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Introduction

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In ancient civilizations, linen, cotton, and silk were some of the materials that were central in the lives of ancient civilizations, and it was not just a matter of daily living as it contributed to the cultural identity and global trade. The Middle Ages were the period when wool was dominant, and the Renaissance period when mechanized looms were introduced, which formed the base of industrialization. Major innovations were experienced in the 19th century, when people came up with synthetic dyes and sewing machines became very common. The 20th century saw a revolution in synthetic fibers, the introduction of technical textiles, and the adoption of digital printing technologies. The 21st century has changed gears to functional textiles that is the integration of functionality and sustainability principles to traditional materials—stretching the limits of textile innovation as illustrated in Figure 1.1. This historical timeline shows how textiles have been woven into the history of humanity and have always been adjusting to the changing needs of society and the new technological opportunities. The long-term path of textile evolution depicts the active balance of human inventiveness and the advancement of technology that has constantly changed not only the making but also the functionality of cloths [1].

With the changing global needs and the advancement in technology, textiles can no longer be used in their conventional roles as mere sources of basic protection and beauty. They now have to offer multifunctionality, responsiveness, and, most importantly, sustainability. The rising consumer awareness and the demand in the industry especially in the sector like healthcare, sportswear, fashion, and protective clothing are driving the textile industry to a transformational change. Traditionally, textiles were used to protect the human body against the elements, including cold, wind, and rain. Gradually, aesthetic and comfort characteristics were added. But nowadays, applications require a lot more—textiles now need to be able to interact with their surroundings, react to outside stimuli, and are often designed to be smart and sensor-connected. These demands have led to the development of smart textiles and

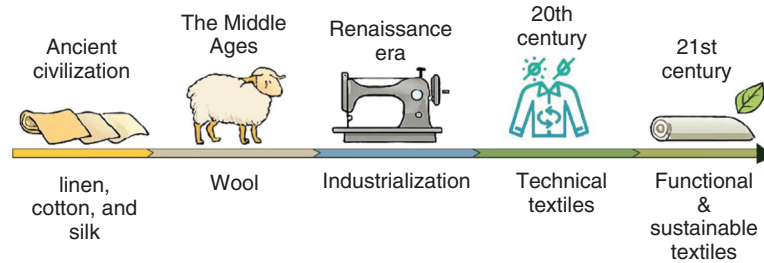


Figure 1.1 Historical timeline of textile evolution.

electronic textiles (e-textiles) that include components such as sensors, actuators, and control units to be used in real-time health monitoring, personal protection, communication, and even energy harvesting [2, 3].

Conventional textiles are characterized by lack of functionality, inefficient moisture regulation, inadequate thermal insulation, and high environmental burden because of chemical processing and the use of nonbiodegradable textiles. These materials are generally not responsive to external stimulus and provide little comfort in extreme weather. Unlike, the textiles in which hydrogels and aerogels are incorporated meet these limitations by adding novel properties of high moisture retention, temperature regulation, lightweight insulation, and responsiveness to stimuli. Hydrogels increase comfort and skin compatibility because of their ability to absorb water, and aerogels offer outstanding thermal insulation and breathability at minimal weight. Collectively, these smart materials are used to create high-performance, durable, and multifunctional textiles that can be used in contemporary applications in healthcare, sports, and extreme conditions [4, 5].

In this respect, hydrogels and aerogels have become revolutionary materials capable of revolutionizing the way textiles are used. The materials have exceptional properties that are highly valued, such as:

- Low density and high porosity, leading to lightweight, breathable, and insulating fabrics.
- Biocompatibility and biodegradability, which are in line with the aims of sustainable and environmentally friendly fashion.
- Thermal insulation, which provides benefits in protective clothing and cold-weather gear.
- Responsiveness to stimuli, including pH, temperature, and moisture responsiveness—allowing the textile to behave adaptively.
- Controlled release and moisture retention, which can be useful in wound dressing and drug delivery systems.
- Electrical conductivity, especially of carbon-based aerogels is opening new horizons in wearable electronics.

Additionally, natural fibers such as cotton, silk, and wool can be used to make hydrogels and aerogels, which further improve their sustainability rating and alignment with the circular economy. As the prospect of bio-fabrication, nanotechnology,

three-dimensional (3D) printing, and engineering of fiber surfaces gains popularity, advanced materials are finding their way into textile matrices without sacrificing softness and wearability [6, 7].

The integration of these multifunctional materials is a paradigm change—it allows the development of not just smart and practical but also eco-friendly textiles. Given the push of regulatory agencies such as the European Union to implement measures that will make textiles sustainable, the production of hydrogel- and aerogel-absorbing textiles should be instrumental in reaching both performance and planetary objectives.

1.1 Hydrogels and Aerogels

Hydrogels are 3D networks of hydrophilic polymer chains that are either physically or chemically cross-linked. Their distinguishing feature is their ability to absorb and retain large amounts of water, leading to high swelling ratios. The cross-linking method strongly influences hydrogel properties: chemically cross-linked hydrogels form covalent bonds, offering higher mechanical stability, whereas physically cross-linked hydrogels rely on weaker intermolecular interactions and are typically less robust [8, 9]. The polymer type, water content, and cross-linking degree all play crucial roles in determining swelling, gel strength, degradation rate, and stability. Hydrogels can be synthesized from natural polymers such as alginate, chitosan, and cellulose—preferred for their biodegradability and biocompatibility—or from synthetic polymers, which generally provide higher mechanical strength but lack inherent biocompatibility [10, 11].

Aerogels are a special class of nanoporous materials, in which the liquid phase of a gel is replaced by gas without collapsing the structure. They are characterized by extremely high porosity, ultralow density, and very large surface areas. Early aerogels were silica-based, but more recent developments have introduced hybrid and biopolymer-based aerogels synthesized from polysaccharides and proteins [12, 13]. These materials can be tailored for specific functions such as biocompatibility, biodegradability, or thermal insulation by adjusting the synthesis parameters and structure.

1.2 Unique Properties Relevant to Textiles

The integration of hydrogels and aerogels into textiles enables the development of multifunctional fabrics with enhanced performance, comfort, and sustainability. The 3D hydrophilic polymer network of hydrogels provides exceptional water absorption and retention capacity, which is highly beneficial for moisture management. This property enhances comfort in sportswear, healthcare textiles, and daily wear by regulating humidity close to the skin. Hydrogels can also be engineered as “smart” textiles by incorporating stimuli-responsive functionalities that react to changes in pH, temperature, or humidity, enabling adaptive apparel with improved responsiveness and wearability. Aerogels contribute unique advantages through

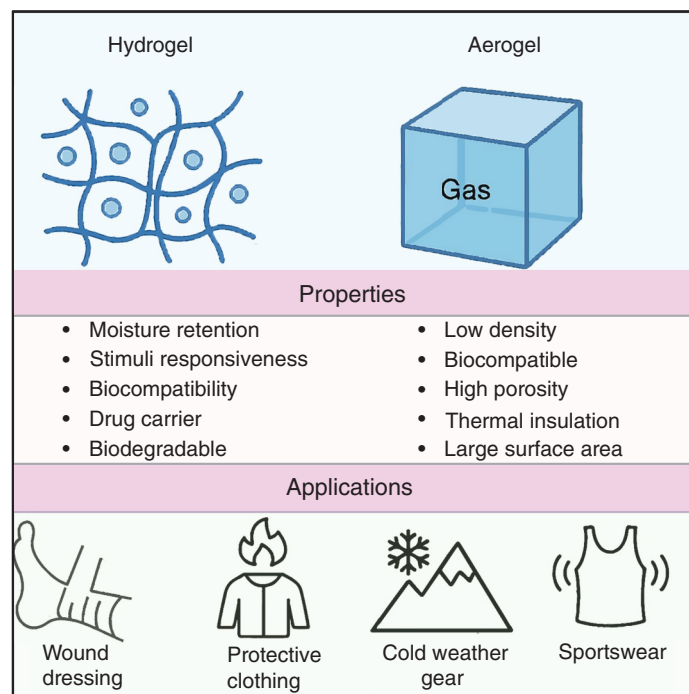


Figure 1.2 Key properties and textile applications of hydrogel and aerogel materials.

their nanostructured porosity and ultralightweight characteristics. Their very low thermal conductivity makes them excellent insulators, particularly valuable in protective clothing, extreme cold-weather garments, and high-performance technical textiles as shown in Figure 1.2. Beyond insulation, aerogels can impart flame-retardant properties and structural stability while maintaining breathability and flexibility of the base fabric [14, 15].

1.3 Why Hydrogels and Aerogels in Textiles?

The increasing demand for multifunctional and sustainable textiles has highlighted the need for materials that go beyond conventional fibers. Hydrogels and aerogels, due to their biocompatibility, biodegradability, and eco-friendly preparation routes, align well with the goals of sustainable textile development. Many hydrogel composites are synthesized from natural polymers such as alginate, chitosan, gelatin, and cellulose, which are abundant, nontoxic, and derived from renewable sources. Their incorporation into textiles not only reduces dependence on petroleum-derived synthetic fibers but also supports the global shift towards bio-based materials. Similarly, aerogels prepared from biopolymers such as chitosan or cellulose can be designed as lightweight, high-performance insulators while retaining biodegradability [16–18].

Waste minimization by means of multifunctionality is another point of sustainability. Textile composites based on hydrogel and aerogel can carry out multiple

functions at the same time, which include moisture management, thermal insulation, flame retardancy, and antimicrobial protection, whereas the same functions require multiple chemical finishes to be applied that may emit toxic effluents. Furthermore, their porosity and high surface area may enable sophisticated roles, such as oil–water separation and chemical resistance, providing environmentally friendly solutions to protective and filtration textiles [19, 20]. Therefore, the new high-performance soft materials are promising in the textile of the next generation that is both sustainable and not compromised in their performances.

Hydrogels and aerogels will confer special properties that make textiles more comfortable, safe, and versatile. High-water absorption and retention capacity: hydrogels control moisture by absorbing sweat or exudates of a wound and slowly releasing it, enhancing the breathability and comfort of wearers of medical dressings, sportswear, and ordinary clothes. Their responsiveness to stimuli allows the fabrics to react to temperature, humidity, or pH and makes adaptive textiles that can be used in healthcare monitoring or performance wear. Moreover, the textile-reinforced hydrogel composites address the typical weakness of the mechanical strength, providing better flexibility, durability, and even conductivity when supplemented with functional fillers such as silver ions [17, 21].

These properties are supplemented by the high thermal insulating properties, ultralightweight structure, and nanoporous morphology of aerogels. They provide body heat in harsh environments and are becoming more popular in protective clothing, cold-weather clothing, and industrial insulation systems. Coatings and composites based on aerogels also provide a flame retardancy, UV protection, and sound absorption as well as water repellency and extend the utility of textiles considerably. As an example, the addition of aluminum hydroxide aerogel to fabrics decreases flammability without loss of flexibility, and silica aerogels added to nonwovens enhance sound absorption and thermal stability [22–24]. In combination, hydrogels and aerogels can transform textiles beyond passive materials into multifunctional systems that can be used to deliver comfort, protection, and environmental responsibility. Their incorporation is one of the important milestones in the way of connecting sustainability and high-performance textile engineering.

1.4 Scope and Structure of the Book

1.4.1 Scope

The book examines the science, synthesis, functional properties, and applications of hydrogels and aerogels to textiles and links basic concepts with industrial developments. It explores their compositions, preparation techniques and types, noting natural, synthetic, hybrid and responsive systems, and different aerogel types and compositions. It focuses on synthesis of natural and synthetic fibers, functional properties of moisture management, thermal insulation, flame retardance, antimicrobial property, and biodegradability, and their disruptive nature in sustainable fashion, biomedical textiles, smart wearables, and protective garments. The book also discusses the issues of the present-environmental impact, recycling,

biocompatibility, and economic feasibility, as well as the future of sustainable innovation, market trends, interdisciplinary research, and regulation standards. As a reference and guide, it provides useful knowledge to researchers, textile engineers, material scientists, and other stakeholders in the industry that are interested in developing next-generation hydrogel- and aerogel-based textiles.

1.4.2 Structure

This book offers a complete insight into hydrogels and aerogels in textiles, their science and technology, synthesis processes, functional capabilities, and the variety of applications in fashion, healthcare, protection, and smart systems. Starting with the scientific background, the initial chapters describe the structural properties, methods of preparation, and property-tuning approaches of hydrogels and aerogels, defining how these versatile materials can be designed to perform specific textile functions by using various sources of fibers, natural, synthetic, or a mixture of both. Based on this background, the synthesis methods are explained on natural- and synthetic-based systems with a focus on their incorporation in textile substrates to develop high-performance fabrics with tunable moisture management, insulation, and durability. The book then moves to functional applications, demonstrating how hydrogels and aerogels enhance breathability, microbial resistance, flame suppression, and biodegradability, and how hybrid systems can combine the responsiveness of hydrogels with the insulation of aerogels for adaptive, sustainable textiles. In the context of sustainable fashion, these materials are presented as solutions to pressing environmental challenges by enabling biodegradable, recyclable, and energy-efficient apparel and accessories. Biomedical applications are explored through plant- and animal-derived hydrogel and aerogel systems, which support advanced wound healing, tissue engineering, drug delivery, and wearable biosensors, highlighting their role as next-generation biomaterials. Their integration into smart and electronic textiles is discussed with emphasis on wearable monitors, drug-delivery dressings, energy storage, and extreme-environment protection, demonstrating their ability to transform fabrics into intelligent, multifunctional systems. Specific focus is given to aerogels in protective clothing, where their superior thermal insulation, flame resistance, and lightweight robustness make them indispensable for military, industrial, and space applications. The book also addresses the major challenges hindering commercialization, such as high production costs, environmental concerns, and recycling difficulties, while proposing sustainable solutions through bio-based polymers, green chemistry, and circular economy models. Finally, it looks toward the future horizon, highlighting interdisciplinary collaboration, advances in additive manufacturing, and emerging market trends in eco-fashion, medical textiles, and protective gear. Collectively, the chapters illustrate how hydrogels and aerogels can act as enablers of next-generation textiles that are sustainable, intelligent, and adaptive, bridging scientific innovation with ecological and societal needs.

1.5 Target Audience and Applications

This book is intended for a diverse readership of researchers, graduate and undergraduate students, and industry professionals engaged in textiles, materials science, polymer chemistry, biomedical engineering, and sustainable design. For researchers and students, it provides a strong scientific foundation on the chemistry, structure, and synthesis of hydrogels and aerogels, along with insights into their integration into textile systems. For industry professionals, it highlights practical applications, case studies, and future market opportunities where these advanced materials can transform conventional practices. The applications discussed in this book span a wide spectrum: in fashion and sustainable apparel, hydrogels and aerogels enable biodegradable, recyclable, and performance-enhancing fabrics; in biomedical textiles, they support wound healing, tissue engineering, drug delivery, and wearable biosensors; in protective clothing, they provide superior thermal insulation, flame resistance, and impact protection for defense, industrial, and extreme environments. Additionally, the book explores their role in smart textiles and e-textiles, where their responsiveness and multifunctionality can support energy harvesting, sensing, and adaptive comfort. Collectively, the content aims to inspire interdisciplinary innovation, bridging academia and industry for the development of next-generation sustainable textiles.

1.6 Challenges and Opportunities

Despite their remarkable promise, hydrogel- and aerogel-based textiles face several challenges that limit their large-scale adoption. High production costs, particularly those associated with energy-intensive drying techniques and specialized crosslinking processes, remain major barriers. Environmental concerns also arise from the use of nonbiodegradable polymers, toxic solvents, and the difficulty of recycling hybrid textile–gel composites. Moreover, issues related to mechanical fragility, long-term stability, and biocompatibility require careful evaluation, especially for wearable and medical applications where safety is critical. However, these challenges also open the door to significant opportunities. Advances in green chemistry, bio-based polymers, additive manufacturing, and dynamic covalent chemistry are paving the way for cost-effective, scalable, and eco-friendly production methods. The growing global focus on circular economy models and sustainable product lifecycles further supports the development of recyclable and regenerative textile systems. With rising demand for smart fashion, biomedical solutions, and protective gear, the potential for hydrogel and aerogel textiles is vast. By fostering interdisciplinary collaboration and aligning innovation with environmental and regulatory frameworks, these materials are poised to redefine the textile industry, transforming it into a sector that is not only technologically advanced but also ecologically responsible.

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