Intelligent Human Systems Integration (IHSI 2025), Vol. 160, 2025, 639–649
https://doi.org/10.54941/ahfe1005870

Innovative Nanofiber Membrane Hydration Bladder for Camping: A Sustainable Approach to Lightweight, Portable, and Safe Water Storage

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ABSTRACT

With the increasing popularity of outdoor activities, about 57 million people go camping every year in the United States alone, and they often face challenges in drinking and storing water in the wild. Traditional plastic or metal water storage containers usually have problems such as being too heavy, inconvenient to carry, and environmental pollution. These containers are not only inconvenient to carry, but also difficult to degrade after being discarded, causing long-term pollution to the environment. This study proposes to use a revolutionary ultra-lightweight nanofiber membrane to design a portable camping water bag to solve these problems. The nanofiber membrane is made of recyclable and bio-based materials, which not only has excellent waterproofness, elasticity and durability, but also has environmental sustainability. In addition, reducing the density of the nanofiber membrane can give it a certain water filtration function, achieving basic water purification effects in outdoor environments. The material can also effectively prevent bacterial penetration, thereby avoiding water resource pollution and ensuring safe water storage in outdoor environments. This material can degrade in the natural environment, greatly reducing the impact on the ecological environment compared to traditional plastic products. The designed water bag has high waterproofness of 10,000 mm H2O, excellent air permeability of 25,000 g/m/24hrs, and outstanding tensile strength. It can be easily folded for easy carrying and storage, allowing campers to store more water without increasing the carrying burden. A series of performance tests such as pressure resistance, tear resistance, and temperature resistance showed that the nanofiber membrane water bag demonstrated excellent functionality in a variety of outdoor environments. The results of the study indicate that nanofiber membranes have broad application prospects in the design of high-performance, environmentally friendly, and multifunctional camping equipment, which not only enhances the user experience but also minimizes environmental impact. Future research will further optimize the material properties and explore its wider application in outdoor equipment.

Keywords: Nanofiber, Portable water bag, Water filtration, Lightweight camping gear, Environmental sustainability

INTRODUCTION

Background

In recent years, outdoor activities, especially camping, have grown rapidly worldwide, becoming an important part of the tourism industry. Studies show that the number of campers is increasing every year. In the United States alone, around 57 million people participate in camping each year (Farrington et al., 2023). This trend has made campers face challenges with water storage and drinking in the wild, especially in remote areas or during long outdoor activities. Finding an efficient and convenient way to store and carry water has become an urgent issue.

Traditional water containers mainly include plastic, stainless steel, glass, and aluminium products. However, each of these materials has its limitations. PET plastic bottles, due to their non-biodegradable nature, have been proven to cause serious environmental pollution. Especially in outdoor activities, if not properly disposed of, plastic particles can enter the soil and water, threatening the health of ecosystems (Lamichhane et al., 2023). In addition, while glass and stainless-steel bottles are durable and reusable, they are heavy, which makes them less portable for campers who need to carry a large amount of water during long hikes.

This study aims to explore the use of revolutionary ultra-light breathable nanofiber membrane materials to design a portable camping water bag. It seeks to address the limitations of traditional water containers in terms of portability, environmental sustainability, and functionality. By introducing high-density nanofiber membranes in the design to improve waterproof performance, and using low-density nanofiber membranes for basic water filtration, this study will present a camping water bag that combines high performance with eco-friendliness. It offers a better water solution for outdoor enthusiasts.

Research Objectives

The core objective of this study is to design a portable camping water bag using nanofiber membrane materials to overcome the limitations of traditional water containers in terms of portability, environmental friendliness, and functionality. The specific objectives include:

Material Application

Design a lightweight and foldable water bag by utilizing the excellent waterproof properties of high-density nanofiber membranes, effectively preventing water leakage while ensuring easy portability and storage.

Environmental Friendliness

Use biodegradable and recyclable bio-based nanofiber membrane materials to reduce environmental pollution, replacing traditional plastic and metal materials commonly used in outdoor gear.

Emergency Water Filtration

Achieve a basic level of water filtration by reducing the density of the nanofiber membrane, allowing the water bag to provide initial purification

of water in emergency situations where clean water is scarce, ensuring safe drinking water for users.

Multifunctional Design
While ensuring portability, design the water bag to be multifunctional, allowing it to meet various water storage and usage needs in outdoor environments, enhancing its practicality for campers during outdoor activities.

This study aims to provide outdoor enthusiasts with a high-performance, eco-friendly, and multifunctional portable water bag design, while also offering new research directions and practical foundations for future camping equipment design and material applications.

LITERATURE REVIEW

Limitations of Traditional Materials and Design

Traditional water storage systems have long been used in outdoor activities, but they present significant limitations:

- Plastic Bottles: While lightweight and convenient, they are environmentally harmful, prone to cracking, and contribute to long-term plastic pollution (Zolotova et al., 2022).
- Stainless Steel Bottles: Durable and reusable, but heavy (Heikonen, 1997), making them unsuitable for long hikes.
- Hydration Bladders: Effective for carrying large volumes of water, but prone to leakage and difficult to clean, leading to potential hygiene issues (Shah, 2023).
- Water Filters: Require clean water sources and regular maintenance, limiting their practicality in remote or emergency situations (Wainaina et al., 2023).

These limitations highlight the need for innovative materials like nanofiber membranes, which combine durability, lightweight design, and environmental sustainability.

Application of Nanofilm in Outdoor Camping

Nanofiber Membranes
Waterproofness and breathability: Nanofiber membranes are of particular interest in outdoor clothing and tent design because of their excellent water resistance and breathability. The material allows water vapor to escape while keeping moisture out, making it ideal for use in gear that needs to stay dry. For example, a research project at the Technical University of Liberec developed nanofiber membranes specifically for sports and outdoor activities, demonstrating the material's wide applicability in a variety of applications (Knížek & Karhánková, 2019).

Lightweight and Durable: The lightweight nature of nanofiber materials allows them to significantly reduce the overall weight of outdoor gear without

sacrificing durability. This is especially important during hiking and camping activities where you need to carry gear for extended periods of time.

Functional Textiles

High-visibility clothing: Advances in textile technology have led to the development of high-visibility clothing that uses light-responsive properties. These materials use fluorescent and phosphorescent coatings to improve visibility for outdoor athletes in low-light conditions and enhance safety during nighttime activities (Santos et al., 2021).

UV protection: Introducing nanoparticles such as titanium dioxide (TiO2) into fabrics can produce textiles with UV protective properties. Such materials can be used in outdoor clothing and sunshades (such as tents) to provide users with the necessary UV protection (Tomljenović, Pezelj, & Sluga, 2007).

Infrared Camouflage Materials

Military applications: Advanced infrared camouflage fabrics were originally developed for military use, but they are equally suitable for outdoor activities such as covert camping or hunting. These materials can adapt to different environments and enhance concealment capabilities while remaining lightweight and portable (Su, Yu, & Zhao, 2023).

Thermal Comfort and Moisture Management

Performance improvement: In outdoor sportswear, researchers are focused on optimizing the thermal comfort of materials. Materials that can effectively manage humidity and temperature can significantly improve sports performance, keeping the wearer dry and comfortable during physical activities such as skiing and hiking (Pezzoli, 2014).

Sustainable Practice

Recyclable materials: Many newly developed materials for outdoor gear emphasize sustainability, such as products made from recycled plastics or biodegradable materials. These materials not only reduce environmental impact while maintaining high performance levels, pointing the way to an environmentally friendly future for outdoor gear.

Durability and Maintenance

Enhanced durability: New materials are often more resistant to wear and tear, making them suitable for use in harsh outdoor conditions. These materials are treated with special treatments, such as water- and stain-resistant coatings, which further improve their lifespan and ease of maintenance.

Comparative Analysis With Global Studies

Research on nanofiber membranes has primarily focused on applications in textiles, air filtration, and medical equipment. However, their application in portable water storage solutions remains underexplored. Recent studies highlight their potential:

A study demonstrated that nanofiber membranes exhibit superior water filtration properties compared to traditional materials (Wainaina et al., 2023).

Research by Chen et al. (2024) revealed high filtration efficiency, achieving up to 99.54% for particulate matter, with minimal pressure drop.

Studies from Hu et al. (2021) and Wu et al. (2023) emphasize the antibacterial and durability properties of nanofiber membranes, making them suitable for water storage applications.

Despite these advancements, few studies have examined the performance of nanofiber membranes specifically in outdoor water bladder systems. This study aims to bridge this gap by evaluating their practical performance in real-world outdoor environments.

Research Gap

While nanofiber membranes have shown promising results in other industries, their application in portable water bladders remains limited. Existing studies lack comprehensive evaluations of membrane durability, filtration efficiency, and usability in harsh outdoor conditions. This research addresses these gaps, contributing to the growing body of knowledge on sustainable and efficient water storage solutions.

RESEARCH METHOD

Design and Produce Prototype Samples

Based on nanofiber membrane materials, we designed and produced portable water bag samples with various structures to explore the waterproof and durable effects of different stitching and sealing technologies in actual use.

Experiments and Performance Testing

A series of rigorous performance tests are conducted in both laboratory and outdoor environments, including water resistance, pressure resistance, abrasion resistance and durability tests, to evaluate the performance of the water bag in various environmental conditions.

Expand Applied Research

Explore the application potential of nanofiber membrane water bags in different scenarios, such as scientific research, disaster relief and urban water resources management, to provide theoretical support for future diversified applications.

MATERIAL PROPERTIES AND DESIGN

Material Properties of Nanofiber Membranes

Density and Structure

Comparison of the properties of high- and low-density nanofiber membranes, showing their performance in terms of water repellency and filtration, respectively.

High-Density Nanofiber Membranes is a typically exhibit enhanced water repellency due to their compact structure, which minimizes the number of pores and increases the surface area that can repel water. This makes them suitable for applications requiring high waterproofing capabilities, such as outdoor clothing and tents (Hu et al., 2022). The dense arrangement of fibbers can create a barrier that prevents water penetration while allowing some vapor permeability, which is crucial for maintaining comfort in wearable applications.

Generally have a more porous structure, which can lead to lower water repellency compared to high-density membranes. However, their high porosity allows for better air flow and moisture management (Ji et al., 2023).

These membranes are often used in applications where breathability is prioritized over complete waterproofing, such as in filtration systems where moisture vapor needs to escape.

Filtration Performance

Often designed for specific filtration applications where fine particles need to be captured effectively. Their dense structure can enhance filtration efficiency by providing more surface area for particle capture,One study highlighted a hierarchical dual-nanonet structure that achieved a filtration efficiency of 99.999% for particles as small as 0.3 μm, which illustrates the high performance possible with advanced nanofiber designs (Hu et al., 2021). Another research indicates that high-density membranes can achieve high filtration efficiencies (e.g., up to 99.54% for certain particulate sizes) due to the reduced pressure drop across the membrane, making them ideal for air and liquid filtration systems (Chen et al., 2024).

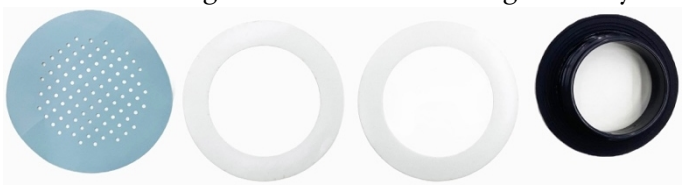
Low-Density Nanofiber Membranes

Although they may have lower filtration efficiency compared to high-density membranes, low-density structures are beneficial for applications requiring high permeability and lower resistance to airflow. Studies have shown that low-density membranes can still achieve significant filtration rates (e.g., between 83% and 99% efficiency depending on the fiber morphology), making them suitable for air filtration where a balance between airflow and filtration is necessary (Chen et al., 2024).

Design of the Hydration Bladder

a. Design renderings

b. The water bag is made of laser-cut high-density nanofiber membrane



c. A prototype disassembly of the filter port, low-density nanofiber membrane, biodegradable cotton sheet, and sealer.

d. High-density Nanofiber membrane water bag sample, without water (foldable), after water filling.

The design process utilized 3D printing to create the model, and the sample was made using the appropriate high-density nanofiber membrane material. The sealing process was done with heat sealing technology. A low-density nanofiber membrane was used for the filter port to simulate the filtration structure of the final product. The water bag is foldable when empty, making it lightweight and easy to carry. The sample has a capacity of approximately 450 ml.

Performance Theory Analysis

Theoretical Basis of Waterproof Performance

High-density nanofiber membranes can effectively prevent the penetration of water molecules. Studies have shown that high-density electrospun nanofiber membranes can indeed effectively prevent the penetration of water molecules. By adjusting the surface roughness and porosity of the membrane, these nanofiber membranes can exhibit superhydrophobicity, thereby improving the water repellency and reducing the penetration of water molecules (Subrahmanya et al., 2021).

Filter Performance

Nanofiber membranes can be used for water filtration at different densities and have been used in some cases of seawater filtration. A study pointed out that PVDF/SiO2/Ag composite nanofiber membrane demonstrated its antibacterial properties alongside effective filtration performance. The membrane was designed to filter out bacteria and showed significant reduction in bacterial counts, indicating its effectiveness in both filtration and antibacterial applications (Wu et al., 2023).

Compression and Tear Resistance

Nanofiber membranes can be combined with different materials to achieve compression resistance. A study pointed out that Ferroelectric PVDF Nanofiber Membrane: Research on ferroelectric PVDF nanofiber membranes highlights their high efficiency in air filtration with low flow resistance. These membranes demonstrate significant mechanical strength, indicating good tear resistance, which is essential for maintaining performance under operational conditions. (Bui et al., 2022). However, what we are going to use is a water storage bag, so the material in this study may not be suitable for water storage, and we need to find more theoretical support to find the compressive resistance of other types of nanofiber membranes.

The Theoretical Analysis Suggests That Nanofiber Membranes Possess the Ability to Achieve Distinct Properties Based on Their Density

High-Density Membranes: Provide excellent waterproofing by minimizing pore size and increasing surface resistance to water molecule penetration.
Low-Density Membranes: Allow efficient water filtration and improved breathability, suitable for emergency water purification.
Mechanical Durability: Theoretical studies indicate that blending nanofiber structures enhances tear and compression resistance, essential for outdoor use.

While experimental validation is pending, theoretical models and previous research support the hypothesis that nanofiber membranes can excel as materials for durable, multifunctional water storage solutions.

APPLICATIONS AND FUTURE WORK

Practical Applications of Nanofiber Water Bags

Nanofiber membrane water bags offer significant potential for use in:

- Outdoor Activities: Ideal for mountain climbing, hiking, and exploration due to their lightweight and foldable nature.
- Disaster Relief: Effective in emergency water storage during field rescue and post-disaster scenarios.
- Humanitarian Aid: Suitable for clean water distribution in underprivileged and remote regions.

Future Design Optimization

Future developments will focus on:

- Enhanced Membrane Density Balance: Improving filtration efficiency without compromising breathability.
- Modular Design: Creating adaptable systems for multi-scenario use.
- Advanced Coating Techniques: Using bio-based coatings to improve antibacterial properties.

Broader Applications in Outdoor Gear

Nanofiber membranes are also applicable to:

- First-Aid Bags: Providing waterproofing and temperature resistance.
- Sleeping Bags: Enhancing insulation and comfort with optimized membrane densities.
- Protective Clothing: Offering lightweight, tear-resistant, and waterproof properties.

Sustainability and Environmental Responsibility

- Biodegradable Materials: Ensuring minimal environmental impact.
- Sustainable Manufacturing: Aligning production with eco-friendly goals.

Nanofiber membranes represent a transformative material for outdoor equipment, balancing functionality, sustainability, and environmental responsibility.

ACKNOWLEDGMENT

The authors would like to thank SUMEC Textile & Light Industry Co., Ltd. for their technical support, particularly Zhao Wei (Head), Dong Gang (Technical Director), and Cheng Shuo (Textile Manager). We also acknowledge Jiangsu Sunfeng Special Material Technology Co., Ltd. for their material support, with special thanks to Xu Haiming, Chen Jie, and Wu Wanyu.

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