Fiber Batteries

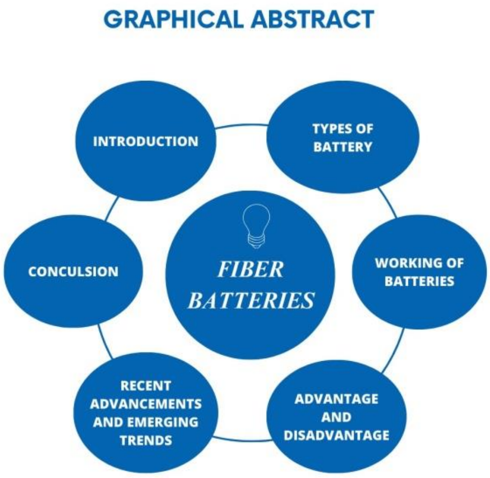
Ishita Syal 1.a) and Kushal Qanungo 2. b)

1.2 Department of Chemistry, University Institute of Science
Chandigarh University, Gharuan, Dist. Mohali, Punjab (140413), India

ishitasyal11@gmail.com
kushala@rediffmail.com, Tel.: +91 160 3051003; fax: +91 160-2710300

Abstract

This review paper provides a comprehensive analysis of the current state of fiber batteries, a promising class of energy storage devices that utilize various types of fibers as integral components. The paper begins with an introduction to fiber batteries, outlining their unique characteristics and potential applications. It then delves into an in-depth examination of different types of fiber batteries, including carbon fiber batteries, nanofiber batteries, textile-based batteries, ceramic fiber batteries, metal fiber batteries, and glass fiber batteries. Each type is analyzed in terms of its working principle, advantages, and disadvantages, providing valuable insights into their performance and suitability for different applications. Furthermore, the paper discusses recent advancements and emerging trends in fiber battery technology, highlighting key research directions and challenges. Overall, this review paper offers a comprehensive overview of fiber batteries, aiming to inform researchers, engineers, and policymakers about the current state of the field and inspire further advancements in energy storage technology.



Keywords:- Fiber batteries **,**Energy storage **,** Carbon fiber **,**Nan fiber **,**Textile-based**,** Ceramic fiber

Introduction: -

The evolution of energy storage technology has been driven by the incessant demand for portable power solutions that are not only efficient but also adaptable to diverse applications. Conventional batteries, while effective in fulfilling this need, have been limited by their rigid and bulky designs, hindering their integration into certain devices and systems. This limitation has prompted researchers and engineers to explore alternative approaches that offer greater flexibility and versatility [1]. One such innovation is the concept of fiber batteries, which represents a departure from the traditional battery architecture by leveraging the unique properties of fibrous materials. Fiber batteries operate on principles akin to conventional batteries, wherein chemical energy is converted into electrical energy [2]. However, what sets them apart is their utilization of fibrous materials as fundamental components within the battery structure. These fibrous elements, which can include carbon fibers, nanofibers, or textile-based fibers, serve various functions within the battery, such as electrodes, electrolytes, or separators [3]. By incorporating these fibrous materials, researchers can create battery designs that are inherently flexible, lightweight, and even conformable to irregular shapes [4]. The potential applications of fiber batteries span a wide spectrum, from consumer electronics to aerospace systems. In the realm of wearable electronics, fiber batteries offer the promise of seamless integration into clothing, accessories, and wearable devices, providing a reliable power source without compromising comfort or mobility [5]. Similarly, in the field of medical devices, fiber batteries hold the potential to revolutionize implantable or wearable technologies by offering biocompatible and flexible power solutions. To realize the full potential of fiber batteries, researchers have developed a range of fabrication methods tailored to the unique properties of fibrous materials [6]. Techniques such as electrospinning, chemical vapor deposition, and textile weaving enable precise control over the morphology, composition, and alignment of fibers, thereby influencing the performance and properties of the resulting batteries [7]. However, despite the significant progress made in the development of fiber batteries, several challenges remain to be addressed, including scalability, manufacturing costs, and integration with existing devices and systems.In light of these challenges, this review aims to provide a comprehensive overview of fiber batteries, encompassing their principles, materials, fabrication methods, applications, challenges, and future prospects [8]. By synthesizing the latest research and advancements in the field, this paper seeks to shed light on the potential of fiber batteries to revolutionize energy storage technology and pave the way for a more flexible and adaptable energy future.

2. Types of battery: -

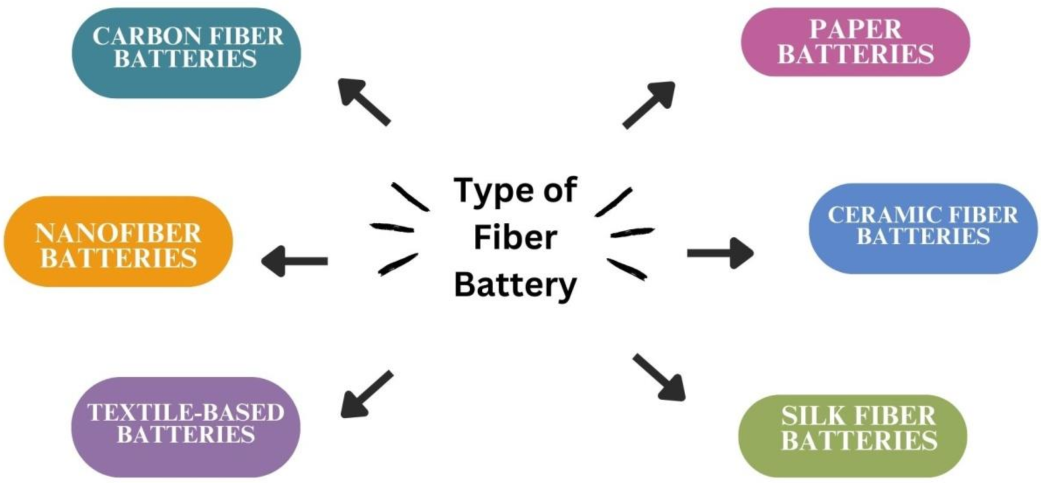


Table: 1 this table provides a overview of seven types of fiber batteries, showcasing their diverse compositions, advantages, and potential applications across various industries.

Type of Fiber Battery	Description	Advantages	Applications	reference
Carbon Fiber Batteries	Utilize carbon-based materials (e.g., CNTs, graphene).	High electrical conductivity, mechanical strength, chemical stability.	Aerospace, electric vehicles, portable electronics.	[9][10]
Nanofiber Batteries	Incorporate nanoscale fibers (e.g., polymer, metal oxides).	High surface area-to-volume ratio, rapid ion transport, enhanced electrochemical performance.	Medical devices, energy storage systems, wearable electronics.	[11][12]
Textile-Based Batteries	Integrate energy storage into textiles, fabrics, or yarns.	Seamless integration into clothing, lightweight, comfortable power sources.	Wearable electronics, smart textiles, medical devices.	[13][14]
Paper Batteries	Use paper-based materials as substrates or separators.	Environmentally friendly, low-cost, simple manufacturing processes.	Disposable electronics, biosensors, packaging, low-power devices.	[15][16]

Fiber Supercapacitors	Constructed using fibrous materials for electrodes and electrolytes.	High power density, fast charging rates, long cycle life.	Portable electronics, electric vehicles, renewable energy systems.	[17][18]
Ceramic Fiber Batteries	Employ ceramic fibers in electrode or separator design.	High temperature tolerance, chemical stability, long-term durability.	Aerospace, industrial applications, energy storage systems.	[19][20]
Silk Fiber Batteries	Utilize silk fibers as structural or functional components.	Biocompatibility, flexibility, potential for bio-integrated devices.	Medical implants, bioelectronics, wearable health monitors.	[21][22]

3. Working of different types of fibre batteries: -

3.1 Carbon Fiber Batteries:

Carbon fiber batteries utilize carbon-based materials such as carbon nanotubes (CNTs) or graphene in their construction. These materials offer high electrical conductivity, mechanical strength, and chemical stability, making them ideal for electrode applications [23]. Carbon fiber batteries find extensive use in aerospace, electric vehicles, and portable electronics, where lightweight and high-performance energy storage solutions are essential. Their unique properties enable them to deliver efficient and reliable power in demanding environments. The carbon-based electrodes serve as the sites where electrochemical reactions occur during the charging and discharging processes [24]. During charging, ions from the electrolyte are absorbed into the carbon structure of the electrode material, storing energy in the form of chemical potential. Conversely, during discharging, the stored ions are released from the electrode, generating electrical current as they return to the electrolyte.

3.1.1 Types of carbon fiber battery: -

There are two main types of carbon fiber batteries :-

A. Dual Carbon Fiber Batteries (DCFBs): Dual Carbon Fiber Batteries (DCFBs) represent a pioneering advancement in battery technology where both the cathode and anode are fabricated using carbon fiber. This innovative design presents several advantages over traditional lithium-ion batteries. Firstly, DCFBs exhibit a higher working potential, allowing for increased energy storage capacity and improved overall performance. Additionally, the utilization of carbon fiber in both electrodes simplifies the manufacturing process, leading to cost savings and enhanced scalability. These batteries have garnered attention as a promising energy storage solution, offering potential applications in various industries seeking compact, efficient, and reliable power sources [25].

B. Structural Batteries with Carbon Fibers: Structural batteries harness the unique properties of carbon fibers to reinforce the structural integrity of battery components or even entire structures. By incorporating carbon fibers into the battery design, these structural batteries can simultaneously provide energy storage capabilities while enhancing mechanical strength. Carbon fibers can be tailored to improve specific mechanical properties, such as stiffness and tensile strength, making them ideal for multifunctional applications where energy storage and structural support are integrated [26]. The integration of carbon fibers enables structural batteries to achieve weight savings, high energy density, and flexibility, demonstrating the versatility of carbon fiber materials in battery technology. This innovative approach holds promise for applications in aerospace, automotive, and construction industries, where lightweight and durable energy storage solutions are highly desirable [27].

3.1.2 Working of carbon fiber battery: -

The carbon fiber battery diagram represents a groundbreaking innovation in battery technology, where both the cathode and anode are constructed using carbon fiber. This novel design seamlessly integrates the advantages of carbon fiber with the principles of dual graphite batteries, resulting in a battery with superior performance characteristics. Notably, this configuration offers a significantly higher working potential compared to traditional lithium-ion batteries, enabling enhanced energy storage capabilities. Additionally, the mature technology of carbon fibers facilitates ease of manufacturing, contributing to cost-effectiveness and scalability [28].

The operation of the carbon fiber battery involves the insertion and detachment of anions/cations into both the carbon fiber cathode and anode. This mechanism allows for the integration of ions into the carbon fiber structures, effectively storing energy within the battery. By utilizing carbon fibers in both electrodes, the battery achieves remarkable performance metrics, including a significantly higher working voltage of 4.4 V. Furthermore, the battery's high mass loading results in a much higher areal capacity, providing substantial energy storage capacity per unit area [29]. Additionally, the carbon fiber battery boasts an impressive energy density of 163 Wh/kg at 0.1C, underscoring its efficiency and suitability for various applications requiring compact and high-performance energy storage solutions.

3.2 Nanofiber Batteries:

Nanofiber batteries operate through electrochemical processes involving the movement of ions between the electrodes and the electrolyte. The use of nanoscale fibers in the electrodes enhances the battery's performance by providing a large surface area for efficient ion transport and energy storage [30]. This enables nanofiber batteries to offer high energy density, fast charging/discharging rates, and long cycle life, making them suitable for various applications in energy storage systems, medical devices, and wearable electronics [31].

Nanofiber batteries function based on electrochemical processes that occur within their components, including electrodes, electrolyte, and separator. Here's a step-by-step explanation of how nanofiber batteries work:

1. **Electrode Structure:** Nanofiber batteries utilize electrodes made of nanoscale fibers, typically composed of materials like polymers or metal oxides. These nanofibers provide an extensive surface area for electrochemical reactions to take place, allowing for efficient ion transport and energy storage.
2. **Electrolyte Medium:** The electrodes are immersed in an electrolyte solution, which contains ions necessary for the battery's operation. This electrolyte serves as a medium for ion movement between the electrodes during charging and discharging [32].
3. **Charging Process:**
    - When the nanofiber battery is connected to an external power source for charging, an electric current is applied.
    - At the anode (positive electrode), ions from the electrolyte are attracted to the nanofiber structure. These ions undergo electrochemical reactions, leading to their insertion or adsorption into the electrode material. This process stores energy in the battery.
    - Simultaneously, at the cathode (negative electrode), ions from the electrode material are released into the electrolyte, completing the electrical circuit and maintaining charge balance [33].

4. **Discharging Process:**

    - When the nanofiber battery is connected to an external device for discharging, stored energy is released as electrical current flows through the circuit.
    - At the anode, ions are released from the nanofiber structure back into the electrolyte, generating electrical current as they return. This process releases the stored energy from the battery.
    - At the cathode, ions from the electrolyte are absorbed into the nanofiber structure, completing the circuit and providing power to the external device [34].

5. **Ion Transport:**
    - The nanoscale fibers in the electrodes facilitate rapid ion transport between the electrolyte and the electrode surfaces. This efficient ion transport enables quick charging and discharging of the battery.

6. **Energy Storage and Release:**
    - During charging, energy is stored in the battery as ions are stored within the nanofiber electrode structures through electrochemical reactions.
    - During discharging, stored energy is released as ions are released from the nanofiber electrodes, generating electrical current that powers external devices [35].

3.3 Textile-Based Batteries:

Textile-based batteries represent an innovative integration of energy storage technology into textiles, fabrics, or yarns, offering a flexible and wearable power solution. These batteries are designed to seamlessly blend with clothing and wearable devices, providing lightweight and comfortable power sources for various applications [36].

- The working principle of textile-based batteries involves embedding energy storage components within the fabric structure. Conductive materials, such as conductive fibers or threads, are used to create electrodes, while the fabric itself serves as the separator and electrolyte reservoir [37]. This integration allows the battery to be flexible and conformable to the shape of the wearer's body, enabling comfortable and unobtrusive power delivery.
- The fabrication of textile-based batteries typically involves several steps, including weaving or knitting conductive fibers into the fabric, coating the fibers with active materials to form electrodes, and integrating electrolyte materials into the fabric structure. Advanced manufacturing techniques, such as screen printing or embroidery, may also be used to create precise electrode patterns on the fabric surface [38].

  Textile-based batteries find applications in a wide range of fields, including wearable electronics, smart textiles, medical devices, fashion accessories, and military garments. They enable the development of innovative products such as smart clothing with built-in health monitoring capabilities, wearable sensors for athlete performance tracking, and textile-integrated power sources for portable electronic devices [39].

3.4 Paper Batteries:

A paper battery is a type of energy storage device that integrates both a power source and a substrate into a single unit, utilizing paper or cellulose-based materials as key components. These batteries combine the advantages of traditional batteries with the flexibility, lightweight, and eco-friendly nature of paper, offering a compact and environmentally sustainable power solution for various applications [40].

- The working principle of a paper battery involves the incorporation of conductive materials, such as carbon nanotubes or conductive polymers, into the paper substrate to serve as electrodes. Additionally, an electrolyte solution is impregnated into the paper to facilitate ion transport between the electrodes during charging and discharging [41].

Here's a breakdown of the key components and working principles of a paper battery:

1. **Paper Substrate:** The paper substrate serves as the structural support for the battery and provides a medium for embedding the electrodes and electrolyte. It is typically made from cellulose-based materials, such as paper or cellulose fibers, which are lightweight, flexible, and biodegradable.

2. **Conductive Electrodes:** Conductive materials, such as carbon nanotubes, graphene, or conductive polymers, are coated or deposited onto the paper substrate to form the electrodes [42]. These electrodes facilitate the flow of electrons during charging and discharging, enabling the storage and release of energy.
3. **Electrolyte:** An electrolyte solution is impregnated into the paper substrate to facilitate ion transport between the electrodes. The electrolyte contains ions that migrate between the electrodes during charging and discharging, completing the electrochemical reactions that store and release energy.
4. **Charging and Discharging:** During charging, an external voltage source is applied to the paper battery, causing ions from the electrolyte to be attracted to the electrodes. At the electrodes, electrochemical reactions occur, leading to the storage of energy in the form of chemical potential [43]. During discharging, the stored energy is released as ions migrate back into the electrolyte, generating electrical current that can be used to power electronic devices.

Paper batteries offer several advantages over traditional batteries, including:

- **Flexibility:** Paper batteries are flexible and can be folded, rolled, or shaped into various forms, making them suitable for use in flexible electronics and wearable devices.
- **Lightweight:** The use of paper as a substrate results in lightweight batteries, which are ideal for applications where weight is a concern, such as portable electronics and medical devices.
- **Eco-friendly:** Paper batteries are made from renewable and biodegradable materials, making them environmentally sustainable alternatives to conventional batteries.
- **Low-cost:** The manufacturing process for paper batteries is relatively simple and cost-effective compared to traditional batteries, making them accessible for mass production [44].

3.5 Ceramic Fiber Batteries:

Ceramic fiber batteries employ ceramic fibers in electrode or separator design, offering high temperature tolerance, chemical stability, and long-term durability. These batteries are commonly used in aerospace, industrial applications, and energy storage systems, where extreme conditions and harsh environments are prevalent. Ceramic fiber batteries provide reliable and robust energy storage solutions for demanding applications [45].Ceramic fiber batteries represent an innovative class of energy storage devices that utilize ceramic fibers as integral components in their construction. These batteries leverage the unique properties of ceramic materials to offer high-temperature tolerance, chemical stability, and long-term durability, making them suitable for demanding applications in aerospace, industrial settings, and energy storage systems [46].

The working principle of ceramic fiber batteries involves the incorporation of ceramic fibers into various battery components, including electrodes, separators, or electrolytes, to enhance their performance and reliability. Here's a breakdown of the key aspects of ceramic fiber batteries:

1. **Electrodes:** Ceramic fibers can be used as electrode materials in ceramic fiber batteries to enhance their electrochemical properties. These electrodes may be composed of ceramic fibers doped with active materials, such as metal oxides or conductive polymers, to facilitate energy storage and release during charging and discharging [47].
2. **Separators:** Ceramic fibers can serve as separators in ceramic fiber batteries, providing mechanical support and preventing direct contact between the electrodes. The use of ceramic fibers as separators enhances the stability and integrity of the battery, particularly in high-temperature or corrosive environments [48].
3. **Electrolytes:** Ceramic fibers may also be incorporated into the electrolyte matrix of ceramic fiber batteries to improve ion conductivity and enhance overall battery performance. Ceramic electrolytes offer advantages such as high ionic conductivity, wide electrochemical stability window, and resistance to chemical degradation, making them suitable for high-temperature applications [49].
4. **High-Temperature Tolerance:** One of the key advantages of ceramic fiber batteries is their ability to withstand high temperatures without degradation. Ceramic fibers have excellent thermal stability, allowing ceramic fiber batteries to operate in extreme temperature conditions encountered in aerospace, automotive, and industrial applications [50].
5. **Chemical Stability:** Ceramic materials exhibit high chemical stability, resisting corrosion and degradation when exposed to harsh chemical environments. This chemical stability enhances the longevity and reliability of ceramic fiber batteries, particularly in applications where exposure to corrosive substances is common [51].
6. **Long-Term Durability:** Ceramic fiber batteries offer long-term durability and reliability, with the ability to withstand mechanical stress, thermal cycling, and prolonged use without significant degradation in performance. This makes them suitable for use in mission-critical applications where reliability is paramount [52].

4 Advantages and disadvantage of fiber battery: -

Type of Fiber Battery	**Advantages**	**Disadvantages**	**Example**	**reference**
Carbon Fiber Batteries	High energy density Lightweight Fast charging/discharging rates Mechanical strength	Costly manufacturing Limited specific capacity Susceptible to degradation over time due to mechanical	Lithium-ion batteries with carbon-based anodes (e.g., Panasonic 18650 cells)	[53] [54]

		stress or exposure to harsh environments		
Nanofiber Batteries	High surface area for improved energy storage Fast ion transport Flexible and lightweight	May require specialized manufacturing techniques Limited scalability Potential toxicity of nanomaterials	Zinc-air batteries with zinc oxide nanofiber electrodes	[55][56]
Textile-Based Batteries	Wearable integration Lightweight and flexible Customizable design	Limited energy density compared to conventional batteries Prone to wear and tear over time Challenges in integrating electronics	Textile-integrated supercapacitors	[57][58]
Ceramic Fiber Batteries	High-temperature tolerance Chemical stability Long-term durability	Limited flexibility compared to other fiber batteries Higher manufacturing costs May require high-temperature processing methods	Solid oxide fuel cells with ceramic fiber electrolytes	[59][60]
Paper Batteries	Eco-friendly and biodegradable Lightweight and flexible Low-cost manufacturing	Limited energy density compared to conventional batteries Susceptible to moisture and degradation if not properly sealed	Paper-based zinc-ion batteries	[61][62]
Metal Fiber Batteries	High electrical conductivity Good mechanical properties Enhanced safety due to reduced risk of thermal runaway	Limited energy density compared to other battery types Potential corrosion of metal fibers over time Manufacturing challenges related to uniformity and scalability	Aluminum-air batteries with aluminum fiber electrodes	[63][64]
Glass Fiber Batteries	High chemical and thermal stability	Limited electrical conductivity compared	Sodium-ion batteries with	

	Low cost and abundant raw materials Potential for high-temperature operation	to other fiber batteries Challenges in integrating glass fibers into battery components	glass fiber separators	[65][66]

5. Recent advancements and emerging trends in fiber battery technology:-

Recent advancements and emerging trends in fiber battery technology have propelled the field forward, paving the way for innovative energy storage solutions with improved performance and versatility. Some notable advancements and trends include:

1. **Enhanced Energy Density**: Researchers are focusing on developing fiber batteries with higher energy densities to meet the increasing demand for longer-lasting and more powerful energy storage solutions. Advancements in electrode materials, such as the use of nanostructured carbon materials and metal oxides, have contributed to improved energy storage capabilities in fiber batteries [67].
2. **Flexible and Wearable Batteries**: The development of flexible and wearable fiber batteries has gained significant attention for applications in smart textiles, wearable electronics, and biomedical devices. Advancements in materials science and fabrication techniques have enabled the integration of energy storage components into flexible and stretchable substrates, allowing for comfortable and unobtrusive power sources [68].
3. **Printable and Scalable Manufacturing**: Printable and scalable manufacturing methods, such as screen printing, inkjet printing, and roll-to-roll processing, are being explored for the mass production of fiber batteries. These techniques offer cost-effective and efficient ways to fabricate large-area batteries with customized designs, paving the way for commercialization and widespread adoption [69].
4. **Multifunctional Fibers**: There is growing interest in developing multifunctional fibers that combine energy storage capabilities with other functionalities, such as sensing, actuation, and data transmission. Integrating multiple functions into a single fiber enables the creation of smart and adaptive systems for diverse applications, ranging from structural health monitoring to wearable healthcare devices [70].
5. **Integration with Internet of Things (IoT) Devices**: Fiber batteries are being integrated into Internet of Things (IoT) devices to provide autonomous and self-powered operation. These devices leverage the lightweight and compact nature of fiber batteries to enable wireless communication, remote sensing, and data processing in IoT applications, enhancing connectivity and efficiency [71].
6. **Environmental Sustainability**: With a growing emphasis on environmental sustainability, researchers are exploring eco-friendly and recyclable materials for fiber batteries. Biodegradable and non-toxic components, such as cellulose-based fibers and aqueous electrolytes, are being investigated to reduce the environmental impact of battery manufacturing and disposal [72].

7. **High-Temperature and Harsh Environment Applications**: Ceramic fiber batteries capable of operating in high-temperature and harsh environments are gaining traction for aerospace, automotive, and industrial applications. These batteries offer superior thermal stability, chemical resistance, and long-term durability, enabling reliable energy storage in extreme conditions [73].

Overall, recent advancements and emerging trends in fiber battery technology are driving innovation and expanding the potential applications of energy storage devices. By addressing key challenges and exploring new opportunities, researchers and engineers are poised to unlock the full potential of fiber batteries for a wide range of future technologies.

Conclusion: -

In conclusion, fiber batteries offer promising solutions for energy storage needs across a wide range of applications, from portable electronics to renewable energy systems and beyond. While each type of fiber battery has its own set of advantages and disadvantages, ongoing research and development efforts are actively addressing these challenges to further enhance their performance and applicability in various industries. The diverse array of fiber battery technologies, including carbon fiber, nanofiber, textile-based, ceramic fiber, metal fiber, and glass fiber batteries, provides options to tailor energy storage solutions to specific requirements and constraints. By leveraging the unique properties of different types of fibers, such as lightweight, flexibility, high surface area, or chemical stability, researchers and engineers can design batteries optimized for specific applications and environments. Overall, fiber batteries represent a significant advancement in energy storage technology, with the potential to revolutionize the way we power devices and systems in the future. By continuing to invest in research and development, fostering collaboration between academia, industry, and policymakers, and embracing emerging trends in materials science and engineering, we can unlock the full potential of fiber batteries and accelerate the transition to a more sustainable and energy-efficient future.

Reference: -

1. Zhou, Y., Wang, C. H., Lu, W., & Dai, L. (2020). Recent advances in fiber-shaped supercapacitors and lithium-ion batteries. *Advanced Materials*, *32*(5), 1902779.
2. Yang, S., Cheng, Y., Xiao, X., & Pang, H. (2020). Development and application of carbon fiber in batteries. *Chemical Engineering Journal*, *384*, 123294.
3. Zhang, Y., Zhao, Y., Ren, J., Weng, W., & Peng, H. (2016). Advances in wearable fiber-shaped lithium-ion batteries. *Advanced Materials*, *28*(22), 4524-4531.
4. Zhang, C., Zhu, J., Lin, H., & Huang, W. (2018). Flexible fiber and fabric batteries. *Advanced Materials Technologies*, *3*(10), 1700302.
5. Xiao, X., Yin, J., Shen, S., Che, Z., Wan, X., Wang, S., & Chen, J. (2022). Advances in solid-state fiber batteries for wearable bioelectronics. *Current Opinion in Solid State and Materials Science*, *26*(6), 101042.

6. Man, Z., Zhu, X., Ye, S., Wu, G., & Bao, N. (2022). Recent Advances and Future Perspectives of Fiber-Shaped Batteries. *Energy & Fuels*, *36*(17), 9866-9881.
7. Qu, H., Semenikhin, O., & Skorobogatiy, M. (2014). Flexible fiber batteries for applications in smart textiles. *Smart Materials and Structures*, *24*(2), 025012.
8. Ye, L., Hong, Y., Liao, M., Wang, B., Wei, D., Peng, H., ... & Peng, H. (2020). Recent advances in flexible fiber-shaped metal-air batteries. *Energy Storage Materials*, *28*, 364-374.
9. Chen, J., Zhou, Y., Islam, M. S., Cheng, X., Brown, S. A., Han, Z., ... & Wang, C. H. (2021). Carbon fiber reinforced Zn–MnO2 structural composite batteries. *Composites Science and Technology*, *209*, 108787.
10. Yang, S., Cheng, Y., Xiao, X., & Pang, H. (2020). Development and application of carbon fiber in batteries. *Chemical Engineering Journal*, *384*, 123294.
11. Cao, X., Ma, C., Luo, L., Chen, L., Cheng, H., Orenstein, R. S., & Zhang, X. (2023). Nanofiber materials for lithium-ion batteries. *Advanced Fiber Materials*, *5*(4), 1141-1197.
12. Shi, F., Chen, C., & Xu, Z. L. (2021). Recent advances on electrospun nanofiber materials for post-lithium ion batteries. *Advanced Fiber Materials*, *3*(5), 275-301.
13. Gao, Y., Xie, C., & Zheng, Z. (2021). Textile composite electrodes for flexible batteries and supercapacitors: opportunities and challenges. *Advanced Energy Materials*, *11*(3), 2002838.
14. Normann, M., Kyosev, Y., Ehrmann, A., & Schwarz-Pfeiffer, A. (2016). Multilayer textile-based woven batteries. *Recent developments in braiding and narrow weaving*, 129-136
15. Nyström, G., Razaq, A., Strømme, M., Nyholm, L., & Mihranyan, A. (2009). Ultrafast all-polymer paper-based batteries. *Nano letters*, *9*(10), 3635-3639.
16. Cheng, Q., Song, Z., Ma, T., Smith, B. B., Tang, R., Yu, H., ... & Chan, C. K. (2013). Folding paper-based lithium-ion batteries for higher areal energy densities. *Nano letters*, *13*(10), 4969-4974.
17. Senthilkumar, S. T., Wang, Y., & Huang, H. (2015). Advances and prospects of fiber supercapacitors. *Journal of Materials Chemistry A*, *3*(42), 20863-20879.
18. Chen, D., Jiang, K., Huang, T., & Shen, G. (2020). Recent advances in fiber supercapacitors: materials, device configurations, and applications. *Advanced materials*, *32*(5), 1901806.
19. Zhao, X., Zhang, Z., Yang, S., & Liang, G. (2017). Inorganic ceramic fiber separator for electrochemical and safety performance improvement of lithium-ion batteries. *Ceramics International*, *43*(17), 14775-14783.
20. Jia, C., Xu, Z., Luo, D., Xiang, H., & Zhu, M. (2022). Flexible ceramic fibers: Recent development in preparation and application. *Advanced Fiber Materials*, *4*(4), 573-603
21. Pereira, R. F., Brito-Pereira, R., Gonçalves, R., Silva, M. P., Costa, C. M., Silva, M. M., ... & Lanceros-Méndez, S. (2018). Silk fibroin separators: a step toward lithium-ion batteries with enhanced sustainability. *ACS applied materials & interfaces*, *10*(6), 5385-5394.
22. Choi, D., & Choy, K. L. (2020). Spider silk binder for Si-based anode in lithium-ion batteries. *Materials & Design*, *191*, 108669.

23. Kjell, M. H., Jacques, E., Zenkert, D., Behm, M., & Lindbergh, G. (2011). PAN-based carbon fiber negative electrodes for structural lithium-ion batteries. *Journal of The Electrochemical Society*, *158*(12), A1455.
24. Lim, G. J. H., Chan, K. K., Sutrisnoh, N. A. A., & Srinivasan, M. (2022). Design of structural batteries: carbon fibers and alternative form factors. *Materials Today Sustainability*, *20*, 100252.
25. Kercher, A. K., Kiggans, J. O., & Dudney, N. J. (2010). Carbon fiber paper cathodes for lithium ion batteries. *Journal of The Electrochemical Society*, *157*(12), A1323.
26. Yu, Y., Zhang, B., Feng, M., Qi, G., Tian, F., Feng, Q., ... & Wang, S. (2017). Multifunctional structural lithium ion batteries based on carbon fiber reinforced plastic composites. *Composites Science and Technology*, *147*, 62-70.
27. Gan, Q., & Fu, Y. (2023). Emerging dual carbon fiber batteries. *Electrochimica Acta*, *439*, 141597.
28. Hagberg, J., Maples, H. A., Alvim, K. S., Xu, J., Johannisson, W., Bismarck, A., ... & Lindbergh, G. (2018). Lithium iron phosphate coated carbon fiber electrodes for structural lithium ion batteries. *Composites Science and Technology*, *162*, 235-243.
29. Deng, R., Wang, M., Yu, H., Luo, S., Li, J., Chu, F., ... & Wu, F. (2022). Recent advances and applications toward emerging lithium–sulfur batteries: working principles and opportunities. *Energy & Environmental Materials*, *5*(3), 777-799.
30. Pampal, E. S., Stojanovska, E., Simon, B., & Kilic, A. (2015). A review of nanofibrous structures in lithium ion batteries. *Journal of Power Sources*, *300*, 199-215.
31. Senthilkumar, S. H., Ramasubramanian, B., Rao, R. P., Chellappan, V., & Ramakrishna, S. (2023). Advances in electrospun materials and methods for Li-ion batteries. *Polymers*, *15*(7), 1622.
32. Sun, G., Sun, L., Xie, H., & Liu, J. (2016). Electrospinning of nanofibers for energy applications. *Nanomaterials*, *6*(7), 129.
33. Ilango, P. R., Savariraj, A. D., Huang, H., Li, L., Hu, G., Wang, H., ... & Peng, S. (2023). Electrospun flexible nanofibres for batteries: design and application. *Electrochemical Energy Reviews*, *6*(1), 12.
34. Li, W., Li, M., Adair, K. R., Sun, X., & Yu, Y. (2017). Carbon nanofiber-based nanostructures for lithium-ion and sodium-ion batteries. *Journal of materials chemistry A*, *5*(27), 13882-13906.
35. Huang, Q., Wang, D., & Zheng, Z. (2016). Textile-based electrochemical energy storage devices. *Advanced Energy Materials*, *6*(22), 1600783.
36. Hu, L., La Mantia, F., Wu, H., Xie, X., McDonough, J., Pasta, M., & Cui, Y. (2011). Lithium-ion textile batteries with large areal mass loading. *Adv. Energy Mater*, *1*(6), 1012-1017.
37. Gulzar, U., De Angelis, F., Zaccaria, R. P., & Capiglia, C. (2016). Recent Advances in Textile Based Energy Storage Devices. *World*, *2*, 7.
38. Gulzar, U., Goriparti, S., Miele, E., Li, T., Maidecchi, G., Toma, A., ... & Zaccaria, R. P. (2016). Next-generation textiles: from embedded supercapacitors to lithium ion batteries. *Journal of Materials Chemistry A*, *4*(43), 16771-16800.

39. Nyholm, L., Nyström, G., Mihranyan, A., & Strømme, M. (2011). Toward flexible polymer and paper-based energy storage devices. *Advanced Materials*, *23*(33), 3751-3769.
40. Wang, Z., Pan, R., Sun, R., Edstrom, K., Strømme, M., & Nyholm, L. (2018). Nanocellulose structured paper-based lithium metal batteries. *ACS Applied Energy Materials*, *1*(8), 4341-4350.
41. Fraiwan, A., Mukherjee, S., Sundermier, S., Lee, H. S., & Choi, S. (2013). A paper-based microbial fuel cell: Instant battery for disposable diagnostic devices. *Biosensors and bioelectronics*, *49*, 410-414.
42. Hu, L., Wu, H., La Mantia, F., Yang, Y., & Cui, Y. (2010). Thin, flexible secondary Li-ion paper batteries. *ACS nano*, *4*(10), 5843-5848.
43. Nery, E. W., & Kubota, L. T. (2013). Sensing approaches on paper-based devices: a review. *Analytical and bioanalytical chemistry*, *405*, 7573-7595.
44. Cheong, H. W., Ha, S. H., & Choi, Y. S. (2012). Surface modified ceramic fiber separators for thermal batteries. *J Ceram Process Res*, *13*(2), 308-311.
45. Gong, Y., Fu, K., Xu, S., Dai, J., Hamann, T. R., Zhang, L., ... & Wachsman, E. D. (2018). Lithium-ion conductive ceramic textile: A new architecture for flexible solid-state lithium metal batteries. *Materials today*, *21*(6), 594-601.
46. Mujib, S. B., Ribot, F., Gervais, C., & Singh, G. (2021). Self-supporting carbon-rich SiOC ceramic electrodes for lithium-ion batteries and aqueous supercapacitors. *RSC advances*, *11*(56), 35440-35454.
47. Zhu, W., Liu, Q., Yi, X., & Zhu, Q. (2022, April). Effect analysis of ceramic fiber with different thickness on thermal runaway propagation of lithium-ion battery. In *Proceedings of the 3rd Asia-Pacific Conference on Image Processing, Electronics and Computers* (pp. 88-93).
48. Singh, R., Janakiraman, S., Agrawal, A., Nayak, D., Ghosh, S., & Biswas, K. (2020). A high ionic conductive glass fiber-based ceramic electrolyte system for magnesium–ion battery application. *Ceramics International*, *46*(9), 13677-13684.
49. Bai, W., Zhu, J., Wang, Y., Xu, M., & Jiang, J. (2024). Achieving highly stable sodium metal batteries with self-adapting and high-ionic-mobility ceramic fiber membranes. *Journal of Colloid and Interface Science*, *660*, 393-400.
50. Nestler, T., Schmid, R., Münchgesang, W., Bazhenov, V., Schilm, J., Leisegang, T., & Meyer, D. C. (2014, June). Separators-technology review: ceramic based separators for secondary batteries. In *AIP conference proceedings* (Vol. 1597, No. 1, pp. 155-184). American Institute of Physics.
51. Huang, Z. (2020). Polymer/ceramic Hybrid Separators for Lithium-ion Batteries.
52. Cheng, B., Tao, X., Shi, L., Yan, G., & Zhuang, X. (2014). Fabrication of ZrO2 ceramic fiber mats by solution blowing process. *Ceramics International*, *40*(9), 15013-15018.
53. Mo, F., Liang, G., Huang, Z., Li, H., Wang, D., & Zhi, C. (2020). An overview of fiber-shaped batteries with a focus on multifunctionality, scalability, and technical difficulties. *Advanced Materials*, *32*(5), 1902151
54. Zhou, Y., Wang, C. H., Lu, W., & Dai, L. (2020). Recent advances in fiber-shaped supercapacitors and lithium-ion batteries. *Advanced Materials*, *32*(5), 1902779.

55. Yang, S., Cheng, Y., Xiao, X., & Pang, H. (2020). Development and application of carbon fiber in batteries. *Chemical Engineering Journal, 384*, 123294.
56. Man, Z., Zhu, X., Ye, S., Wu, G., & Bao, N. (2022). Recent Advances and Future Perspectives of Fiber-Shaped Batteries. *Energy & Fuels*, *36*(17), 9866-9881.
57. Xiao, X., Yin, J., Shen, S., Che, Z., Wan, X., Wang, S., & Chen, J. (2022). Advances in solid-state fiber batteries for wearable bioelectronics. *Current Opinion in Solid State and Materials Science*, *26*(6), 101042.
58. Qu, H., Lu, X., & Skorobogatiy, M. (2018). All-solid flexible fiber-shaped lithium ion batteries. *Journal of the Electrochemical Society*, *165*(3), A688.
59. Kritzer, P., & Cook, J. A. (2007). Nonwovens as separators for alkaline batteries: an overview. *Journal of the Electrochemical Society*, *154*(5), A481.
60. Ma, W., Zhang, Y., Pan, S., Cheng, Y., Shao, Z., Xiang, H., ... & Zhu, M. (2021). Smart fibers for energy conversion and storage. *Chemical Society Reviews*, *50*(12), 7009-7061.
61. Wang, M., Chen, X., Wang, H., Wu, H., Jin, X., & Huang, C. (2017). Improved performances of lithium-ion batteries with a separator based on inorganic fibers. *Journal of materials chemistry A*, *5*(1), 311-318.
62. Sousa, R. E., Costa, C. M., & Lanceros-Méndez, S. (2015). Advances and future challenges in printed batteries. *ChemSusChem*, *8*(21), 3539-3555.
63. J. Varma, S., Sambath Kumar, K., Seal, S., Rajaraman, S., & Thomas, J. (2018). Fiber-type solar cells, nanogenerators, batteries, and supercapacitors for wearable applications. *Advanced Science*, *5*(9), 1800340.
64. Yu, L., Gu, J., Pan, C., Zhang, J., Wei, Z., & Zhao, Y. (2022). Recent developments of composite separators based on high-performance fibers for lithium batteries. *Composites Part A: Applied Science and Manufacturing*, *162*, 107132.
65. Lee, J., Jeon, S., Seo, H., Lee, J. T., & Park, S. (2021). Fiber-based sensors and energy systems for wearable electronics. *Applied Sciences*, *11*(2), 531.
66. Xia, X., Yang, J., Liu, Y., Zhang, J., Shang, J., Liu, B., ... & Li, W. (2023). Material choice and structure design of flexible battery electrode. *Advanced Science*, *10*(3), 2204875.
67. Chen, X., Ali, I., Song, L., Song, P., Zhang, Y., Maria, S., ... & Ramakrishna, S. (2020). A review on recent advancement of nano-structured-fiber-based metal-air batteries and future perspective. *Renewable and Sustainable Energy Reviews*, *134*, 110085.
68. Su, Y. D., Preger, Y., Burroughs, H., Sun, C., & Ohodnicki, P. R. (2021). Fiber optic sensing technologies for battery management systems and energy storage applications. *Sensors*, *21*(4), 1397.
69. Rafique, A., Ferreira, I., Abbas, G., & Baptista, A. C. (2023). Recent advances and challenges toward application of fibers and textiles in integrated photovoltaic energy storage devices. *Nano-Micro Letters*, *15*(1), 40.
70. Tan, M. Y., Safanama, D., Goh, S. S., Lim, J. Y., Lee, C. H., Yeo, J. C. C., ... & Fam, D. W. H. (2022). Concepts and emerging trends for structural battery electrolytes. *Chemistry–An Asian Journal*, *17*(21), e202200784.

71. Wakihara, M. (2001). Recent developments in lithium ion batteries. *Materials Science and Engineering: R: Reports*, *33*(4), 109-134.
72. Senthilkumar, S. H., Ramasubramanian, B., Rao, R. P., Chellappan, V., & Ramakrishna, S. (2023). Advances in electrospun materials and methods for Li-ion batteries. *Polymers*, *15*(7), 1622.
73. Raza, W., Ali, F., Raza, N., Luo, Y., Kim, K. H., Yang, J., ... & Kwon, E. E. (2018). Recent advancements in supercapacitor technology. *Nano Energy*, *52*, 441-473.