medicine [3], and aerospace engineering [4–6]. However, ceramics inherent brittleness and rigidity limit their applications, especially in environments requiring flexibility, durability and abrasion resistance under extreme conditions [7]. For example, the nose cones of rockets must withstand the scouring and friction of high-temperature airflows and high-frequency vibrations, making their ceramic components prone to destruction. To address these challenges, researchers have flexible ceramics through techniques such as microcrack toughening [8] and grain size controlling [9]. However, these methods often fail to produce ceramics that can endure large bending deformations, highlighting the need for new materials that combine flexibility with high-temperature stability.

Flexible ceramic fibers (FCFs) have emerged as a solution to these limitations, offering a unique combination of the thermal and chemical stability of ceramics with the mechanical flexibility of fibers [10,11]. These fibers are engineered to maintain their structural integrity and performance even at elevated temperatures, making them ideal for high-temperature applications where conventional ceramics falter. FCFs are particularly suited for thermal insulation [12], catalyst [13], and gas filtration [14] due to their high thermal stability, low thermal conductivity, and large surface area. Despite these advantages, the applications of FCFs have primarily focused on leveraging the inherent properties of ceramic materials, with limited exploration in the realm of electronic devices. Recent efforts have been made to enhance the mechanical properties of FCFs by eliminating flaws [15], improving toughening mechanism [16], and

https://doi.org/10.70322/htm.2025.10007

increasing melting point [17]. However, only a small portion of FCF research has been directed towards multifunctionalization and integration into high-temperature electronics [18].

To unlock the full potential of FCFs, it is essential to develop strategies that enhance their properties and enable new functionalities. For example, modifications and surface treatments can introduce novel properties such as electromagnetic wave absorption [19], ion transmission [20], and flexible sensing [21], while maintaining their inherent flexibility and high-temperature resistance. This review aims to provide a comprehensive overview of the fundamentals, multifunctionalization strategies, and high-temperature applications of FCFs. According to the review framework shown in Figure 1 [22–27], we begin by classifying the basic types of FCFs based on their characteristics and describing their manufacturing processes. We then explore new strategies for multifunctionalization, including modification, morphology design, and deposition. Finally, we analyze the advantages and challenges of integrating FCFs into practical high-temperature devices and discuss future opportunities for their development.

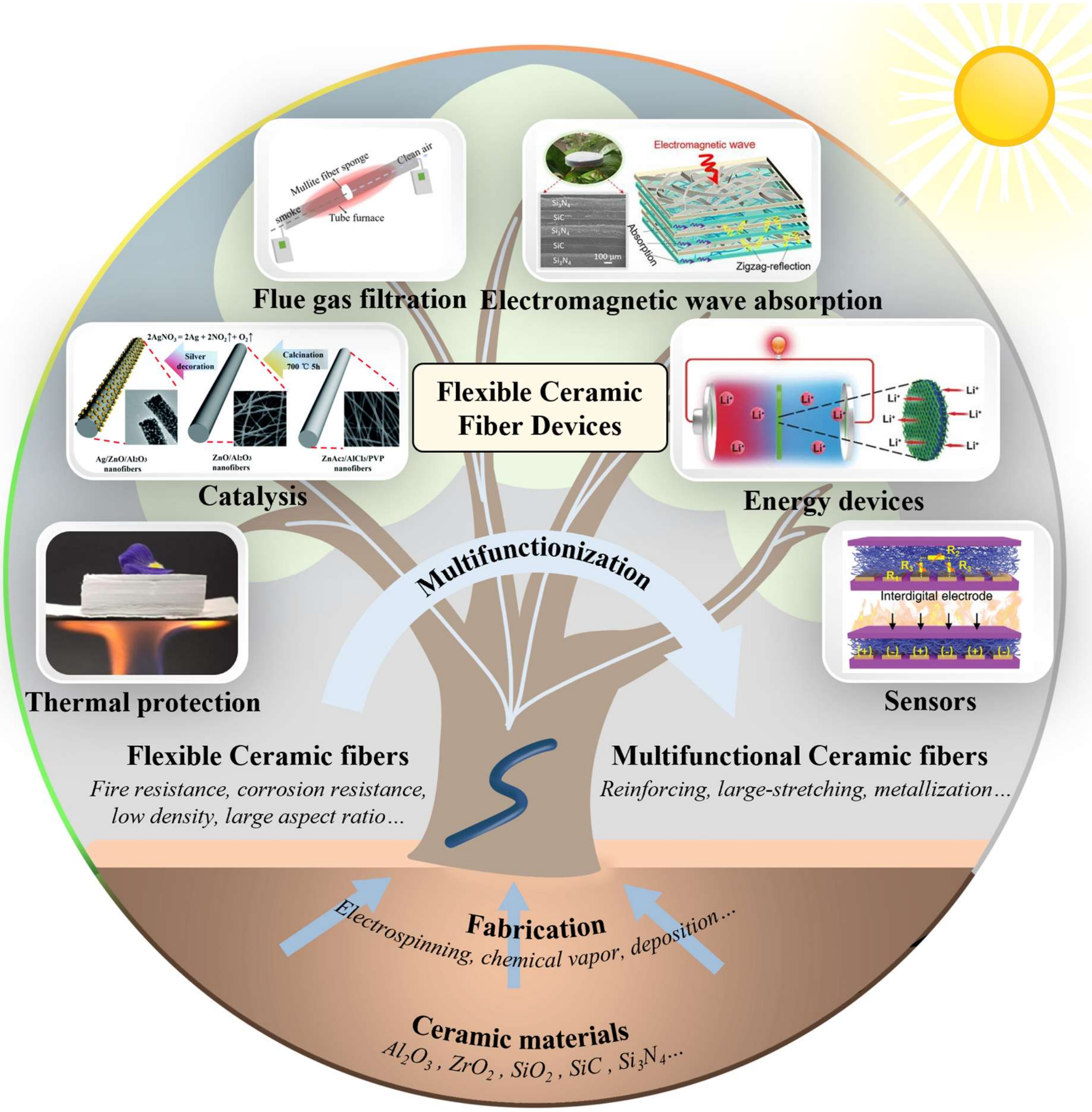

Figure 1. The framework of this review [22–27].

2. Fundamentals of FCFs

2.1. Materials

FCFs encompass a wide range of materials, typically categorized based on their chemical composition. Each category reflects distinct physical and chemical properties suited for specific applications in high-temperature or extreme environments. Generally, ceramic fibers can be divided into oxide ceramic fibers and non-oxide ceramic fibers based on their chemical composition.

Oxide ceramic fibers are widely recognized for their excellent thermal stability, chemical inertness, and oxidation resistance, making them essential for high-temperature applications. They are commonly used in thermal insulation systems, such as furnace linings and aerospace heat shields, as well as reinforcements in ceramic matrix composites (CMCs) to enhance mechanical strength and thermal shock resistance. Examples include alumina (Al_2O_3) fibers [28], zirconia (ZrO_2) fibers [29], silica (SiO_2) fibers [30] and mullite [31], which are notable for their high operating temperatures (over 1200 °C) and corrosion resistance. Despite their advantages, oxide ceramic fibers face challenges such as brittleness, high production costs, and poor electrical conductivity.

Non-oxide ceramic fibers, such as carbide ceramic fibers, nitride ceramic fibers, and expanded non-ceramic fibers, also play an important role in extreme conditions. Non-oxide ceramic fibers containing silicon, such as silicon carbide (SiC) [32], silicon nitride (Si_3N_4) [33], and silicoboron carbonitride (SiBCN) [34] have been widely studied. Similar to oxide ceramic fibers, non-oxide ceramic fibers generally have the advantage of thermal and corrosive stability. Furthermore, some non-oxide ceramic fibers have electrical conductivity, microwave-transparent, or other electromagnetic-related properties that oxide ceramic fibers usually lack, leading to a broader range of applications in industry and military equipment. However, non-oxide ceramic fibers tend to require more stringent process conditions, higher cost preparation, and exhibit poor durability in oxidizing atmospheres.

2.2. Structure

According to differences in dimension, FCFs can be categorized into three primary morphologies: one-dimensional (1D) [35], two-dimensional (2D) [36], and three-dimensional (3D) structures [10,22]. Each dimension of FCFs has various high-temperature applications. Regardless of the dimension, each ceramic fiber's large aspect ratio and good continuity are essential advantages. In addition, ceramic fibers exhibit diverse morphologies, which can be broadly categorized into nanowires [37], nanofibers [38], continuous filaments [39], and ceramic yarns [40]. These distinct forms are defined by their dimensions and structural characteristics, influencing their fabrication methods and functional applications. For example, nanowires, typically less than 100 nm in diameter, are notable for their high aspect ratios and surface areas, making them ideal for applications such as sensors and catalysts. In this review, we mainly discuss surveys of nanofibers, which means that the diameter of a single FCF mainly focuses on $1\sim10^3$ nm. FCFs of different structures and scales benefit from the development of advanced fabrication.

2.3. Fabrication

The fabrication of FCFs involves several techniques, each tailored to achieve specific fiber properties and applications. Electrospinning is a widely used method due to its ability to produce fibers with controlled diameters and morphologies [41–43]. This technique leverages electric forces to draw fibers from a polymer solution, allowing for precise control over fiber structure through solution composition and processing parameter adjustments. Chemical vapor deposition (CVD) is another method that enables the production of high-purity ceramic fibers with uniform structures [37]. Solution blow spinning combines electrospinning's precision with the scalability of traditional fiber spinning, making it suitable for large-scale production [44]. Freeze-drying is employed to create porous ceramic fibers by sublimating ice from a frozen suspension, resulting in fibers with high surface areas [45]. Lastly, centrifugal spinning uses centrifugal force to extrude fibers from a polymer solution, offering versatility in fiber diameter control [46]. Each method has its unique advantages and is chosen based on the desired fiber properties and application requirements.

Electrospinning is a highly effective method for the preparation of nano-ceramic fibers, offering significant advantages in terms of fiber diameter [47]. Compared to other spinning methods such as blow-spinning, melt-spinning, wet-spinning, and centrifugal spinning (Table 1), electrospinning can produce fibers with much smaller diameters, typically ranging from tens of nanometers to several micrometers. This fine fiber diameter is crucial for applications requiring high surface area and porosity, such as catalysis, filtration, and sensing. For instance, electrospinning can create fibers with diameters down to nanometers, which is significantly finer than those produced by other methods [48]. In contrast, blow-spinning and melt-spinning tend to produce fibers with larger diameters, usually in the micrometer range. Wet-spinning and centrifugal spinning can also produce fine fibers, but they often require more complex processes and may result in less uniform fiber diameters. Therefore, electrospinning stands out for its ability to produce ultra-fine nano-ceramic fibers with high precision and uniformity, making it a preferred method in many advanced applications.

Currently, the preparation of oxide ceramic nanofibers by electrospinning is highly dependent on the addition of organic polymers to obtain spinnable inorganic sol. This is because the inorganic sols themselves often lack the necessary viscosity and stability to form continuous fibers. The addition of organic polymers can improve the rheological properties of the solution, making it more suitable for electrospinning [49]. For example, polyvinyl pyrrolidone (PVP) [50], polyvinyl alcohol (PVA) [51] and polyethylene oxide (PEO) [52] are commonly used as a polymer matrix in the precursor solution for electrospinning oxide ceramic nanofibers. They help increase the solution's viscosity and provide the necessary mechanical strength to the as-spun fibers. However, this approach also has some limitations. The presence of organic polymers may introduce additional impurities and affect the purity and properties of the final ceramic fibers. Moreover, the removal of the organic components during the calcination process may lead to structural defects and affect the performance of the fibers [53]. Therefore, there is a need to explore alternative methods to reduce the dependence on organic polymers in the electrospinning of oxide ceramic nanofibers, such as direct electrospinning of inorganic sol, but it is not necessary to add any organic polymer template [54].

Table 1. Comparison of spinning methods.

Method	Advantages and Disadvantages	Diameter of FCFs	Reference
Electrospinning	Raw materials simple process, but need template	0.5 nm~1 μm (SiO_2)	[54]
		500 ± 30 nm ($MgSiO_3$)	[55]
Blow-spinning	High efficiency, but need template	0.5~2 μm ($ZrSiO_4$)	[44]
		0.5~5 μm (Mullite)	[56]
Melt-spinning	High efficiency, but poor controllability	10 μm (YAG)	[57]
		8~9 μm (Al_2O_3-HfO_2)	[58]
Wet-spinning	Simple process, but poor stability	320 μm (Si_3N_4)	[59]
		25.3 (±3.0) μm (PVP/BNNT)	[60]
Centrifugal spinning	High efficiency and low requirements for additives, but poor continuity	15.5 μm (ZrC)	[46]

3. Multifunctionalization of FCFs

FCFs have shown great potential in high-temperature applications due to their excellent thermal stability, mechanical strength, and flexibility. However, to further enhance their performance and expand their application scope, various multifunctionalization strategies have been developed. These strategies include modification, morphology design, and deposition, which aim to improve the mechanical strength, thermal stability, and electrical properties of FCFs.

3.1. Modification: Reinforcing

Modification is an effective method to enhance the mechanical and thermal properties of FCFs. Surface etching is one traditional modification method that changes the ceramic material's surface morphology and affects mechanical performance [61]. However, it is not suitable for ultra-fine fibers, as they tend to be more difficult to control the degree of etching than bulk materials. For fiber networks, increasing the number of node connections can significantly enhance their strength [62]. It is a good modification method if the fibers can be cross-linked by physical or chemical methods. For example, Mao et al. [63] demonstrated that cross-linking zirconia-silica (ZrO_2-SiO_2) nanofibers with montmorillonite (MMT) nanosheets through electrospinning and calcination could significantly improve the mechanical stability and thermal resistance of flexible ceramic membranes (Figure 2a). The resulting MMT@ZrO_2-SiO_2 membranes exhibited a tensile strain of about 1% and tensile strength of 1.83 MPa, with impressive thermal stability, maintaining mechanical properties from −196 °C to 1000 °C. The membranes also demonstrated excellent thermal insulation with low thermal conductivity (0.026 W m^{-1} K^{-1}).

Cheng et al. [64] introduced a novel fire-reborn strategy to synthesize flexible and transformable silica-alumina hybrid ceramic aerogels (FR-SACAs) for effective thermal superinsulation in extreme high-temperature (EHT) environments. This strategy rearranged silica aerogel microparticles and Al_2O_3 ceramic fibers, and it resulted aerogels with an ultra-low density of 0.01 g/cm^3, thermal conductivity of 0.029 W/m·K and the ability to reduce temperature by over 80% when exposed to a 1300 °C flame. The FR-SACAs also exhibited remarkable compressibility, reversible up to 80%, and can be easily applied on various substrates for high-temperature protection by rearranging silica aerogel microparticles and Al_2O_3 ceramic fibers, showing great promise for applications in aerospace, construction, and fire safety.

In addition to the introduction of the second phase inside the fiber, the modification of nanosheets or particles between the fibers can also be obtained by coaxial spinning and other methods to obtain cross-linked composite ceramic fibers. Wang et al. [38] developed grooved TiO_2/ZrO_2 ceramic fibers using coaxial electrospinning, which exhibit enhanced thermal insulation and mechanical properties. These fibers consist of a TiO_2 shell that improves infrared reflectivity and a ZrO_2 core that ensures mechanical strength. The unique coaxial structure prevents TiO_2 grain coarsening, boosting tensile strength to 1.47 MPa, and results in thermal conductivity as low as 0.0278 W/m·K. The fibers' excellent insulation performance was confirmed through practical tests, demonstrating substantial temperature reduction on the cold side when exposed to high temperatures.

3.2. Morphology Design: Large-Stretching

Morphology design is a powerful strategy for enhancing the mechanical properties and thermal stability of FCFs. By carefully engineering the internal structure of the fibers, researchers can achieve significant improvements in flexibility, stretchability, and overall performance. One notable approach involves creating unique fiber architectures, such as Janus structures and spiral crimped designs [65]. Specifically, in terms of stretchability enhancement, fibers of two or more materials are wound side by side into Janus fibers to expand their own properties, or turning straight fibers into curved fibers to increase the elasticity of axial stretch with some elaborate preparation methods to increase the elasticity of axial stretch. In brief, these strategies can significantly enhance the material's mechanical flexibility and maintain thermal and electrical functionalities at high temperatures.

In order to solve the intrinsic brittleness of ceramic materials, it is a good choice to design the morphology toughening of a single FCF. Dong et al. [66] developed a coelectrospinning technique that allows the fabrication of high-quality ceramic fibers from nonspinnable sols, resulting in fibers with reduced porosity and controlled diameters. The TiO_2 fibers with morphology of nanospring produced showed improved flexibility, with a Young's modulus of 54.3 MPa and fracture strain of about 3% (3.2 times larger than the straight fibers). Su et al. [67] developed a highly stretchable, crack-insensitive, and compressible ceramic aerogel using curly SiC-SiO_x bicrystal nanowires, which demonstrated reversible stretchability up to 20% strain and an ability to recover from up to 80% compressive strain. The aerogel also exhibited excellent thermal stability at temperatures ranging from −196 °C to 1200 °C, making it ideal for high-performance thermal insulation and other applications in extreme environments. In short, curved structures have been proven to be able to determine and improve tensile properties.

Furthermore, large-stretching modification of FCFs has also been reported. For example, Jiao et al. [68] introduced a novel approach to fabricate stretchable ceramic membranes using TiO_2/SiO_2 spiral crimped Janus fibers. The Janus structure, characterized by two distinct surfaces with different properties, was created through conjugate electrospinning, a technique that allows for the simultaneous spinning of two different materials (Figure 2b). The spiral crimped design further enhanced the stretchability of the fibers, enabling the membranes to endure up to 70.59% elongation at the break without significant degradation in performance. This design not only improved the mechanical properties but also maintained excellent thermal insulation and high-temperature resistance, with the membranes demonstrating stability across a wide temperature range from −196 °C to 1300 °C.

The development of such large-stretching ceramic materials is crucial for applications in flexible electronics, high-temperature sensing, and thermal insulation, where materials must withstand significant mechanical stress and maintain performance at elevated temperatures.

3.3. Deposition: Metallization

Metallization through deposition is a crucial technique for enhancing the functionality of FCFs, particularly for applications requiring electrical conductivity and high-temperature stability. Especially for non-conductive FCFs, metallization means making them electrical conductivity so that they can be leads or electrodes of electrical devices like metal materials. This method involves depositing conductive materials onto the surface of FCFs to improve their electrical properties while maintaining their inherent thermal and mechanical characteristics.

Sputtering deposition is a simple way to electrify a surface. For example, Wei et al. [69] functionalized ceramic fibers by sputter coating them with copper, significantly altering their surface morphology and improving surface conductivity. The author found that increasing the coating thickness from 20 nm to 100 nm enhanced the interfacial adhesion and reduced the surface resistance, making the ceramic fibers more suitable for applications requiring improved electrical conductivity and surface properties. Guo et al. [27] developed Au–Cu@SiO_2 nanofiber films based on the chemical plating method, with stable electrical resistance of about 23 mΩ·cm from 200 °C to 500 °C. However, due to the limitations of metal-ceramic adhesion strength and patterning requirements, this method is still rarely reported in the metallization of ceramic fibers.

Nowadays, the printing deposition method has received extensive attention from researchers, which has more significant advantages in patterning than sputtering. Xie et al. [70] demonstrated a novel approach to fabricate such paper entirely composed of ceramic fibers with an equimolar ratio of $ZrO_2/Y_2O_3/Al_2O_3$, addressing the issue of strength degradation in traditional ceramic fiber papers under high-temperature conditions. The resulting ceramic fiber paper exhibited a tensile strength of 2.63 MPa and could reliably operate at temperatures up to 1200 °C (Figure 2c). This innovation opens new possibilities for high-temperature applications in electronics, providing an alternative to traditional materials that suffer from performance limitations at elevated temperatures. Similarly, Xiao et al. [45] developed a flexible ceramic aerogel pressure sensor (FCAPS) based on ZrO_2–SiO_2 nanofiber aerogel (ZSNFA) with interwoven Ag-Pd paste through direct ink writing (DIW) technique. FCAPS operates stably from −196 °C to 800 °C with high sensitivity (0.262 kPa^{-1}). Integrated with deep learning, the sensor enables precise object recognition for intelligent firefighting applications. Printing deposition allows for customized conductive fiber electrode designs, but resolution and uniformity often depend on ink compatibility with FCFs [71].

Metallization of FCFs is often used as the basis for electrical devices such as sensors. The development of simple, low-cost, and high-precision metallization deposition strategies is the mainstream research direction in the future.

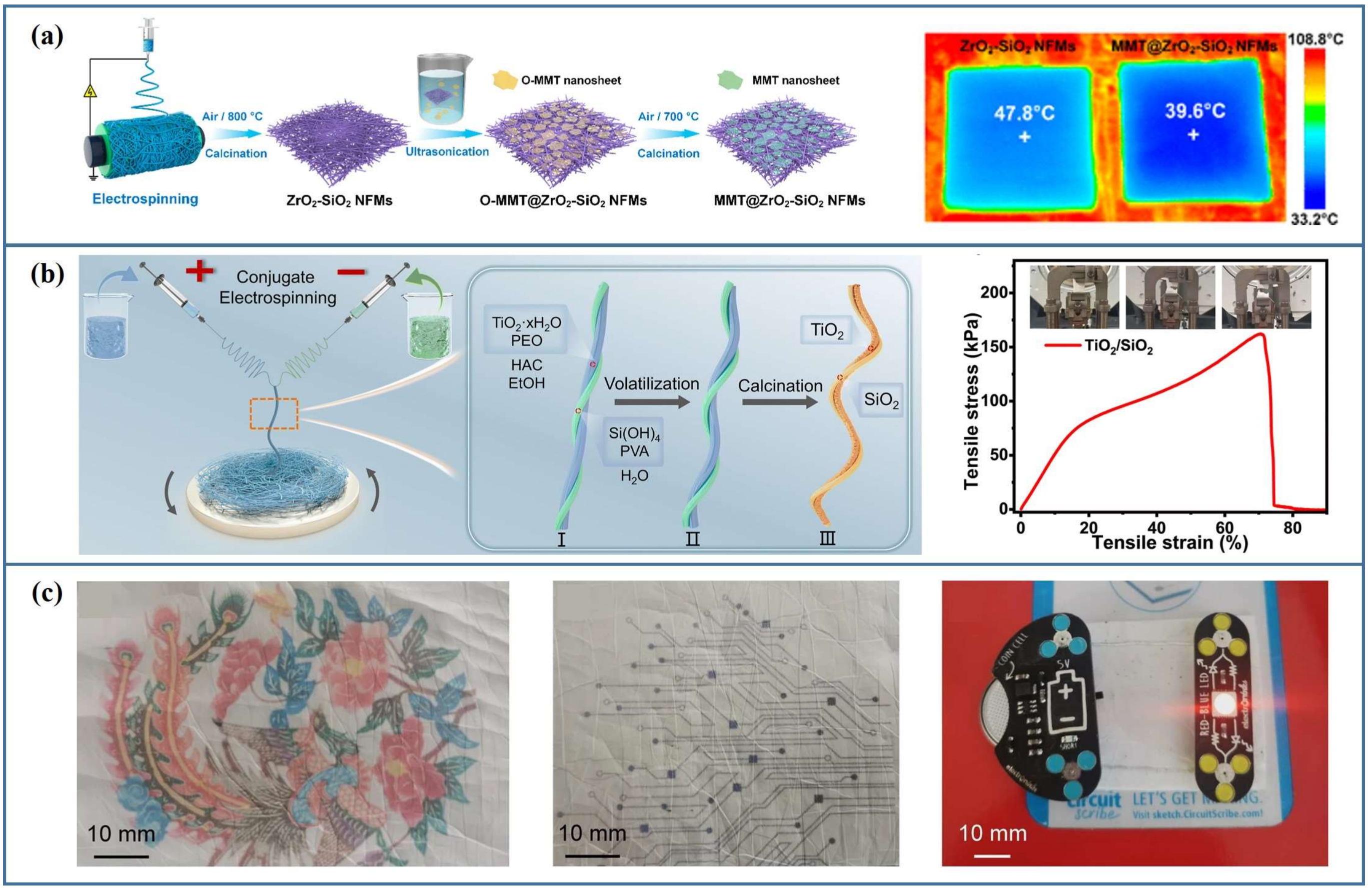

Figure 2. Multifunctionalization of FCFs. (**a**) Reinforcing by modification: Cross-linked MMT@ZrO_2-SiO_2 membranes, which can be stable from −196 °C to 1000 °C [63]. (**b**) Large-stretching by morphology design: TiO_2/SiO_2 Janus fibers with maximum 70.59% tensile strain through conjugate electrospinning [68]. (**c**) Metallization by deposition: $ZrO_2/Y_2O_3/Al_2O_3$ paper for flexible circuit substrate [70].

4. High-Temperature Applications of FCFs

FCFs have demonstrated significant potential across a variety of high-temperature applications due to their unique combination of thermal stability, mechanical flexibility, and chemical resistance. These applications span multiple fields, including thermal insulation, high-temperature flue gas filtration, catalysis, electromagnetic wave absorption, energy storage, and high-temperature sensing. Each application leverages the distinct advantages of FCFs to address specific challenges in extreme environments.

4.1. Thermal Insulation

The demand for advanced thermal insulation materials has surged in recent years due to the increasing complexity of aerospace, energy, and defense applications. High-temperature environments, such as those encountered in aero-engines, scramjet engines, and articulated warheads, require materials that resist extreme heat and maintain structural integrity under mechanical stress and thermal cycling. With their unique combination of low density, high thermal stability, and mechanical flexibility, FCFs have emerged as a promising solution for these challenges [72]. By leveraging novel material designs and fabrication techniques, these materials have demonstrated their potential to provide robust thermal insulation in extreme environments, ensuring the safety and functionality of critical systems.

Refractory materials, including alumina silica, magnesia oxide and other ceramic materials, are widely used in high-temperature environments due to their melting point of thousands of degrees Celsius and resistance to chemical attack. These materials are essential for industrial and aerial equipment that usually faces high-temperature challenges. FCFs made from these refractory materials like silica fibers can often have flame retardants, which are extremely suitable as building materials for roofs and walls to extend the escape time [73]. In the context of thermal insulation, refractory materials play a crucial role in protecting structures and equipment from extreme heat and thermal shock. For instance, FCFs are selective materials for thermal insulation due to their low thermal conductivity, low density and high-temperature resistance to thermal decomposition, deformation, and brittleness (Figure 3a) [12]. Compared with traditional ceramics, the thermal insulation performance of micro-nano FCFs has been significantly improved [74]. Thanks to high NIR reflection, low density, and high porosity, FCFs can reduce heat convection in the heat transfer process (Figure 3b) [75].

Cheng et al. [76] developed 3D interwoven crimped-nanofiber structured ceramic aerogels (ICCAs), which are fabricated from mullite sol by 3D reaction electrospinning (Figure 3c). These ICCAs exhibited robust fire resistance with a low thermal conductivity of 22.8 mW m^{-1} K^{-1} and mechanical flexibility with 40% tensile strain, even when exposed to a butane flame (about 800~1300 °C).

Zhang et al. [77] further advanced this field by engineering a stretchable SiO_2-based ceramic meta-aerogel with low thermal conductivity (33.01 mW m^{-1} K^{-1}), using kirigami stacking and nanofiber freeze-drying techniques (Figure 3d). When tested in a heat pipe was rapidly heated to 1000 °C, the ceramic meta-aerogels maintained stability, with a maximum surface temperature of approximately 260 °C, effectively insulating electronic components inside an articulated warhead (below 900 °C). This development underscores the potential of FCFs for thermal insulation in compact systems where weight and space are critical constraints.

Dang et al. [78] introduced a two-component off-axial electrospinning method to create zirconia-silica structured ceramic aerogels, with ultra-large stretchability (150% tensile strain), high thermal stability (from −196 °C to 1000 °C) and low thermal conductivity (106.7 mW m^{-1} K^{-1} at 1000 °C) (Figure 3e). These aerogels were tested in a morphing wing, maintaining an internal temperature of only 35 °C after 100 cycles of heating to 1000 °C for 10 minutes. This application demonstrates the versatility of FCFs in dynamic environments where materials must endure repeated thermal and mechanical loading.

Besides aerospace applications, thermal insulation is one of the most fundamental applications of FCFs. Extensive research has been conducted in this area. However, achieving effective thermal insulation often requires thick membranes, typically on the order of centimeters, which can significantly increase the weight of the material and limit its use in compact systems. Reducing the thickness of these membranes while maintaining thermal insulation efficiency is a significant challenge, as thinner membranes often struggle to balance heat conduction suppression and mechanical strength. To address this issue, innovative structural designs and composite material strategies are needed to enhance performance under reduced thickness conditions.

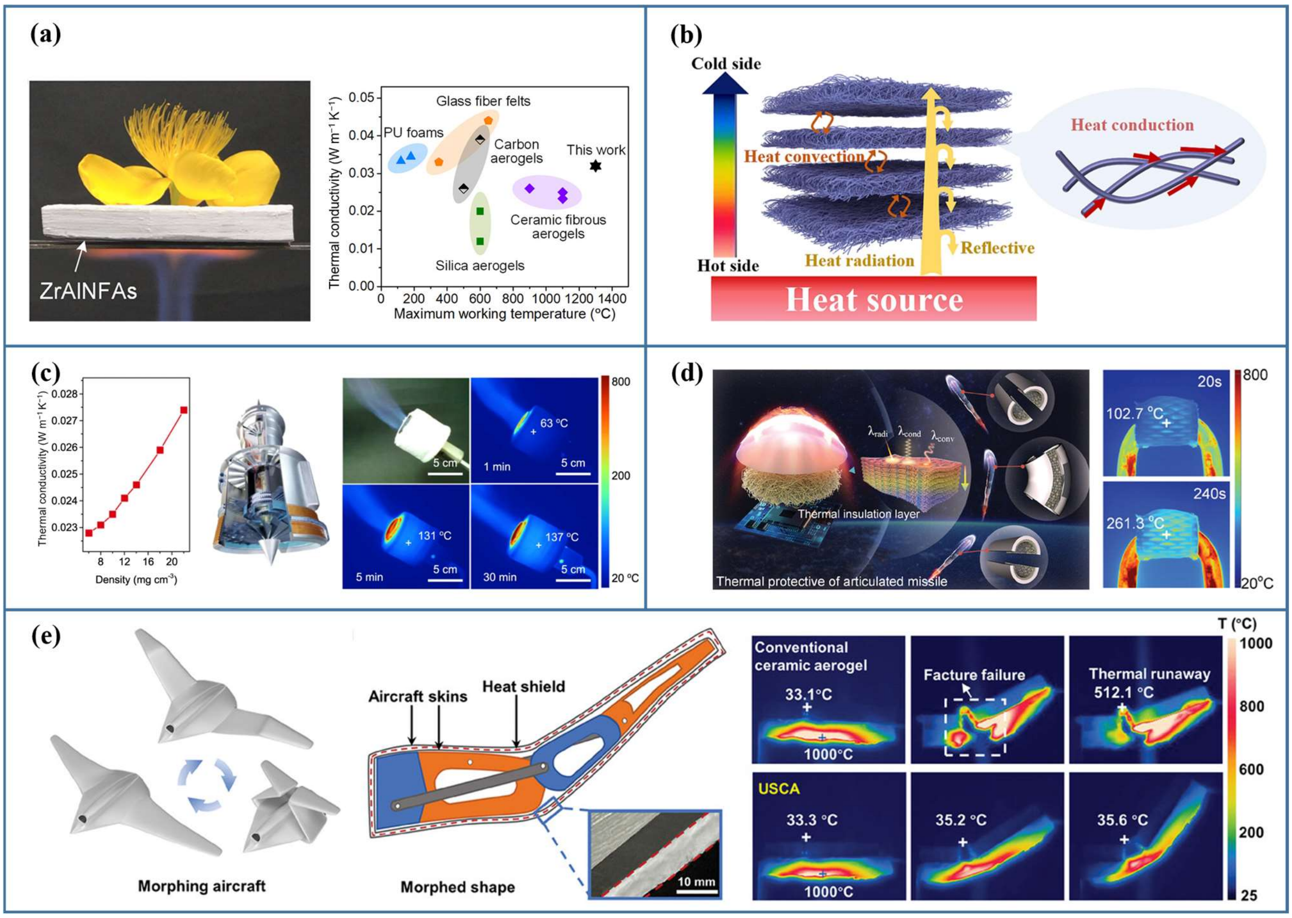

Figure 3. Applications of thermal insulation based on FCFs. (**a**) Thermal insulator with high fire resistance [12]. (**b**) Heat transfer mechanism diagram [75]. (**c**) Thermal insulation in aero-engines or scramjet engines [76]. (**d**) Thermal insulation of electronic components inside articulated warhead [77]. (**e**) Thermal insulation of morphing wing [78].

4.2. High-Temperature Flue Gas Filtration

With the development of human society and technology, the problem of air pollution has increasingly gained widespread attention. Nowadays, half the world's population is exposed to increasing air pollution, leading to millions of people's deaths every year [79]. Airborne particulate matter (PM), a main pollutant with a wide range of particle sizes and typical chemical composition, seriously threatens environmental protection and human health [80]. According to data analysis, about 58% of PM emissions originate from high-temperature exhaust such as coal combustion, industrial activities, and vehicle exhaust [81]. An efficient method to reduce PM in the air is high-temperature flue gas filtration. To achieve high-temperature flue gas filtration, filter materials should be efficient and high-temperature resistant. Traditional materials that withstand high temperatures are mostly ceramic filters, renowned for their exceptional chemical inertness, enabling them to withstand corrosion from acidic and alkaline gases in hot exhaust streams. Benefiting from a larger specific surface area and smaller pores, ceramic fiber materials are suitable for PM filters of high-temperature flue gas filtration [82].

Wang et al. [83] developed an elastic, high-temperature resistant, and high-efficiency air filter based on yttrium-stabilized zirconia (YSZ) nanofiber sponges using solution blow spinning technology (Figure 4a). The YSZ nanofiber sponges exhibit a filtration efficiency of 99.4% and a pressure drop of only 57 Pa for 20–600 nm NaCl particles at a flow velocity of 4.8 cm s^{-1} at room temperature. Even though at a high temperature of 750 °C, the YSZ nanofiber sponges maintained a high filtration efficiency of 99.97% for $PM_{0.3–2.5}$ under a high airflow velocity of 10 cm s^{-1}, proving its potential application in filtration of automobile exhaust gas.

Jia et al. [84] created a flexible and thermally stable Al_2O_3-stabilized ZrO_2 (ASZ) submicron fiber air filter paper for efficient filtration using a solution blow spinning method followed by calcination (Figure 4b). This flexible ASZ paper can be thermally stable up to 1100 °C and is very flexible. At an area density of 56 mg cm^{-2}, ASZ paper demonstrated a 99.56% filtration efficiency and a pressure drop of only 108 Pa when filtering NaCl particles (15–615 nm) at an airflow speed of 5.4 cm s^{-1}. Besides, the material maintained over 99.3% removal efficiency in a 6-h test, showcasing its potential for sustained high-temperature filtration applications.

Tan et al. [85] developed flexible Zr-doped TiO_2 nanofibrous membranes (Zr–TiO_2 NFMs) using electrospinning and calcination for high-efficiency removal of oily particulate matter (PM) from high-temperature flue gas (Figure 4c). The incorporation of Zr^{4+} ions improved the mechanical strength, thermal stability, and specific surface area of the TiO_2 nanofibers by reducing nanocrystal size and surface defects. The Zr–TiO_2 NFMs demonstrated outstanding filtration efficiency (>99.98%) for PM2.5 at 350 °C with low-pressure drop and great regeneration performance over five filtration cycles. This work shows the potential of Zr–TiO_2 NFMs for advanced flue gas filtration under extreme conditions, offering insights into temperature-dependent PM capture mechanisms.

Li et al. [86] utilized the solution blow spinning technique to develop mullite nanofiber (MNF) films featuring both thick and thin fibers with average diameters of 606 nm and 186 nm, respectively (Figure 4d). Because of this dual-scale structure, the MNF films enhanced filtration efficiency of 98.23%, a low areal density of 3.8 mg cm^{-2} and achieved a pressure drop of 141 Pa for $PM_{0.3}$ at an airflow velocity of 5.3 cm s^{-1}, exhibiting flexibility (winding radius can be up to 9 mm) and high-temperature resistance (no significant changes at 1300 °C for 5 min) for use in high-temperature flue gas filtration.

The same as other fibers or materials, the filtering efficiency of ceramic fiber materials is seriously decided by their fiber diameter [87]. Smaller fiber diameter and areal density result in higher efficiency of filtrate and removal particles, but it increases the difficulty and cost of manufacturing. In the future, the development of ceramic fiber materials with smaller fiber diameter, higher porosity, and greater thermal stability under conditions of lower areal density, higher gas temperatures, and faster airflow rates will be a key research direction of high-temperature flue gas filtration.

Additionally, fiber diameter has a significant effect on the filtration property [87]. To improve the filtration property of ceramic fiber materials, we need to overall prepare smaller-diameter fibers. Besides, the cost-effective ceramic fiber aerogels with excellent porosity can be used to develop high dust capacity filtering materials to increase their dust capacity.

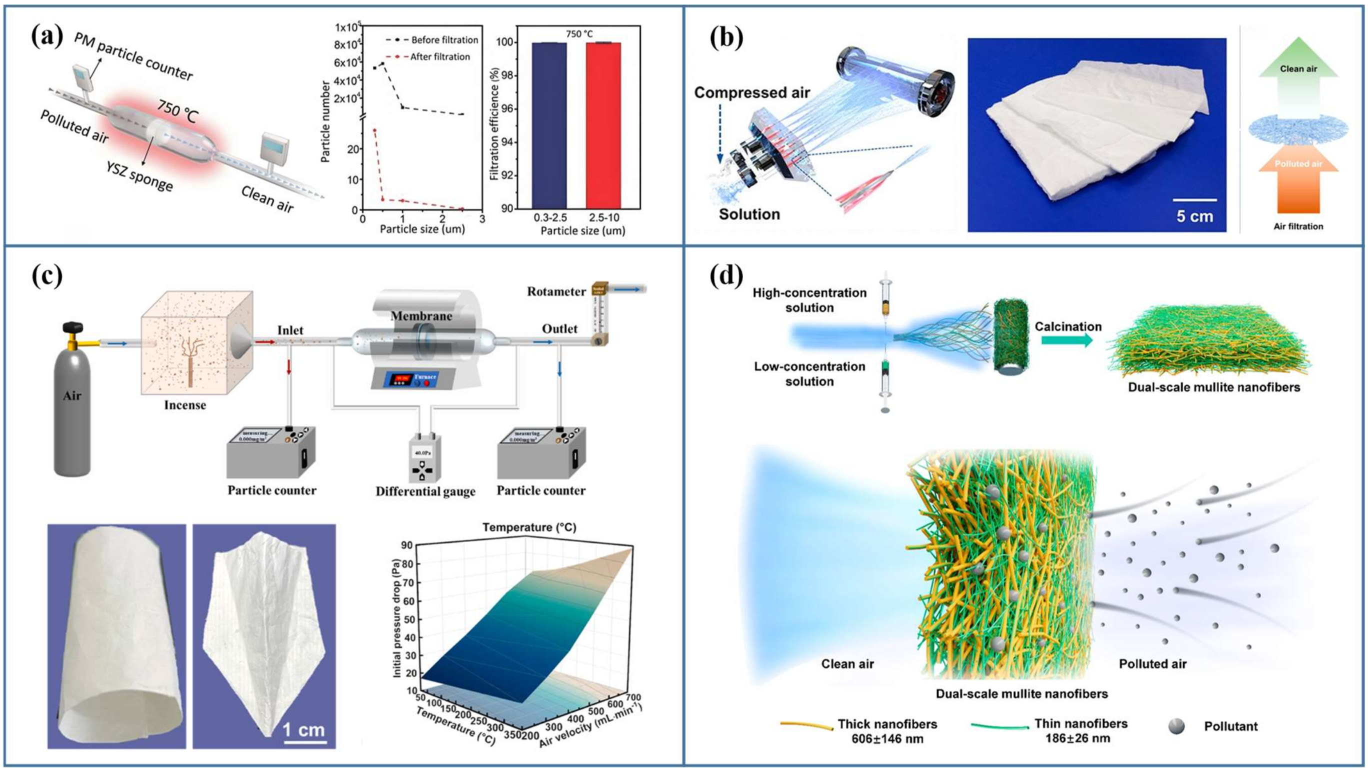

Figure 4. Applications of high-temperature flue gas filtration based on FCFs. (**a**) Filtering of $PM_{0.3–2.5}$ and $PM_{2.5–10}$ at 750 °C airflow [83]. (**b**) Filtering of NaCl particles in different nanometer sizes with ASZ paper [84]. (**c**) Filtering of oily PM at 25–350 °C [85]. (**d**) Filtering of $PM_{0.3}$ with MNF films [86].

4.3. Catalysis

Catalysis of ceramic fibers have garnered significant attention due to their unique advantages, such as high thermal stability, mechanical strength, and large surface areas, which make them indispensable candidates for high-temperature and complex catalytic reactions. FCFs can be the carriers of catalysts by loading catalysts on the surface or inside of the FCFs. When it comes to reactions with high temperature or corrosion, such as gas synthesis and reduction reactions, it is usually better to use FCFs rather than organic films or fibers [88].

FCFs can be endowed with photothermal catalysis. For example, Zhang et al. [89] developed elastic TiO_2 nanofibrous aerogels with a hierarchically ordered structure and enhanced conductivity (38.2 mS cm^{-1}) via sol-gel electrospinning and lithium reduction (Figure 5a). These aerogels, which calcined at 600 °C in argon, have an obvious photothermal effect and served as self-supported electrocatalysts for nitrogen fixation, achieving an ammonia yield of 4.19×10^{-10} mol s^{-1} cm^{-2} and Faradaic efficiency of 20.3%.

Also, FCFs can be used to catalyze synthetic reactions with the help of catalytically active particles. Fu et al. [90] meticulously crafted loofah-like γ-Al_2O_3 mesoporous nanofibers (MNFs) via the sol-gel electrospinning technique, subsequently depositing Pt nanocrystals onto the MNFs using an impregnation method (Figure 5b). The synthesized catalyst exhibited exceptional thermal stability at 500 °C and achieved a remarkable reduction reaction rate of 6.8 $S^{-1}\cdot mg^{-1}$ for the thermo-catalytic reduction of p-nitrophenol, which was a significant fourfold increase in speed compared to the use of net-like Pt nanocrystals.

Compared with photocatalysis, thermal catalysis can better reflect the advantages of FCFs, especially for gas synthesis reactions at temperatures of hundreds or thousands of degrees Celsius. Sánchez et al. [91] investigated ceramic fiber-based structures as catalyst supports for CO_2 methanation, focusing on mass and heat transport behavior. They found ceramic fibers with small diameters provided high surface areas, enabling efficient external mass and heat transfer, but radial heat dispersion remained a bottleneck (Figure 5c). Yan et al. [92] developed ultra-flexible Al_2O_3 fibers using the blow-spinning method, demonstrating remarkable mechanical flexibility and thermal stability from −196 °C to 1200 °C (Figure 5d). By loading nickel nanoparticles onto the fibers, Ni/Al_2O_3 fibers can demonstrate great catalytic performance for dry reforming of methane (DRM), achieving stable CH_4 and CO_2 conversions (~87% and ~92%, respectively) and high H_2 selectivity (~96%) at 800 °C over 150 h.

These advancements have demonstrated their potential in critical applications such as nitrogen fixation, CO_2 methanation, and methane reforming. However, it is a challenge to enhance the compatibility between active catalyst particles and supports. By overcoming these challenges, FCFs can play a transformative role in sustainable and high-performance catalytic systems.

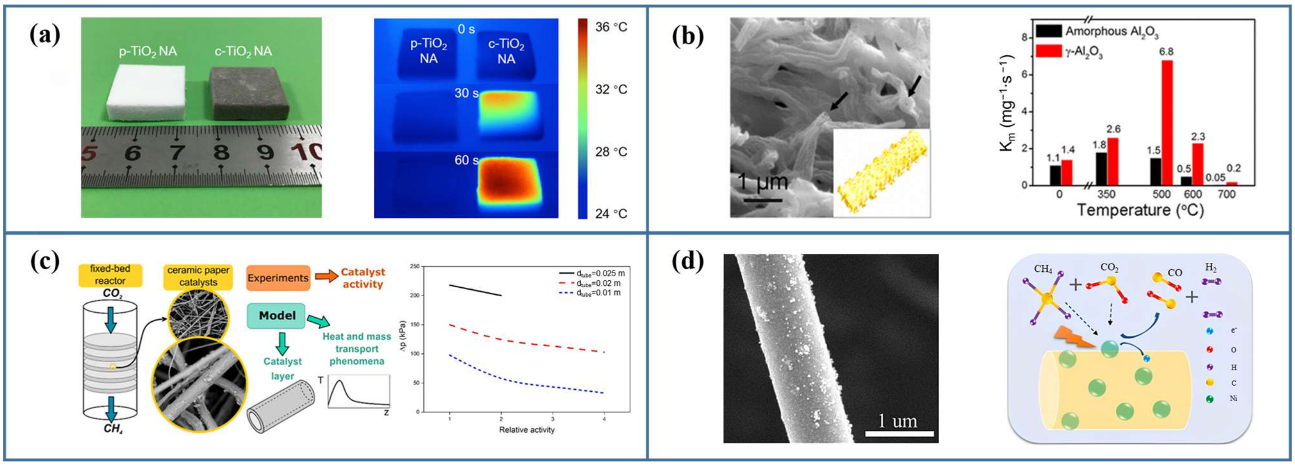

Figure 5. Applications of high-temperature catalysis based on FCFs. (**a**) Photothermal catalysis of nitrogen fixation [89]. (**b**) Thermo-catalytic reduction of p-nitrophenol [90]. (**c**) CO_2 methanation Piezoresistive pressure sensor [91]. (**d**) Dry reforming of methane [92].

4.4. Electromagnetic Wave Absorption

With the rapid development of modern communication technologies and electronic devices, electromagnetic wave (EMW) pollution has become a pressing issue, leading to the demand for high-performance EMW absorption materials [93]. FCFs have garnered significant attention for this application due to their unique combination of lightweight structure, thermal stability, and EMW attenuation capabilities [94]. The inherent advantages of FCFs, such as their porous 3D structures, high specific surface areas, and tunable dielectric properties, make them ideal candidates for EMW absorption in extreme environments, including aerospace and stealth technologies [95].

In recent years, advances have shown that SiC-based FCFs are highly effective for EMW absorption. Their 3D porous structures and core-shell configurations optimize impedance matching and enhance dielectric loss. For instance, Zhang et al. [96] developed $SiC@SiO_2$ nanofiber aerogels that achieved a minimum reflection loss (RLmin) of −50.36 dB and an effective absorption bandwidth (EAB) of 8.6 GHz at a thickness of only 1.6 mm (Figure 6a). This demonstrates the potential of FCF-based aerogels for lightweight and efficient EMW absorbers in high-performance applications.

To obtain great EMW absorption, the diameter of fibers should be small. Kang et al. [97] fabricated submicron SiC fibers via electrospinning and high-temperature sintering, achieving a reflection loss of −63.34 dB at 12.85 GHz with a thickness of 1.7 mm (Figure 6b). These fibers demonstrated exceptional thermal stability up to 1800 °C and oxidation resistance at 1400 °C.

Besides, the microstructure of fibers also influences EMW absorption performance. SiBCN fibers after heat treatment at 1200–1600 °C were investigated. Ding et al. [98] fabricated SiBCN fibers through electrospinning and studied how heat treatment leads to the microstructure evolution of SiBCN fibers, which ultimately affects the EMW absorbing performance (Figure 6c). Upon heat treatment at 1200 °C, turbostratic carbon precipitated, yielding a minimum reflection loss (RLmin) of −63 dB and an efficient absorption bandwidth (EAB) of 5.2 GHz. At 1400 °C, the simultaneous formation of turbostratic carbon and nano-SiC grains further enhanced the performance, achieving an RLmin of −67 dB. This superior performance is attributed to conductive loss, dipole polarization, and interfacial polarization. Their study highlights the potential of SiBCN fibers as high-performance EMW absorbers for extreme environments.

Future efforts should focus on microstructure-function integrated control and developing large-scale manufacturing methods to address these limitations and expand their application in extreme environments.

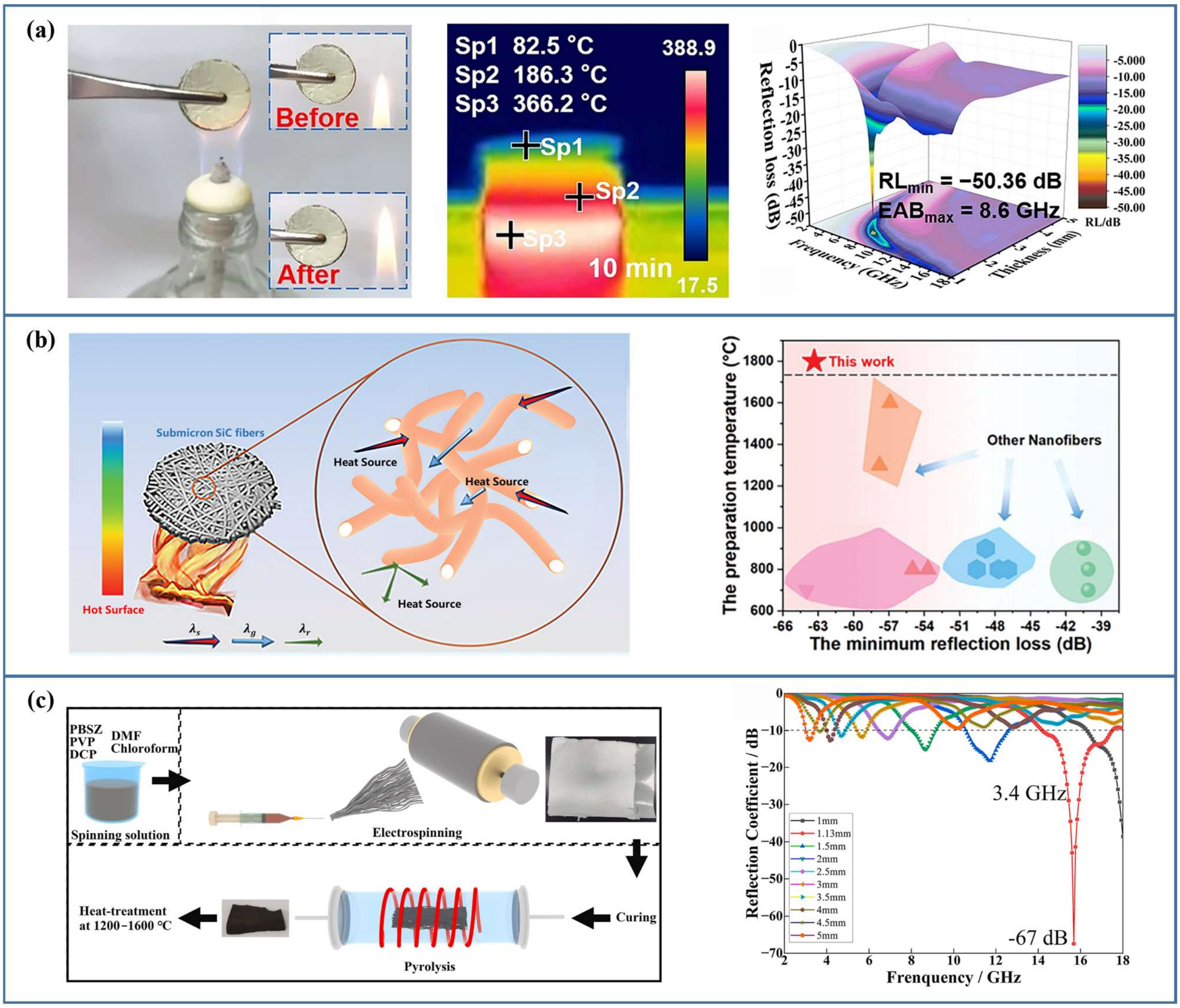

Figure 6. Applications of electromagnetic wave absorption based on FCFs. (**a**) $SiC@SiO_2$ fibers [96]. (**b**) SiC fibers [97]. (**c**) SiBCN fibers [98].

4.5. Energy Devices

Energy storage is a cornerstone of human society, enabling advancements in modern technology and industry [99]. As the demand for efficient, durable, and safe energy devices grows, researchers are exploring new materials and architectures to address critical challenges [100]. Flexibility is emerging as a key requirement, particularly for applications in wearable electronics, foldable devices, and next-generation portable systems [101]. Flexible energy storage devices, typically including batteries and supercapacitors, promise lightweight, adaptable, and multifunctional solutions. However, their development faces several significant hurdles, like aging, dendrite growth, swelling, and self-ignition explosion. Under high current densities or elevated temperatures, it is critical to avoid the failure of materials inside energy devices [102].

Conventional polymer-based components in energy devices, such as separators and electrolytes, struggle to meet the demands of flexibility and safety. For instance, polymer separators often suffer from low porosity, poor thermal stability, and flammability, compromising their performance and reliability. Similarly, liquid electrolytes pose risks of leakage and combustion. To overcome these challenges, researchers are turning to ceramic materials, particularly FCFs, which offer a unique combination of mechanical flexibility, high thermal stability, and electrochemical inertness.

Some researchers have reported that FCFs have been used to be electrodes, electrolytes, and separators, which are parts of batteries and the main constructures of batteries. For electrodes, Sang et al. [103] developed graphene-modified SiOC ceramic cloths with hierarchical porous structures via a polymer-derived ceramic approach (Figure 7a). These materials demonstrated fast lithium-ion diffusion and high electrical conductivity, achieving a remarkable reversible capacity of 686 mAh g^{-1} at 0.5 A g^{-1} after 500 cycles. Notably, the ceramic cloths retained their mechanical flexibility even under repeated bending, showcasing their potential as flexible anodes for wearable and portable electronics.

For electrolytes, Pan et al. [104] developed a garnet-type $Li_7La_3Zr_2O_{12}$ (LLZO) ceramic fabric composite solid electrolyte (CF-CSE) using a silk template, achieving a unique 3D structure with high ceramic content (70 wt%) for fast ion conduction (Figure 7b). The LLZO CF-CSE exhibited enhanced ionic conductivity (8.89×10^{-5} S cm^{-1} at 30 °C), wide electrochemical stability (5.1 V), and great thermal stability (decomposition temperature of 320 °C and low combustibility). Integrated into all-solid-state lithium metal batteries (ASSLBs) enabled stable cycling for 700 h and suppressed lithium dendrite growth. When paired with a $LiFePO_4$ cathode, the ASSLB delivered high capacities (149.3 mAh g^{-1} after 100 cycles at 0.2 C) and outstanding safety, making it a promising candidate for high-energy, safe ASSLBs.

For separators, Jing et al. [29] developed a flexible ZrO_2 ceramic nanofiber membrane using a sol-assisted electrospinning method followed by high-temperature burnout (Figure 7c). The membrane demonstrated high thermal and mechanical stability, high porosity (63.45%), superior electrolyte wettability, and high ionic conductivity (3.5 mS cm^{-1}). When used as a separator in lithium-ion and sodium-ion batteries, it enabled superior rate performance, extended cycling stability, and flame resistance compared to commercial separators like Celgard and glass fiber. This study positions the ZrO_2 membrane as a promising fully inorganic separator for next-generation high-power batteries under extreme conditions.

The development of FCF-based materials marks a significant step forward in energy technology. By addressing critical issues such as dendrite growth, thermal instability, and flammability, FCFs offer a promising pathway to safer and more efficient energy devices. Recent studies have demonstrated the potential of FCF-based electrodes, electrolytes, and separators to deliver outstanding performance in terms of flexibility, thermal stability, and electrochemical properties.

Nowadays, there is little research on the application of FCFs in batteries. Looking ahead, in order to achieve the true lightweight and high safety of flexible batteries, the ultimate goal is to develop fully FCFs-based energy devices.

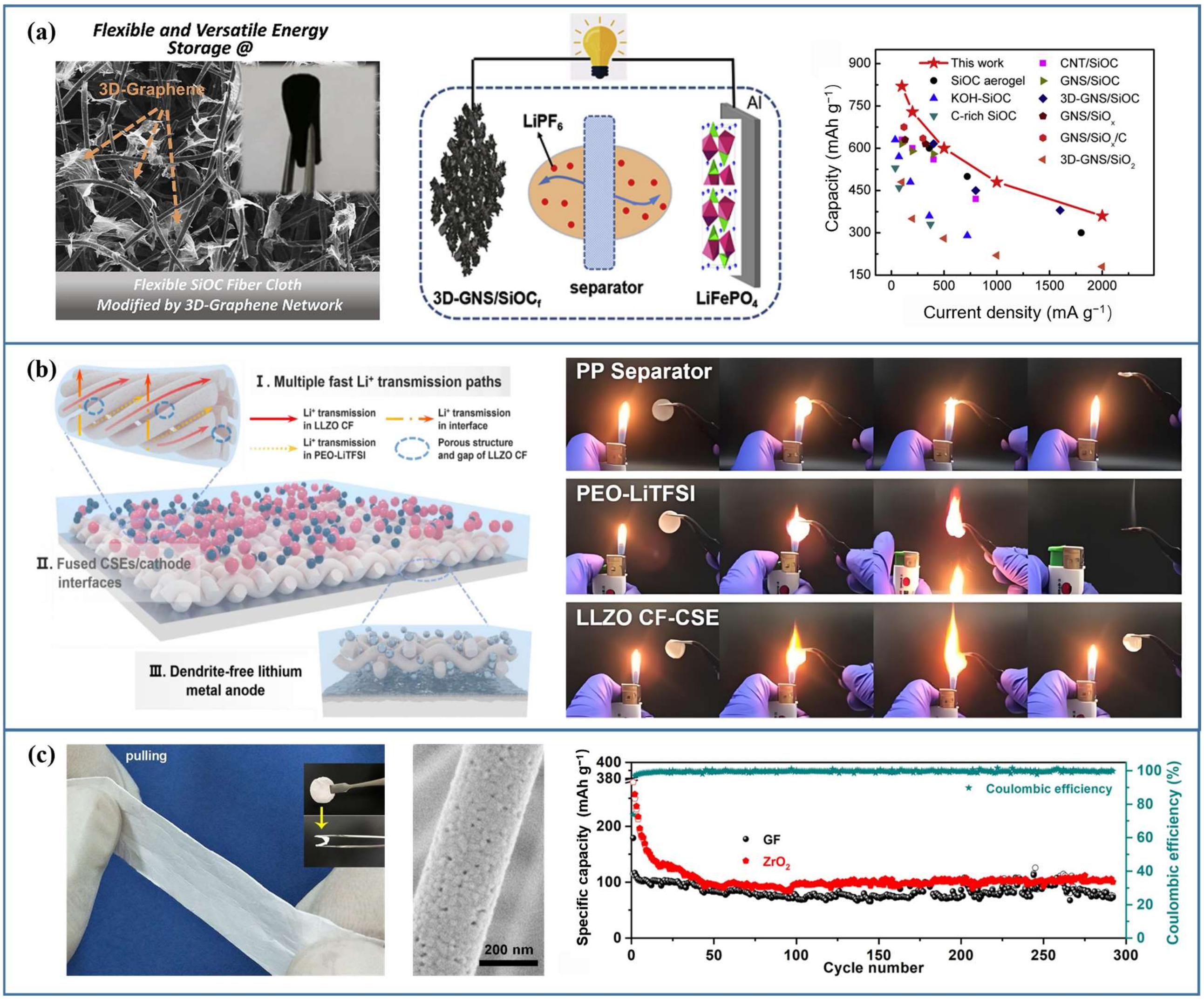

Figure 7. Applications of energy devices based on FCFs. (**a**) Electrodes [103]. (**b**) Electrolytes [104]. (**c**) Separators [29].

4.6. Sensors

In recent years, the development of flexible high-temperature resistant sensors has gained significant attention with the continuous advancement of material science. These sensors, which combine flexibility with thermal durability, usually rely on innovative materials like carbon fibers, ceramic fibers and so on. Their ability to operate under extreme conditions while maintaining accuracy and sensitivity has made them essential in applications requiring real-time monitoring of strain [105], temperature [106,107], and pressure [27,108,109], at elevated temperatures.

For strain sensing, Sun et al. [105] developed a bioinspired flexible strain sensor based on ceramic fiber paper (CFP) coated with gold nanoparticles (Au NPs) and SiO_2 aerogel inspired by scorpions *Heterometrus petersii* (Figure 8a). The sensor demonstrated ultra-sensitivity and superhydrophobicity, withstanding high temperatures up to 220 °C. Its biomimetic design enabled effective strain detection through the synergistic interaction of the ceramic fibers and coatings, ensuring mechanical durability and stability. This innovation addresses the need for lightweight and flexible strain sensors capable of reliable operation in aerospace, offering a robust alternative to conventional rigid strain gauges.

For temperature sensing, Liu et al. [106] developed a flexible thermocouple temperature sensor by screen-printing indium oxide and indium tin oxide (In/In_2O_3) onto an aerogel blanket substrate (Figure 8b). This sensor operated across a wide temperature range, from cryogenic conditions to 1200 °C, enabling real-time monitoring of air flow temperatures in aviation engines. Its lightweight and flexible structure ensured durability in dynamic environments, outperforming traditional rigid sensors.

For pressure sensing**,** Fu et al. [109] developed a high-temperature-resistant pressure sensor by integrating carbon fiber cloth with a dielectric TiO_2 nanofiber film. This sandwich-structured capacitive pressure sensor exhibited exceptional performance, including high sensitivity (≈4.4 kPa^{-1}), an ultralow limit of detection (<0.8 Pa), and a fast response speed (<16 ms) (Figure 8c). Operating at temperatures up to 370 °C, the sensor demonstrated remarkable stability under high-pressure conditions. Besides capacitive pressure sensor, Guo et al. [27] proposed a novel strategy for fabricating piezoresistive pressure sensors using a combination of ceramic fibers and metal components (Figure 8d). By depositing and inducing *in situ* thermal reactions, stable ceramic-metal contact was achieved between SiO_2 nanofiber films and Au-Cu alloy. The resulting interdigital electrode arrays (Au-Cu@SiO_2) were applied in flexible sensors capable of recognizing human body parts and measuring pressure under temperatures up to 600 °C, with transient operation possible at 1300 °C.

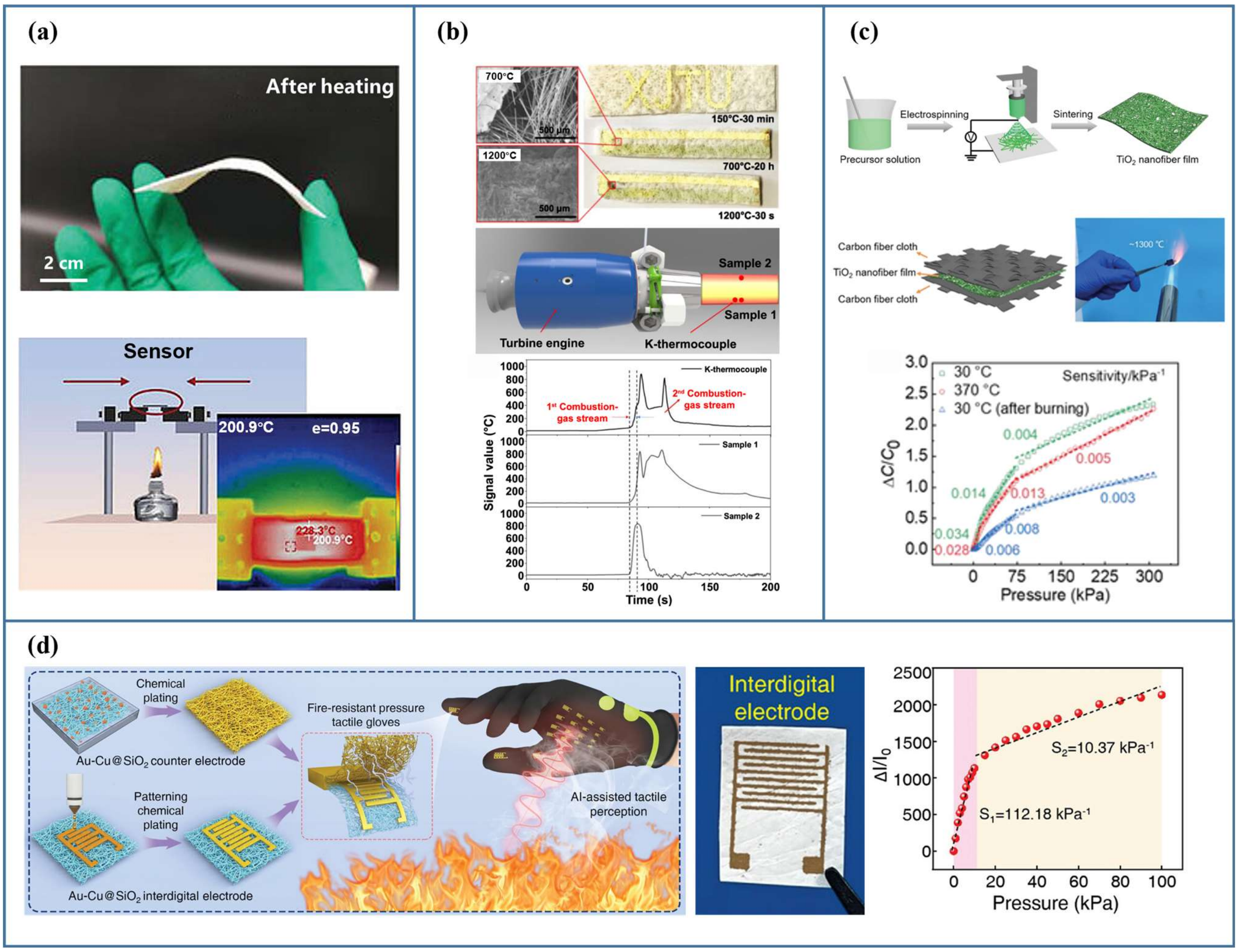

Figure 8. Applications of high-temperature sensing based on FCFs. (**a**) Resistive strain sensing [105]. (**b**) Thermoelectric temperature sensor [106]. (**c**) Capacitive pressure sensor [109]. (**d**) Piezoresistive pressure sensor [27].

Despite significant advancements, high-temperature flexible sensors have relatively simple structures and functions, and their long-term durability under high temperatures presents significant challenges. One major issue is their long-term durability under prolonged exposure to high-temperature. For instance, the interfaces between ceramic and metallic components in hybrid designs, leading to performance deterioration, such as solid-state deweting [110] and thermal expansion [111]. Additionally, these sensors have relatively simple structures and functions, which are still limited to multifunctional monitoring of firefighters, industry devices, and aerospace electronics.

5. Outlook and Conclusions

The review of FCFs highlights their significant potential in high-temperature applications across various fields, including thermal insulation, flue gas filtration, catalysis, electromagnetic wave absorption, energy devices, and sensing. The unique combination of thermal stability, mechanical flexibility, and chemical resistance makes FCFs ideal for addressing the challenges posed by extreme environments. The recent advances in material science and engineering have enabled the development of multifunctional FCFs, which not only maintain their structural integrity at high temperatures but also exhibit enhanced properties such as electromagnetic wave absorption, ion transmission, and flexible sensing.

The multifunctionalization of FCFs is a key direction for future development. By incorporating modification, morphology designs, and surface treatments, researchers have successfully enhanced the properties of FCFs, making them suitable for a broader range of applications. For instance, the development of stretchable ceramic membranes and printable ceramic fiber papers has opened new possibilities for high-temperature flexible electronics. These advancements underscore the versatility and potential of FCFs as a transformative material for next-generation high-temperature applications.

Despite these achievements, several challenges remain. The integration of FCFs into functional devices often requires additional materials or components that may degrade under high-temperature conditions, limiting the overall performance of the system. Addressing this challenge will require further advancements in both material design and system integration. Additionally, the long-term durability and reliability of FCF devices under continuous high-temperature exposure need to be thoroughly investigated.

Looking ahead, the future of FCFs is highly promising. As multifunctional devices continue to evolve, FCFs are expected to play a crucial role in addressing global challenges such as sustainable energy production, carbon capture, and waste management. The development of advanced manufacturing techniques, such as additive manufacturing and improved electrospinning methods, will further enhance the structural complexity and functional versatility of FCFs, unlocking new possibilities for their integration into next-generation devices. In particular, the ability to tailor FCFs for specific functions will enable them to serve as standalone electronic devices in extremely high-temperature environments, such as space exploration or nuclear power plants, where specialized performance is essential.

In conclusion, the review underscores the importance of FCFs in high-temperature applications and highlights the need for continued research and development to realize their full potential. The multifunctionalization of FCFs represents a significant step forward in material science, offering a versatile and robust solution for a wide range of high-temperature applications.

Acknowledgments

The authors acknowledge the State Key Laboratory of Manufacturing Equipment and Technology, Institute for Advanced Electronics Manufacturing for the support in the writing of this manuscript. During the preparation of this work the authors used Grammarly in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Author Contributions

Conceptualization, Z.X. and K.L.; Investigation, Z.X., C.H. and Y.B.; Data Curation, Z.X., Y.L. and Y.H. (Yanqi Han); Writing—Original Draft Preparation, Z.X., Y.L. and Y.H. (Yanqi Han); Writing—Review & Editing, Z.X. and K.L.; Visualization, Z.X.; Project Administration, Y.H. (YongAn Huang) and K.L.; Funding Acquisition, Y.H. (YongAn Huang) and K.L.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Funding

This research was funded by the National Natural Science Foundation of China (Grant No. 52375566), the National Natural Science Foundation of China (Grant No. 52427809) and the Xplorer Prize (2020-1036).

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

1. Kurian M, Thankachan S. 1—Introduction: Ceramics classification and applications. In *Ceramic Catalysts*; Kurian M, Thankachan S, Nair SS, Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 1–17.
2. Li D, Xu D, Zhao W, Avdeev M, Jing H, Guo Y, et al. A high-temperature performing and near-zero energy loss lead-free ceramic capacitor. *Energy Environ. Sci.* **2023**, *16*, 4511–4521. doi:10.1039/D3EE01545A.
3. Ye S, Cao Q, Ni P, Xiong S, Zhong M, Yuan T, et al. Construction of Microfluidic Chip Structure for Cell Migration Studies in Bioactive Ceramics. *Small* **2023**, *19*, 2302152. doi:10.1002/smll.202302152.
4. Shvydyuk KO, Nunes-Pereira J, Rodrigues FF, Páscoa JC, Lanceros-Mendez S, Silva AP. Holistic Characterization of MgO-Al_2O_3, MgO-$CaZrO_3$, and Y_2O_3-ZrO_2 Ceramic Composites for Aerospace Propulsion Systems. *Ceramics* **2024**, *7*, 364–384.
5. Tulshibagwale N, Brodnik N, Muir C, Hilmas A, Kiser JD, Smith CE, et al. Acoustic Emission in Ceramic Matrix Composites. *Appl. Mech. Rev.* **2024**, *76*, 040801. doi:10.1115/1.4064763.
6. An Z, Zhang R, Zhang B. Drawing on bionics, a flexible silica fiber paper is designed with high temperature resistance and hydrophobic properties. *Mater. Lett.* **2024**, *377*, 137441. doi:10.1016/j.matlet.2024.137441.
7. Zhang X, Hou F, Du H, Yan L, Guo A, Ma X, et al. Preparation of Ceramic Fiber Threads with Enhanced Abrasion Resistance Performance. *Materials* **2024**, *17*, 599.
8. Chen W, Shui A, Wang C, Li J, Ma J, Tian W, et al. Preparation of aluminum titanate flexible ceramic by solid-phase sintering and its mechanical behavior. *J. Alloys Compd.* **2019**, *777*, 119–126. doi:10.1016/j.jallcom.2018.09.317.
9. Shan Q, Chen C, Xu Q, Xue Y, Ma Q, Zhou Y, et al. The influence of sintering temperature on the mechanical evolution of Al_2TiO_5 flexible ceramics based on the acoustic emission. *J. Alloys Compd.* **2022**, *898*, 163004. doi:10.1016/j.jallcom.2021.163004.
10. Wu F, Qiang S, Zhang X, Wang F, Yin X, Liu L, et al. The Rising of Flexible and Elastic Ceramic Fiber Materials: Fundamental Concept, Design Principle, and Toughening Mechanism. *Adv. Funct. Mater.* **2022**, *32*, 2207130. doi:10.1002/adfm.202207130.
11. Zhou N, Zhao M, Xu B, Xie L, Liu D, Qu L, et al. Effects of fiber aspect ratio and fabrication temperature on the microstructure and mechanical properties of elastic fibrous porous ceramics by press-filtration method. *Ceram. Int.* **2023**, *49*, 11038–11046. doi:10.1016/j.ceramint.2022.11.299.
12. Zhang X, Wang F, Dou L, Cheng X, Si Y, Yu J, et al. Ultrastrong, Superelastic, and Lamellar Multiarch Structured ZrO_2–Al_2O_3 Nanofibrous Aerogels with High-Temperature Resistance over 1300 °C. *ACS Nano* **2020**, *14*, 15616–15625. doi:10.1021/acsnano.0c06423.
13. Zheng F, Zhu Z. Flexible, Freestanding, and Functional SiO_2 Nanofibrous Mat for Dye-Sensitized Solar Cell and Photocatalytic Dye Degradation. *ACS Appl. Nano Mater.* **2018**, *1*, 1141–1149. doi:10.1021/acsanm.7b00316.
14. Han Y, Zou D, Kang Y, Zhong Z, Xing W. One-step sintering process for high-performance SiC membranes for efficient filtration of dust-laden gas. *J. Membr. Sci.* **2024**, *692*, 122265. doi:10.1016/j.memsci.2023.122265.
15. Venkatesh R, Ramanan SR. Influence of processing variables on the microstructure of sol–gel spun alumina fibres. *Mater. Lett.* **2002**, *55*, 189–195. doi:10.1016/S0167-577X(01)00644-9.
16. Yang C, Li X, Yu J, Yuan J, Li M, Hu X, et al. Microstructure evolution of zirconium boride whiskers prepared by electrospinning and their toughening effect. *J. Am. Ceram. Soc.* **2024**, *107*, 8638–8649. doi:10.1111/jace.20057.
17. Wang H, Xu J, Wei M, Meng X, Lin L, Feng X, et al. Low thermal conductivity lanthanum zirconate nanofibrous membranes for thermal insulation. *Int. J. Ceram. Eng. Sci.* **2023**, *5*, e10181. doi:10.1002/ces2.10181.
18. Zhou Y-L, Cheng W-N, Bai Y-Z, Hou C, Li K, Huang Y-A. Rise of flexible high-temperature electronics. *Rare Met.* **2023**, *42*, 1773–1777. doi:10.1007/s12598-023-02298-w.
19. Song L, Wu C, Zhi Q, Zhang F, Song B, Guan L, et al. Multifunctional SiC aerogel reinforced with nanofibers and nanowires for high-efficiency electromagnetic wave absorption. *Chem. Eng. J.* **2023**, *467*, 143518. doi:10.1016/j.cej.2023.143518.
20. Das M, Ghosh K, Raja MW. Flexible ceramic based 'paper separator' with enhanced safety for high performance lithium-ion batteries: Probing the effect of ceramics impregnation on electrochemical performances. *J. Power Source* **2024**, *606*, 234573. doi:10.1016/j.jpowsour.2024.234573.
21. Zhang D, Wang Y, Sun S, Wan C, Li M, Tang A, et al. Ceramic hybrid nanofiber-based elastic scaffold pressure sensor with good sensitivity, breathability, and washability. *Ceram. Int.* **2024**, *50*, 3453–3460. doi:10.1016/j.ceramint.2023.11.093.
22. Zhang X, Cheng X, Si Y, Yu J, Ding B. Elastic and highly fatigue resistant ZrO_2-SiO_2 nanofibrous aerogel with low energy dissipation for thermal insulation. *Chem. Eng. J.* **2022**, *433*, 133628. doi:10.1016/j.cej.2021.133628.
23. Cheng Z, Zhao S, Han L. A novel preparation method for ZnO/γ-Al_2O_3 nanofibers with enhanced absorbability and improved photocatalytic water-treatment performance by Ag nanoparticles. *Nanoscale* **2018**, *10*, 6892–6899. doi:10.1039/C7NR09683F.
24. Zhu J, Zhu R, Hu Y, Wang Z. Low-cost and temperature-resistant mullite fiber sponges with superior thermal insulation and high-temperature PM filtration. *Sep. Purif. Technol.* **2023**, *305*, 122445. doi:10.1016/j.seppur.2022.122445.

25. Cai Z, Su L, Wang H, Niu M, Tao L, Lu D, et al. Alternating Multilayered Si_3N_4/SiC Aerogels for Broadband and High-Temperature Electromagnetic Wave Absorption up to 1000 °C. *ACS Appl. Mater. Interfaces* **2021**, *13*, 16704–16712. doi:10.1021/acsami.1c02906.
26. Li H, Wu D, Wu J, Dong L-Y, Zhu Y-J, Hu X. Flexible, High-Wettability and Fire-Resistant Separators Based on Hydroxyapatite Nanowires for Advanced Lithium-Ion Batteries. *Adv. Mater.* **2017**, *29*, 1703548. doi:10.1002/adma.201703548.
27. Guo Y, Zhang X, Jiang F, Tian X, Wu J, Yan J. Large-Scale Synthesis of Flexible Cermet Interdigital Electrodes with Stable Ceramic-Metal Contact for Fire-Resistant Pressure Tactile Sensors. *Adv. Funct. Mater.* **2024**, *34*, 2313645. doi:10.1002/adfm.202313645.
28. Wang N, Xie Y, Lv J, Zhang J, Zhu L, Jia Z, et al. Preparation of ultrafine flexible alumina fiber for heat insulation by the electrospinning method. *Ceram. Int.* **2022**, *48*, 19460–19466. doi:10.1016/j.ceramint.2022.03.249.
29. Jing PP, Liu MT, Wang PF, Yang J, Tang MJ, He CP, et al. Flexible nonwoven ZrO_2 ceramic membrane as an electrochemically stable and flame-resistant separator for high-power rechargeable batteries. *Chem. Eng. J.* **2020**, *388*, 124259. doi:10.1016/j.cej.2020.124259.
30. Si Y, Mao X, Zheng H, Yu J, Ding B. Silica nanofibrous membranes with ultra-softness and enhanced tensile strength for thermal insulation. *RSC Adv.* **2015**, *5*, 6027–6032. doi:10.1039/C4RA12271B.
31. Wu Z, Xu T, Xu X, Dong X, Wang Z, Wu J, et al. Fabrication of mullite micro/nano fiber-based porous ceramic with excellent mechanical and thermal insulation properties. *Ceram. Int.* **2024**, *50*, 2415–2423. doi:10.1016/j.ceramint.2023.11.024.
32. Yu P, Lin Z, Mu Y, Yu J. Highly flexible and strong SiC fibre mats prepared by electrospinning and hot-drawing. *Adv. Appl. Ceram.* **2021**, *120*, 144–155. doi:10.1080/17436753.2021.1904767.
33. Gong Z, Leng X, Bai X, Qiao R. An Innovative Design for the Fabrication of Flexible Composite Films from Si_3N_4 Fiber Paper. *Adv. Eng. Mater.* **2023**, *25*, 2201706. doi:10.1002/adem.202201706.
34. Ding Q, Yang J, Gu S, Chen C, Cheng Z, Liu Y, et al. Novel fire-resistant SiBCN fiber paper with efficient electromagnetic interference shielding and Joule-heating performance. *Chem. Eng. J.* **2024**, *497*, 154485. doi:10.1016/j.cej.2024.154485.
35. Beausoleil C, Yazdani Sarvestani H, Katz Z, Gholipour J, Ashrafi B. Deep and high precision cutting of alumina ceramics by picosecond laser. *Ceram. Int.* **2020**, *46*, 15285–15296. doi:10.1016/j.ceramint.2020.03.069.
36. Mao X, Shan H, Song J, Bai Y, Yu J, Ding B. Brittle-flexible-brittle transition in nanocrystalline zirconia nanofibrous membranes. *CrystEngComm* **2016**, *18*, 1139–1146. doi:10.1039/C5CE02382C.
37. Su L, Wang H, Niu M, Fan X, Ma M, Shi Z, et al. Ultralight, Recoverable, and High-Temperature-Resistant SiC Nanowire Aerogel. *ACS Nano* **2018**, *12*, 3103–3111. doi:10.1021/acsnano.7b08577.
38. Wang L, Yang L, Ma D, Xu C, Liu X, Gan X, et al. Grooved TiO_2/ZrO_2 ceramic fibers with thermal insulation and mechanical properties prepared by coaxial electrospinning. *Ceram. Int.* **2024**, *50*, 53288–53295. doi:10.1016/j.ceramint.2024.10.179.
39. Liu Z, Li Z, Li Q, Wang C, Chen P, Yang L, et al. Ultra-High strength and toughness continuous SiCf/SiC ceramic matrix composites prepared by an additive manufacturing manipulator. *J. Eur. Ceram. Soc.* **2025**, *45*, 117176. doi:10.1016/j.jeurceramsoc.2024.117176.
40. Dai Z, Yan F, Qin M, Yan X. Fabrication of flexible SiO_2 nanofibrous yarn via a conjugate electrospinning process. *e-Polymers* **2020**, *20*, 600–605. doi:doi:10.1515/epoly-2020-0063.
41. Wen X, Xiong J, Lei S, Wang L, Qin X. Diameter Refinement of Electrospun Nanofibers: From Mechanism, Strategies to Applications. *Adv. Fiber Mater.* **2022**, *4*, 145–161. doi:10.1007/s42765-021-00113-8.
42. Teymuri Sangari MM, Bagherzadeh E, Zebarjad SM. Fiber Diameter Dependency of Electrospun Polysulfone/SiO_2/TiO_2 Nanocomposite Membranes on the Solution Properties. *J. Ultrafine Grained Nanostruct. Mater.* **2022**, *55*, 15–20. doi:10.22059/jufgnsm.2022.01.03.
43. Lu N, Yan L, Ma Y, Sun H, Zhu Z, Liang W, et al. Electrospun Modified SiO_2 Nanofiber Membranes as Superamphiphobic Self-Cleaning Filters with High Heat Stability for Efficient Particle Matter Capture. *ACS Applied Nano Materials* **2022**, *5*, 9871–9881. doi:10.1021/acsanm.2c02035.
44. He J, Song C, Chen L, Xin S, Xiang P, Li W, et al. High-efficiency solution blow spinning of flexible Zr-based ceramic fibers for advanced thermal insulation applications. *Prog. Nat. Sci. Mater. Int.* **2024**, *34*, 1274–1280. doi:10.1016/j.pnsc.2024.10.010.
45. Xiao W, Lu L, Xu Z, Huang Y, Zhuang Q, Qian X, et al. A superelastic ceramic aerogel for flexible pressure sensor in harsh environment. *Compos. Part B Eng.* **2025**, *292*, 112110. doi:10.1016/j.compositesb.2024.112110.
46. Wang K, Meng Q, Zhao K, Li X, Bai Q, Jiao H, et al. A facile method to prepare ZrC ceramic fibers by centrifugal melt-spinning using zirconium-containing polymeric precursors. *Mater. Lett.* **2022**, *312*, 131693. doi:10.1016/j.matlet.2022.131693.
47. Ji D, Lin Y, Guo X, Ramasubramanian B, Wang R, Radacsi N, et al. Electrospinning of nanofibres. *Nat. Rev. Methods Primers* **2024**, *4*, 1. doi:10.1038/s43586-023-00278-z.
48. Bhagure S, Rao A. A Review: Electrospinning and Electrospinning Nanofibre Technology, Process & Application. *Int. J. Innov. Sci. Res. Technol.* **2020**, *5*, 528–538. doi:10.38124/IJISRT20JUN521.
49. Xu Z, Kong W, Su X, Zhai Y, Luo D, Li J, et al. Solution blow spun flexible zirconia nanofibers toward high-performance 2D and 3D nanostructures. *Ceram. Int.* **2024**, *50*, 17419–17427. doi:10.1016/j.ceramint.2024.02.230.

50. Shahraki A, Malek Khachatourian A, Rezaei B, Nemati A. Influence of calcination temperatures on the structural, microstructural, and thermal characteristics of electrospun alumina nanofibers. *Ceram. Int.* **2025**. doi:10.1016/j.ceramint.2025.01.275.
51. Sohrabi-Kashani L, Madani SM, Ghanbari H, Sarpoolaky H. Cost-effective fabrication of mesoporous alumina nanofibers via electrospinning: Enhanced ceramic-to-polymer ratio. *Ceram. Int.* **2025**, *in press*. doi:10.1016/j.ceramint.2025.01.550.
52. Guo H, Sun J, Ge J, Han D, Lv Y, Hu P, et al. Flexible mullite nanofiber membranes with high-temperature resistance and excellent thermal insulation. *Ceram. Int.* **2024**, *50*, 4936–4944. doi:10.1016/j.ceramint.2023.11.236.
53. Wang J, Yao S, Yu S, Huang Y, Liu W, Zhu M. Polymer templates effects on microstructure and mechanical properties of electrospun mullite nanofibers. *Ceram. Int.* **2022**, *48*, 5787–5794. doi:10.1016/j.ceramint.2021.11.126.
54. Liu C, Tang L, Zhang Y, Jiang P, Wang N, Yin X, et al. Synthesis of flexible, strong, and lightweight oxide ceramic nanofibers via direct electrospinning of inorganic sol for thermal insulation. *J. Text. Inst.* **2025**, *116*, 119–128. doi:10.1080/00405000.2024.2319358.
55. Xu C, Liu X, Wang L, Gan X, Ge P, Yue X, et al. Structural, morphological, mechanical, and thermal insulation properties of multiple-phase magnesium silicate ceramic fibers electrospun from dual-precursor sols. *Ceram. Int.* **2024**, *50*, 25355–25364. doi:10.1016/j.ceramint.2024.04.267.
56. Jin X, Li J, Zhang C, Liu K, He C, Li W. Solution blow spinning mass production of mullite nanofiber from environment friendly aqueous Al–Si solutions. *Prog. Nat. Sci. Mater. Int.* **2023**, *33*, 691–700. doi:10.1016/j.pnsc.2023.12.006.
57. Lu B, Gai K, Wang Q, Zhao T. Continuous yttrium aluminum garnet ceramic fiber with high tensile strength by melt-spinning from polymer precursor. *Ceram. Int.* **2023**, *49*, 32318–32323. doi:10.1016/j.ceramint.2023.07.098.
58. Gai K, Wang Q, Li J, Lu B, Liang L, Tai J, et al. Studies on the Crystallization Behavior of Al_2O_3-HfO_2 Ceramic Fibers Prepared by Melt-spinning of Polymer Precursors. *J. Eur. Ceram. Soc.* **2023**, *43*, 5587–5595. doi:10.1016/j.jeurceramsoc.2023.05.011.
59. Wei C, Zhang Z, Xue Y, Wang P, Liu L, Duan X, et al. Toughening and ablation mechanism of Si_3N_4 short fiber toughened ZrB_2-based ceramics. *J. Eur. Ceram. Soc.* **2023**, *43*, 5425–5435. doi:10.1016/j.jeurceramsoc.2023.05.025.
60. Lim H, Kim Y-K, Kim H-S, Lee T, Hossain MM, Jeong H-O, et al. Lyotropic Boron Nitride Nanotube Liquid Crystals: Preparation, Characterization, and Wet-Spinning for Fabrication of Composite Fiber. *ACS Appl. Mater. Interfaces* **2023**, *15*, 24681–24692. doi:10.1021/acsami.3c00189.
61. Wang X, Zimmer K, Ehrhardt M, Zhang F, Wang J, Wang P, et al. One-step in-situ low damage etching of SiC/SiC composites by high-temperature chemical-assisted laser processing. *Ceram. Int.* **2022**, *48*, 34472–34482. doi:10.1016/j.ceramint.2022.08.028.
62. He H, Wei X, Yang B, Liu H, Sun M, Li Y, et al. Ultrastrong and multifunctional aerogels with hyperconnective network of composite polymeric nanofibers. *Nat. Commun.* **2022**, *13*, 4242. doi:10.1038/s41467-022-31957-2.
63. Mao X, Hong J, Wu Y-X, Zhang Q, Liu J, Zhao L, et al. An Efficient Strategy for Reinforcing Flexible Ceramic Membranes. *Nano Lett.* **2021**, *21*, 9419–9425. doi:10.1021/acs.nanolett.1c02657.
64. Cheng Y, Ma B, Hu P, Zhang J, Hu D, Wang J. Flexible and Transformable Ceramic Aerogels via a Fire-Reborn Strategy for Thermal Superinsulation in Extreme Conditions. *Adv. Funct. Mater.* **2023**, *33*, 2309148. doi:10.1002/adfm.202309148.
65. Wang M-L, Yu D-G, Bligh SWA. Progress in preparing electrospun Janus fibers and their applications. *Appl. Mater. Today* **2023**, *31*, 101766. doi:10.1016/j.apmt.2023.101766.
66. Dong S, Maciejewska BM, Schofield RM, Hawkins N, Siviour CR, Grobert N. Electrospinning Nonspinnable Sols to Ceramic Fibers and Springs. *ACS Nano* **2024**, *18*, 13538–13550. doi:10.1021/acsnano.3c12659.
67. Su L, Wang H, Jia S, Dai S, Niu M, Ren J, et al. Highly Stretchable, Crack-Insensitive and Compressible Ceramic Aerogel. *ACS Nano* **2021**, *15*, 18354–18362. doi:10.1021/acsnano.1c07755.
68. Jiao W, Cheng W, Fei Y, Zhang X, Liu Y, Ding B. TiO_2/SiO_2 spiral crimped Janus fibers engineered for stretchable ceramic membranes with high-temperature resistance. *Nanoscale* **2024**, *16*, 12248–12257. doi:10.1039/D4NR01069H.
69. Wei Q, Shao D, Deng B, Xu Q. Functionalization of ceramic fibers by metallic sputter coating. *J. Coat. Technol. Res.* **2010**, *7*, 99–103. doi:10.1007/s11998-009-9164-6.
70. Xie Y-S, Cheng Y, Lyu Y, Li R, Han J-C. Printable, flexible ceramic fiber paper based on electrospinning. *Rare Met.* **2024**, *43*, 2739–2746. doi:10.1007/s12598-023-02562-z.
71. Zeng Y, Chen G, Wu C, Pan X, Lin F, Xu L, et al. Thin-Film Platinum Resistance Temperature Detector with a SiCN/Yttria-Stabilized Zirconia Protective Layer by Direct Ink Writing for High-Temperature Applications. *ACS Appl. Mater. Interfaces* **2023**, *15*, 2172–2182. doi:10.1021/acsami.2c18611.
72. Wang H, Xu J, Wei M, Feng X, Wu J, Zhang P, et al. Flexible dual-phase rare-earth zirconate high-entropy ceramic nanofibrous membranes for superior thermal insulation. *J. Am. Ceram. Soc.* **2024**, *107*, 3857–3867. doi:10.1111/jace.19666.
73. Tsai M-T, Chang S-W, Chen Y-J, Chen H-L, Lan P-H, Chen D-C, et al. Scalable, flame-resistant, superhydrophobic ceramic metafibers for sustainable all-day radiative cooling. *Nano Today* **2023**, *48*, 101745. doi:10.1016/j.nantod.2022.101745.
74. Wang W, Fu Q, Ge J, Xu S, Liu Q, Zhang J, et al. Advancements in Thermal Insulation through Ceramic Micro-Nanofiber Materials *Molecules* **2024**, *29*, 2279.

75. Deng Z, Peng Y, Qin WW, Liu B, Zhang G, Wang X, et al. Flexible, high strength and low thermal conductivity of a novel high entropy oxide ceramic fiber membranes. *Chem. Eng. J.* **2023**, *475*, 146260. doi:10.1016/j.cej.2023.146260.
76. Cheng X, Liu Y-T, Si Y, Yu J, Ding B. Direct synthesis of highly stretchable ceramic nanofibrous aerogels via 3D reaction electrospinning. *Nat. Commun.* **2022**, *13*, 2637. doi:10.1038/s41467-022-30435-z.
77. Zhang X, Yu J, Si Y. Programmable Shape-Morphing Enables Ceramic Meta-Aerogel Highly Stretchable for Thermal Protection. *Adv. Mater.* **2024**, *37*, 2412962. doi:10.1002/adma.202412962.
78. Dang S, Guo J, Deng Y, Yu H, Zhao H, Wang D, et al. Highly-Buckled Nanofibrous Ceramic Aerogels with Ultra-Large Stretchability and Tensile-Insensitive Thermal Insulation. *Adv. Mater.* **2025**, *37*, 2415159. doi:10.1002/adma.202415159.
79. Shaddick G, Thomas ML, Mudu P, Ruggeri G, Gumy S. Half the world's population are exposed to increasing air pollution. *Npj Clim. Atmos. Sci.* **2020**, *3*, 23. doi:10.1038/s41612-020-0124-2.
80. Harrison RM. Airborne particulate matter. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2020**, *378*, 20190319. doi:10.1098/rsta.2019.0319.
81. Zhang R, Jing J, Tao J, Hsu SC, Wang G, Cao J, et al. Chemical characterization and source apportionment of $PM_{2.5}$ in Beijing: Seasonal perspective. *Atmos. Chem. Phys.* **2013**, *13*, 7053–7074. doi:10.5194/acp-13-7053-2013.
82. Gong Y, Zou D, Zhong Z, Xing W. High-performance mullite fibrous ceramic filter enhanced by composite sintering aids for dust-laden gas filtration. *Sep. Purif. Technol.* **2022**, *292*, 120967. doi:10.1016/j.seppur.2022.120967.
83. Wang H, Lin S, Yang S, Yang X, Song J, Wang D, et al. High-Temperature Particulate Matter Filtration with Resilient Yttria-Stabilized ZrO_2 Nanofiber Sponge. *Small* **2018**, *14*, 1800258. doi:10.1002/smll.201800258.
84. Jia C, Liu Y, Li L, Song J, Wang H, Liu Z, et al. A Foldable All-Ceramic Air Filter Paper with High Efficiency and High-Temperature Resistance. *Nano Lett.* **2020**, *20*, 4993–5000. doi:10.1021/acs.nanolett.0c01107.
85. Tan J, Zeng Y, Low Z-X, Lin Z, Xu X, Feng S, et al. Zr doped flexible TiO_2 nanofibrous membranes for high-efficiency oily particulate matter removal from high temperature flue gas. *J. Membr. Sci.* **2023**, *679*, 121700. doi:10.1016/j.memsci.2023.121700.
86. Li J, Zhao J, Xu Z, Zhai Y, Su X, Luo D, et al. High-Temperature-Resistant Dual-Scale Ceramic Nanofiber Films toward Improved Air Filtration. *ACS Appl. Mater. Interfaces* **2024**, *16*, 60608–60615. doi:10.1021/acsami.4c15332.
87. Li P, Wang C, Zhang Y, Wei F. Air Filtration in the Free Molecular Flow Regime: A Review of High-Efficiency Particulate Air Filters Based on Carbon Nanotubes. *Small* **2014**, *10*, 4543–4561. doi:10.1002/smll.201401553.
88. Ishihara H, Koga H, Kitaoka T, Wariishi H, Tomoda A, Suzuki R. Paper-structured catalyst for catalytic NOx removal from combustion exhaust gas. *Chem. Eng. Sci.* **2010**, *65*, 208–213. doi:10.1016/j.ces.2009.05.042.
89. Zhang M, Wang Y, Zhang Y, Song J, Si Y, Yan J, et al. Conductive and Elastic TiO_2 Nanofibrous Aerogels: A New Concept toward Self-Supported Electrocatalysts with Superior Activity and Durability. *Angew. Chem. Int. Ed.* **2020**, *59*, 23252–23260. doi:10.1002/anie.202010110.
90. Fu W, Dai Y, Li JPH, Liu Z, Yang Y, Sun Y, et al. Unusual Hollow Al_2O_3 Nanofibers with Loofah-Like Skins: Intriguing Catalyst Supports for Thermal Stabilization of Pt Nanocrystals. *ACS Appl. Mater. Interfaces* **2017**, *9*, 21258–21266. doi:10.1021/acsami.7b04196.
91. Sánchez A, Milt VG, Miró EE, Güttel R. Ceramic Fiber-Based Structures as Catalyst Supports: A Study on Mass and Heat Transport Behavior Applied to CO_2 Methanation. *Ind. Eng. Chem. Res.* **2020**, *59*, 16539–16552. doi:10.1021/acs.iecr.0c01997.
92. Yan H, Wang K, Zhao L, Zhang P, Liu J, Gao L. Ultra-flexible Al_2O_3 fibers: A novel catalyst support material for sustainable catalysis. *Ceram. Int.* **2023**, *49*, 30257–30265. doi:10.1016/j.ceramint.2023.06.283.
93. Lan D, Hu Y, Wang M, Wang Y, Gao Z, Jia Z. Perspective of electromagnetic wave absorbing materials with continuously tunable effective absorption frequency bands. *Compos. Commun.* **2024**, *50*, 101993. doi:10.1016/j.coco.2024.101993.
94. Zhang M, Chang M, Tian W, Tang J, Sun J, Pan K. Interfacial modulation of SiC/TiC hybrid nanofibers for fabricating flexible ceramic electromagnetic wave absorbers. *Mater. Res. Bull.* **2024**, *178*, 112883. doi:10.1016/j.materresbull.2024.112883.
95. Fu Z, Pang A, Luo H, Zhou K, Yang H. Research progress of ceramic matrix composites for high temperature stealth technology based on multi-scale collaborative design. *J. Mater. Res. Technol.* **2022**, *18*, 2770–2783. doi:10.1016/j.jmrt.2022.03.164.
96. Song L, Zhang F, Chen Y, Guan L, Zhu Y, Chen M, et al. Multifunctional SiC@SiO_2 Nanofiber Aerogel with Ultrabroadband Electromagnetic Wave Absorption. *Nano-Micro Lett.* **2022**, *14*, 152. doi:10.1007/s40820-022-00905-6.
97. Kang W, Shen Y, Yang T, Zhao Z, Gou Y. Multifunctional Submicron SiC Fibers for Extreme Environments: Superior Electromagnetic Absorption and High-Temperature Performance. *Adv. Funct. Mater.* **2025**, *35*, 2415432. doi:10.1002/adfm.202415432.
98. Ding Q, Zhan Z, Zhang Z, Wei Z, Cheng Z, Gao J, et al. Microstructure evolution and excellent electromagnetic wave absorption performance of SiBCN fibers. *Ceram. Int.* **2024**, *50*, 39965–39974. doi:10.1016/j.ceramint.2024.07.379.
99. Khan MK, Raza M, Shahbaz M, Farooq U, Akram MU. Recent advancement in energy storage technologies and their applications. *J. Energy Storage* **2024**, *92*, 112112. doi:10.1016/j.est.2024.112112.
100. Bertaglia T, Costa CM, Lanceros-Méndez S, Crespilho FN. Eco-friendly, sustainable, and safe energy storage: a nature-inspired materials paradigm shift. *Mater. Adv.* **2024**, *5*, 7534–7547. doi:10.1039/d4ma00363b.

101. Liu F, Lorenzelli L. Toward all flexible sensing systems for next-generation wearables. *Wearable Electron.* **2024**, *1*, 137–149. doi:10.1016/j.wees.2024.07.003.
102. Wulandari T, Fawcett D, Majumder SB, Poinern GEJ. Lithium-based batteries, history, current status, challenges, and future perspectives. *Battery Energy* **2023**, *2*, 20230030. doi:10.1002/bte2.20230030.
103. Sang Z, Yan X, Wen L, Su D, Zhao Z, Liu Y, et al. A graphene-modified flexible SiOC ceramic cloth for high-performance lithium storage. *Energy Storage Mater.* **2020**, *25*, 876–884. doi:10.1016/j.ensm.2019.11.014.
104. Pan P, Zhang M, Cheng Z, Jiang L, Mao J, Ni C, et al. Garnet ceramic fabric-reinforced flexible composite solid electrolyte derived from silk template for safe and long-term stable All-Solid-State lithium metal batteries. *Energy Storage Mater.* **2022**, *47*, 279–287. doi:10.1016/j.ensm.2022.02.018.
105. Sun T, Zhang J, Chen Y, Zhao H, Liu L, Liu Y, et al. Bioinspired, Ultra-Sensitive Flexible Strain Sensor Based on Ceramic Fiber Paper With Superhydrophobic and High-Temperature-Resistant Properties. *Adv. Mater. Technol.* **2023**, *8*, 2200972. doi:10.1002/admt.202200972.
106. Liu Z, Tian B, Jiang Z, Li S, Lei J, Zhang Z, et al. Flexible temperature sensor with high sensitivity ranging from liquid nitrogen temperature to 1200 °C. *Int. J. Extrem. Manuf.* **2023**, *5*, 015601. doi:10.1088/2631-7990/aca44d.
107. Liu Z, Tian B, Liu X, Zhang X, Li Y, Zhang Z, et al. Multifunctional nanofiber mat for high temperature flexible sensors based on electrospinning. *J. Alloys Compd.* **2023**, *941*, 168959. doi:10.1016/j.jallcom.2023.168959.
108. Chen Z, Su D, Zhu W, Sun X, Li X, Ji H. A superelastic SiOC@carbon ceramic spring for multifunctional pressure sensor in wide temperature range. *Chem. Eng. J.* **2023**, *468*, 143635. doi:10.1016/j.cej.2023.143635.
109. Fu M, Zhang J, Jin Y, Zhao Y, Huang S, Guo CF. A Highly Sensitive, Reliable, and High-Temperature-Resistant Flexible Pressure Sensor Based on Ceramic Nanofibers. *Adv. Sci.* **2020**, *7*, 2000258. doi:10.1002/advs.202000258.
110. Maekawa Y, Shibuta Y. Dewetting dynamics of nickel thin film on alpha-quartz substrate: A molecular dynamics study. *Chem. Phys. Lett.* **2016**, *658*, 30–36. doi:10.1016/j.cplett.2016.06.016.
111. Shen YL. Thermal expansion of metal–ceramic composites: A three-dimensional analysis. *Mater. Sci.Eng. A* **1998**, *252*, 269–275. doi:10.1016/S0921-5093(98)00698-4.