

A Comprehensive Review of Waterproof Breathable Materials: Advancements and Applications

Mianchen Zhang*

Santa Monica College, 1900 Pico Blvd., Los Angeles 90405, United States

Email: mianchen2006@outlook.com

Abstract

Waterproof breathable materials (WBM) are essential in a variety of industries, providing a critical balance between good water and air permeability. This unique combination deflects water, rain, and other moisture away from wet working conditions - rain beads up and rolls off the surface of your gear so you stay dry, while sweat vapor easily escapes to help keep your inner layers dry. It is widely applied in the field of outdoor sportswear and protection equipment, as well as medical textiles such as surgical gowns and dressings to prevent liquid penetration while allowing air permeability of the skin. Furthermore, they are critical for dealing with extreme weather conditions and even in aerospace applications. In recent years, the need for improved durability, performance and sustainability has driven advances in technology. Among these advances, electrospinning has emerged as a transformative technology that has enabled the creation of efficient WBM. These electrospun membranes often outperform traditional materials like laminated polytetrafluoroethylene (PTFE) by offering superior control over pore size and porosity, which are key determinants of breathability and waterproofing. Additionally, the versatility of electrospinning enables the incorporation of nanoparticles or surface treatments to add multifunctional properties, such as UV protection or antimicrobial activity. In this paper, the application, development technology, the shortcomings of early methods and the latest innovations of electrospinning are reviewed, with emphasis on electrospinning.

Keywords: Waterproof Breathable Membranes; Electrospinning; Microporous; Nanofibers; Hydrophobicity.

Received: 7/9/2025

Accepted: 9/9/2025

Published: 11/19/2025

* Corresponding author.

1. Introduction

Waterproof breathable materials are now very important in modern textiles. These materials block liquid water and they also let internal moisture escape. This balance keeps fabrics breathable. This is important for outdoor sportswear and for industrial protective gear, and also for medical garments. Users not only can stay dry but also can avoid overheating and clammy skin [1,2]. The field has advanced quickly. Early solutions used high-density weaves and laminated layers, but newer work uses nanotechnology and advanced materials science. The main challenge is a trade-off because strong water resistance often reduces airflow, and greater airflow often reduces water resistance [3]. Traditional techniques create waterproof barriers, but they often limit air permeability and raise sustainability concerns. For example, microporous coatings, dense braids, and chemical finishes can repel water, but these methods can feel stifling in warm or active conditions [4]. Also, many products have relied on fluorinated chemicals, which raise environmental and health concerns [2]. Electrospinning has changed the situation. This process creates nanoscale fibers with tight control, and these fibers can deliver high waterproof ratings and strong breathability [2]. Electrospun layers are usually light and flexible, so the result improves comfort in daily wear and supports demanding industrial uses. Recent work focuses on sustainability and versatility. Researchers are testing fluorine-free coatings, biodegradable polymers, and blended systems because the goal is to have a lower environmental impact with equal or better performance [2].

2. Definition

Waterproof breathable material is an engineered textile designed to prevent liquid water from penetrating while allowing water vapor to escape. This dual function is essential for keeping dry and comfortable in a variety of applications.

2.1. Standard of Waterproofness and Breathability

Waterproofness refers to a material's resistance to water penetration. This is usually measured by a hydrostatic pressure test. In this test, pressure is applied to a column of water on the material until water passes through. A higher hydrostatic pressure means better water resistance. Materials like polytetrafluoroethylene (PTFE) and polyurethane (PU) films have been used for WBM because they resist liquid water well. But their dense structure can hinder moisture transfer and so it affects air permeability [5,6]. Breathability is measured by water vapor transmittance (WVTR). This test quantifies how much water vapor passes through the material in certain time. High breathability ensures sweat moisture is expelled so it can keep the wearer dry and comfortable during activity [7]. For example, microporous membranes or hydrophilic coatings are designed to let steam escape through tiny pores or diffusion, but still blocking liquid water. *Achieving a balance between water resistance and air permeability is a central challenge in WBM design. Impermeable materials usually block moisture too, but highly breathable materials may allow water to pass through in wet conditions [8,9].*

3. Types of WBMs Based on Structure

WBMs can be divided into several categories based on their structure and how they achieve a balance between water resistance and air permeability:

- Microporous Membranes
- Monolithic Membranes
- Coated Fabrics
- Electrospinning Nanofiber Membranes

3.1. Microporous Membranes

These materials, like expanded PTFE, contain millions of tiny pores per square inch, which are small enough to block liquid water but large enough to let vapor pass through. Although they are effective in waterproofing, these membranes can lose breathability gradually because of contamination of the pores [1,8].

3.2. Monolithic Membranes

They are solid, continuous membranes (usually hydrophilic) with no pores. They do not allow steam to pass through physical openings, but they transport water through molecular diffusion. These materials tend to provide more consistent air permeability, but they are less efficient at waterproofing than microporous membranes [3,10].

3.3. Coated Fabrics

In coated fabrics, a waterproof coating, usually polyurethane or silicone, is applied to a breathable base fabric. These coatings provide a protective barrier against water and allowing steam to pass through the fabric meanwhile. However, the coating may wear down over time, reducing the material's water resistance [8,6].

3.4. Electrospinning Nanofiber Membranes

Because the rise of electrospinning technology, new types of WBMs are being developed and show higher performance. Electrospinning membranes are composed of nanofibers that can form a high-density network with a high surface area and controllable pore size. This structure allows for high air permeability and excellent water resistance, as steam passes through the fine pores while water droplets are repelled. Electrospinning membranes are also lighter and more flexible than traditional WBMs, making them suitable for advanced applications such as outdoor sports equipment and medical textiles [9,10,11].

4. Application

Waterproof breathable materials are widely used in different industries due to their unique waterproof penetration and ability to provide comfort through moisture permeability. The combination of these characteristics allows WBMs to become an important in fields ranging from outdoor equipment to medical equipment and industrial protective clothing.

4.1. Outdoor Gear and Sportswear

High-performance clothing is essential for athletes and outdoor enthusiasts who are exposed to bad weather conditions. WBMs ensure that these clothes are waterproof, keeping the wearer dry and allowing sweat to escape, to remain comfortable during physical activity [3]. Many popular outdoor brands apply electrospun nanofiber membranes into their gear to improve water resistance and breathability. The electrospun film is lightweight, highly porous and has a fine pore structure that enhances air permeability without affecting the waterproof barrier. This innovation was important to the development of raincoats, hiking boots, and camping gear such as tents and sleeping bags [12].

In addition, WBMs used for outdoor equipment are often versatile. Now many products are not only waterproof and breathable, but also have UV protection and self-cleaning capabilities. For example, some advanced fabrics are coated with hydrophobic nanoparticles or titanium dioxide to improve durability and protect against UV radiation, extending the service life of gears [9].

4.2. Medical and Healthcare Textiles

In the medical sector, WBMs are important in the manufacture of protective clothing such as surgical gowns, gloves, masks, and medical curtains. These materials are essential for maintaining a sterile environment and ensuring the comfort and safe to the doctors and patients. Medical textiles that are made by WBMs provide a barrier against liquids, including blood, allowing air and moisture to pass through to prevent heat buildup and discomfort [8]. For example, electrospinning nanofiber membranes have been incorporated in medical clothing to improve their breathability without sacrificing fluid resistance. This is important in high-risk environments, such as surgery, where water resistance and air permeability are necessary for long-term use. Also, these electrospinning membranes are used in wound dressings. Because they allow water vapor to travel, promoting healing and preventing bacterial infection [12].

In addition, WBMs in medical textiles are being designed with antimicrobial properties to reduce the risk of infection. Silver nanoparticles or titanium dioxide coatings are often added to WBMs to provide these antibacterial functions, making them particularly useful in hospitals and healthcare settings where hygiene is critical [9].

4.3. Medical and Healthcare Textiles

WBMs are also used extensively in industrial and military settings, where protective clothing must meet rigorous standards for water resistance, breathability, and durability. Workers in industries such as oil and gas, firefighting, chemical handling, and the military require garments that protect against harsh environmental conditions while allowing them to remain comfortable under physically demanding conditions [5,6].

Electrospinning nanofibers have a wide range of applications here because, in addition to being water and breathable, they can also be customized to be chemical and flame resistant. For example, firefighter uniforms made with WBMs use a combination of electrospinning film and flame retardant coating to ensure high-

performance protection [5,6].

4.4. Aerospace and Automotive

The aerospace and automotive industries are increasingly adopting WBMs to improve passenger and crew comfort and protection. In the aerospace sector, WBMs are used in seats, pilot clothing, and cabin interiors to regulate humidity and temperature. For example, seats are lined with breathable waterproof material that prevents moisture buildup during long flights and increases passenger comfort [7].

4.5. Fashion and Everyday Clothing

WBMs are increasingly incorporated into fashion and everyday wear, and this style of sportswear is gradually becoming a fashion icon. Fashion designers are using electrospinning to create thin, light, breathable and waterproof fabrics. These materials are especially popular in raincoats, coats, and accessories such as hats and gloves [8].

5. Development of Techniques

Waterproof breathable materials have developed significantly over the years, and the development technology has been continuously improved to balance the dual needs of waterproof and breathable. Earlier methods focused on using dense fabrics, laminated fabrics, and chemical coatings, but these methods had limitations. In recent years, the nanotechnology, especially electrospinning technology, has greatly changed the method of making waterproof and breathable materials.

5.1. Traditional Techniques and Their Limitations

5.1.1. High-Density Weaves

Early WBMs were often made with tightly woven textiles, which are the fibers packed tightly together to prevent water from seeping into the fabric. While these high-density fabrics are effective at repelling water, they tend to limit the spread of moisture, resulting in poor breathability and discomfort in relatively hot and humid environments [6,7].

5.1.2. Microporous and Monolithic Membranes

Membranes such as microporous polytetrafluoroethylene (for GORE-TEX) and integral hydrophilic membranes is one of the important developments in waterproof breathable materials. Microporous membranes contain millions of tiny holes, that can block water droplets and allow steam to pass through meanwhile. However, a key problem with microporous membranes is presented: pores can become clogged, reducing air permeability. Monolithic membranes work through molecular diffusion and are more consistent in air permeability but are less waterproof than micropores [1,7].

5.1.3. Coated Fabrics

Another way to make WBM is to use a waterproof coating such as polyurethane or silicone and apply them to a breathable fabric base. This method can improve water resistance. However, the coating often wears down over time due to mechanical stress or environmental factors, reducing the effectiveness of the material. In addition, these coated fabrics may impair breathability and reduce the comfort of clothing [6,8].

5.1.4. Environmental Concerns with Fluorochemicals

Many early methods of making WBMs relied on the hydrophobicity of fluorine-containing chemicals. However, fluorochemicals such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) have been found harmful to the environment and bioaccumulative. Thus, raising serious concerns about their harmfulness on human health and the environment. The damage to environment led the development of fluoride-free alternatives in recent years, with a growing demand for sustainable, eco-friendly materials[8,9].

5.2. Breakthroughs in New Techniques

5.2.1. Nanotechnology

The integration of nanotechnology into the development of WBM provides a new way to improve water resistance and air permeability. Nanoparticles, such as silicon dioxide and titanium dioxide, are added to the coating and film to enhance water resistance and maintaining air permeability [1,11]. Compared to traditional coatings, these nanoparticles create hydrophobic surfaces that are more durable and resistant to wear.

5.2.2. Hybrid Membranes

Hybrid membranes have become a solution to the challenge of balancing water resistance and air permeability. These membranes typically combine microporous and monolayer layers, or combine hydrophilic and hydrophobic layers to optimize water transport and water resistance. For example, polyvinylidene fluoride (PVDF) membranes combine with hydrophilic hydrogels to provide directional water transport, allowing steam to escape from the inner layer while preventing water from penetrating the outer layer [7].

6. Electrospinning Technology

Electrospinning technology has greatly promoted the production of waterproof breathable materials, providing an innovative method for the production of nanofibers with diameters ranging from a few nanometers to a few microns. This method can develop highly efficient water-based ballistic missiles, which are light in weight and widely used, but also improve the water resistance and air permeability of water-based ballistic missiles.

6.1. The Electrospinning Process

Electrospinning is a technique in which a high-voltage electric field is applied to a polymer solution to create microfibers. The solution is ejected in the form of a thin jet and solidifies into a web on the collector. The

resulting nanofibers create a porous structure with a high surface area to volume ratio, which is ideal for improving WBM's water resistance and air permeability. The process allows material properties to be fine-tuned by adjusting factors such as voltage, polymer concentration and flow rate, making electrospinning a very versatile technique [2,11,12]. The nanofibrous structure generated provides a unique balance of small pore sizes that block liquid water while enabling moisture vapor to escape, which is critical for user comfort in applications such as outdoor gear, medical textiles, and industrial protective clothing.

6.2. The Electrospinning Process

6.2.1. Enhanced Waterproofness and Breathability

Because of good pore structure, it forms a good balance between water resistance and air permeability by applying electrospun nanofiber membrane. The nanofibers can form a dense but breathable barrier that allows moisture to pass through and preventing liquid water from penetrating meanwhile. This makes the electrospun nanofiber membrane become very suitable for applications such as sportswear and outdoor clothing. The WBM created by the electrospinning method can achieve a good balance of water resistance and air permeability, and ensuring the comfort of these materials [1,8,9].

6.2.2. Lightweight and Flexible

Electrospinning membranes are significantly lighter and more flexible than traditional WBMs, such as those made from laminated fabrics or waterproof membranes. The lightweight properties make them more comfortable to wear for long time, such as jackets, boots, and medical textiles. [6,10]

6.2.3. Customizability

One of the main advantages of electrospinning technology is its customizability. Manufacturers can easily control the fiber diameter, porosity, and thickness to customize the properties of the film to satisfy specific requirements. [11,12] This flexibility enables the production of WBM to meet precise performance criteria, such as increased durability, enhanced water resistance and optimized air permeability.

6.2.4. Multifunctionality

Besides being water resistant and breathable, electrostatic spun WBM can also be combined with other properties such as UV protection, antibacterial treatment and self-cleaning surfaces. For instance, electrospinning membranes containing silver nanoparticles or titanium dioxide possess antibacterial activity, and thus can be used in medical applications where maintaining a sterile environment is of significant importance. [8,9] Also, UV-resistant layer can be sprayed on electrospinning WBM to shield the material and the wearer from UV rays, especially when used in outdoor garments [12].

6.3. Sustainability in Electrospinning

In response to the growing concern for environmental sustainability, electrospinning has developed to a kind of environmentally friendly WBM. The use of biodegradable polymers, such as polylactic acid (PLA) and polycaprolactone (PCL), allows electrospinning WBM to break down naturally over time, reducing its environmental impact so that become less harmful to the environment [2,11]. In addition, fluorine-free coatings are being used into electrospinning films to eliminate the use of harmful perfluorinated compounds that have traditionally been used for waterproofing [4,10].

7. Conclusion

Waterproof and breathable materials have recently been evolving in response to the development of material science, especially nanotechnology, and electrospinning technology. The two-stage operation of WBM - to keep the water out and the moisture in - renders them essential in diversified applications including outdoor equipment, sports apparel, medical textiles and industrial protective clothing. The initial production of WBM was based on tight braids and chemical treatments that were good at making them waterproof barriers, though they generally sacrificed breathability and comfort. The access of microporous membranes and hydrophilic coatings has enhanced the air permeability, but still some limitations exist, such as trade-off of water resistance and air permeability. To address these conflicting requirements, a much larger array of new technologies is being developed to meet the increasing demand for high performance materials, particularly electrospinning. The production of WBM has likewise been transformed by the use of electrospinning technology to form nanofibers with outstanding and precisely tunable features. These electrostatics spun nanofiber membranes provide to the greatest extent water resistance, breathability, flexibility, and light weight construction. Not only are these potent agents, but they are industry specific, so allowing producers tailor material attributes to end use applications. Furthermore, electrospun enables multi-functional WBM, for example, antibacterial property, UV protection and self-cleaning surface, thus improving the practicality and prospect of use in other areas outside of conventional field. Sustainability is another area in which there has been progress for WBM. Fluoride-free coatings, biodegradable polymers and environmentally friendly manufacturing processes are being used into the production of WBM, maintaining its high performance and reducing its ecological impact at the same time.

In summary, the development of WBM reflects the ongoing efforts to meet the needs of modern industry -- combining function with sustainability. As the technology continues to evolve, WBM is likely to see even greater improvements in performance, versatility, and environmental impact. The contribution of electrospinning technology will be important in shaping the future of WBM, making it essential in a variety of industries, from fashion and aerospace to healthcare and industrial applications.

Acknowledgements

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