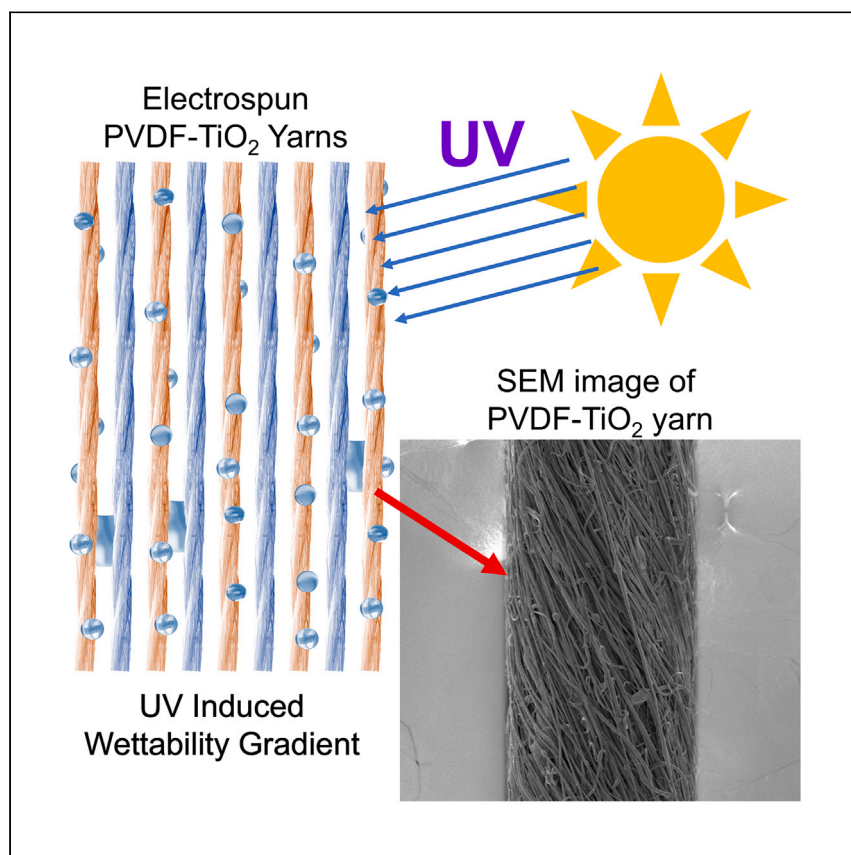


Article

Wettability gradient of photoresponsive electrospun yarns for harp-based fog water harvesting



Fog water harvesting can address water scarcity in arid regions. This study by Parisi et al. introduces electrospun PVDF-TiO₂ yarns with a dynamic wettability gradient, enhancing fog collection. This approach uses electrospun yarns to capture water with harp-like structures, offering scalable, efficient water harvesting solutions and providing viable, accessible water.

Gregory Parisi, Piotr K. Szewczyk, Shankar Narayan, Urszula Stachewicz
ustachew@agh.edu.pl

Highlights

Enhanced fog water harvesting using electrospun yarns with a wettability gradient

Dynamic adjustment from hydrophobic to hydrophilic via UV irradiation and heat

PVDF-TiO₂ yarns made by electrospinning form porous fibers for fog collection

Alternating yarns outperform just hydrophobic/hydrophilic, reaching 400 mg cm⁻² h⁻¹

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Article

Wettability gradient of photoresponsive electrospun yarns for harp-based fog water harvesting

Gregory Parisi,¹ Piotr K. Szewczyk,² Shankar Narayan,¹ and Urszula Stachewicz^{2,3,*}

SUMMARY

Fog water harvesting offers a solution to water scarcity. Here, we introduce a method to enhance fog water harvesting systems utilizing electrospun yarns featuring a wettability gradient. These yarns, made from polyvinylidene fluoride (PVDF) and titanium dioxide (TiO₂), gain photoinduced hydrophilicity under UV light due to TiO₂ photocatalytic properties, allowing dynamic shifts from hydrophobic to hydrophilic states. Experiments show that an alternating PVDF-TiO₂ harp with a wettability gradient surpasses purely hydrophobic or hydrophilic versions in fog collection. The strategic mix of hydrophobic and hydrophilic sections enhances droplet movement and water capture, achieving a 16% increase in collection rate up to 400 mg cm⁻² h⁻¹. This approach introduces a novel method for creating wettability gradients in electrospun yarns via UV irradiation and represents a significant advancement in adaptable fog water harvesting systems.

INTRODUCTION

Water shortage worldwide is one of the most pressing challenges of our time. Global water scarcity poses a significant threat to ecosystems and human societies, necessitating innovative solutions for sustainable water resource management.¹ In many regions, conventional water sources are depleting rapidly, prompting a search for alternative methods to harness fog water² or other sustainable water sources.³ Fog water harvesting was inspired by the Namib desert beetle, which captures water on its bumpy, hydrophilic-hydrophobic patterned back, demonstrating that wettability effects enhance fog capture.⁴ Fog water harvesting has emerged as a promising approach, exploiting the natural occurrence of water droplets suspended in foggy air.⁵ The capture efficiency relies on surface characteristics, with hydrophobic surfaces preventing premature coalescence and facilitating controlled droplet movement.⁶ Conversely, hydrophilic surfaces promote droplet coalescence, enhancing capture efficiency.⁷ Integrating a wettability gradient, encompassing both hydrophobic and hydrophilic regions, presents a dynamic strategy for optimizing fog water collection.⁸ This gradient improves the efficiency of the total surface, allowing for selective and efficient droplet capture,⁹ which is commonly observed in nature.¹⁰ Other groups have demonstrated hydrophobic/hydrophilic Janus systems for fog capture; however, they did not employ yarns for increased fog collection.¹¹ Other forms of sustainable water sources include sorption-based atmospheric water harvesting (AWH), which can capture and release water vapor from the air.¹² Unlike traditional fog water capture, which relies on the presence of fog and requires specific climatic conditions, sorption-based AWH can operate based on a high surface area and an affinity for water molecules. Li et al. demonstrated a solar-driven AWH with bidirectionally aligned nanocomposites.¹³

¹Rensselaer Polytechnic Institute, Department of Mechanical, Aerospace, and Nuclear Engineering, 110 8th Street, Troy, NY 12180, USA

²AGH University of Krakow, Faculty of Metals Engineering and Industrial Computer Science, al. A. Mickiewicza 30, 30-059 Krakow, Poland

³Lead contact

*Correspondence: ustachew@agh.edu.pl
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Polymer fiber meshes are one of the most effective ways to collect water from fog, together with yarns produced from electrospun nanofibers.¹⁴ Electrospinning, a widely adopted technique in which a voltage is applied between a nozzle and a collector, produces nanofibrous structures with high surface area and tunable properties.¹⁵ In this study, we leverage electrospinning to fabricate yarns composed of polyvinylidene fluoride (PVDF) and titanium dioxide (TiO₂) nanoparticles. The incorporation of TiO₂ for switchable wettability has been shown previously¹⁶; however, this work incorporates TiO₂ nanoparticles during electrospinning to create yarns. The resulting electrospun yarns exhibit unique morphological characteristics, making them ideal candidates for fog water harvesting applications. Electrospinning yarns also provide flexibility for different applications like smart textiles,¹⁷ thermal management¹⁸ and coatings,¹⁹ and tissue scaffolds²⁰ or skin patches.²¹ This responsive fog water harvester is easy to scale and can be integrated into existing technologies.

In fog water harvesting, traditional mesh structures have been widely utilized.²² Researchers have tried to improve the efficiency of conventional meshes by employing electrospinning methods for fog capture.²³ Knapczyk-Korczak et al. studied the importance of hydrophobic properties of electrospun meshes,²⁴ incorporating hydrophilic nanofibers,^{25,26} and improved the fog capture efficiency of aligned electrospun fibers.²⁷ However, harp-like structures present advantages over meshes, especially in preventing clogging.²⁸ A fog harp is a specialized structure resembling a vertical array of strings or yarns designed to capture atmospheric water droplets from the fog by providing surfaces for droplet condensation and subsequent collection.²⁹ The unimpeded movement of droplets along harp surfaces ensures continuous and efficient water collection, mitigating the challenges associated with clogging observed in conventional mesh configurations.³⁰ Comparing electrospun yarns to conventional metal yarns reveals distinct advantages. The lightweight and flexible nature of electrospun yarns offers practical benefits, making them more suitable for deployment in various environments. Additionally, the ability to control wettability adds a level of sophistication, allowing for tunable performance in fog water harvesting.³¹ By investigating the fog water collection of hydrophobic, hydrophilic, and alternating wetting harps, we found that the wettability gradient of yarns possesses higher water collection efficiency.

Additionally, integrating smart materials with switchable wettability can improve fog water harvesting systems. Dynamic adjustment of the surface wetting states is controlled by an external stimulus that changes its surface or chemical properties.³² Switchable wettability is commonly used in other applications, such as microfluidics,³³ oil-water separation,³⁴ self-cleaning,³⁵ heat transfer,³⁶ and smart windows.³⁷ In particular, we explore the use of TiO₂ nanoparticles in PVDF yarns, which are further constructed into harps, showcasing their photoinduced hydrophilicity under UV irradiation.³⁸ This switchable wettability allows for dynamic control over the yarns' hydrophobic and hydrophilic states, enabling adaptability to varying environmental conditions.³⁹ The concept of a wettability gradient, where surfaces transition between hydrophobic and hydrophilic states, has gained traction in water harvesting applications,⁴⁰ optimizing droplet movement and capture efficiency.⁴¹ While previous studies have explored the benefits of wettability gradients,⁴² our work introduces a novel method of achieving such gradients using UV irradiation and electrospinning, offering a scalable, dynamic, and adaptable approach to fog water collection.

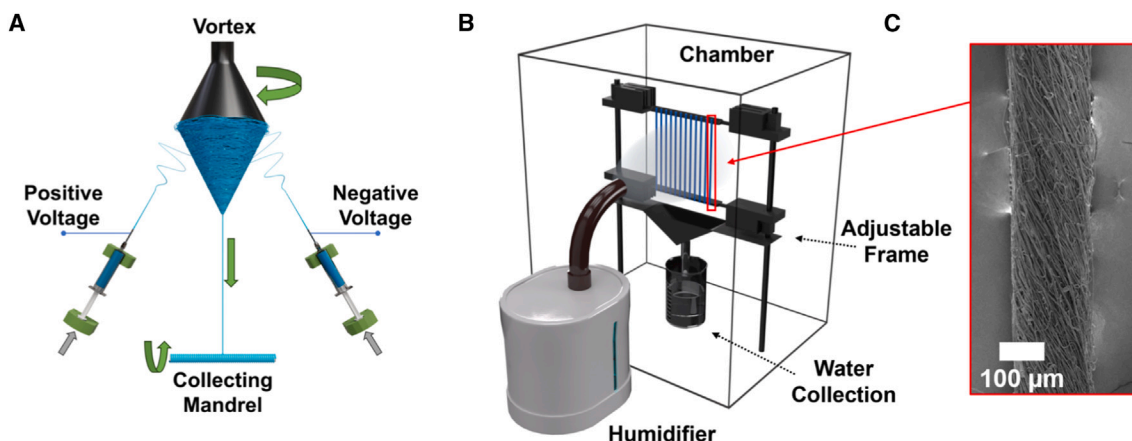


Figure 1. Yarn production and device setup

(A) Electrospinning setup for yarn production consisting of two nozzles, vortex, and rotating mandrel.

(B) Water collection schematic with the inset of the produced electrospun PVDF-TiO₂ yarns.

(C) SEM image of a single yarn. Scale bar, 100 μm.

RESULTS AND DISCUSSION

Fiber morphology and composition

The PVDF-TiO₂ yarns were produced via electrospinning, and a schematic of the electrospinning process, with the finished yarn setup, is shown in Figure 1. The electrospinning process creates fibers made from PVDF-TiO₂. The fibers are collected on a vortex, which twists the fibers into a yarn that is drawn toward the mandrel, where it is continuously collected. The yarns are then strung together in a vertical array to create the fog-collecting harp. Fog water collectors constructed from electrospun yarns excel in water collection and have the capability of adjusting surface wettability for gradient functionality.

The surface morphology of the PVDF-TiO₂ yarns that were created from individual fibers during the electrospinning process as well as the electrospun fibers are shown in Figures 2A and 2B, respectively. It is evident from scanning electron microscopy (SEM) images that the PVDF-TiO₂ fibers are free of beads and do not contain any fiber entanglements. This result demonstrates that the morphology and spinnability of the electrospun yarns are repeatable in different systems.¹⁹ It is also evident that the fibers contain agglomerations of TiO₂ scattered throughout the electrospun yarn. The uniform dispersion of TiO₂ within the polymer fibers shows that the nanoparticles are held within the polymer matrix, creating a strong mechanical bond between the two. This process is advantageous over adding TiO₂ nanoparticles after electrospinning due to the fact that TiO₂ is embedded in the fibers because it is electrospun from a polymer/TiO₂ blend solution.⁴³ The addition of the TiO₂ changes the morphology of the fibers and the fiber diameter.

Furthermore, elemental mapping was employed to show the elemental makeup of PVDF-TiO₂ yarns in Figures 2C–2E. The Fourier transform infrared (FTIR) spectrum for PVDF-TiO₂ yarns can be found in Figure S1. The average fiber diameter of the PVDF-TiO₂ fibers is 1.5 ± 0.5 μm. Histograms indicating yarn size distribution are shown in Figure 2F. The PVDF-TiO₂ yarn diameter is 193.4 ± 8.4 μm, Figure 2G. Additionally, energy-dispersive X-ray spectroscopy (EDX) analysis was conducted to verify the elemental composition of the PVDF-TiO₂ fibers. Figure 2H shows that the PVDF-TiO₂ yarns contain elements present in the polymer solution of PVDF, C and F,⁴⁴ as well as an additional Ti peak, confirming the addition of TiO₂

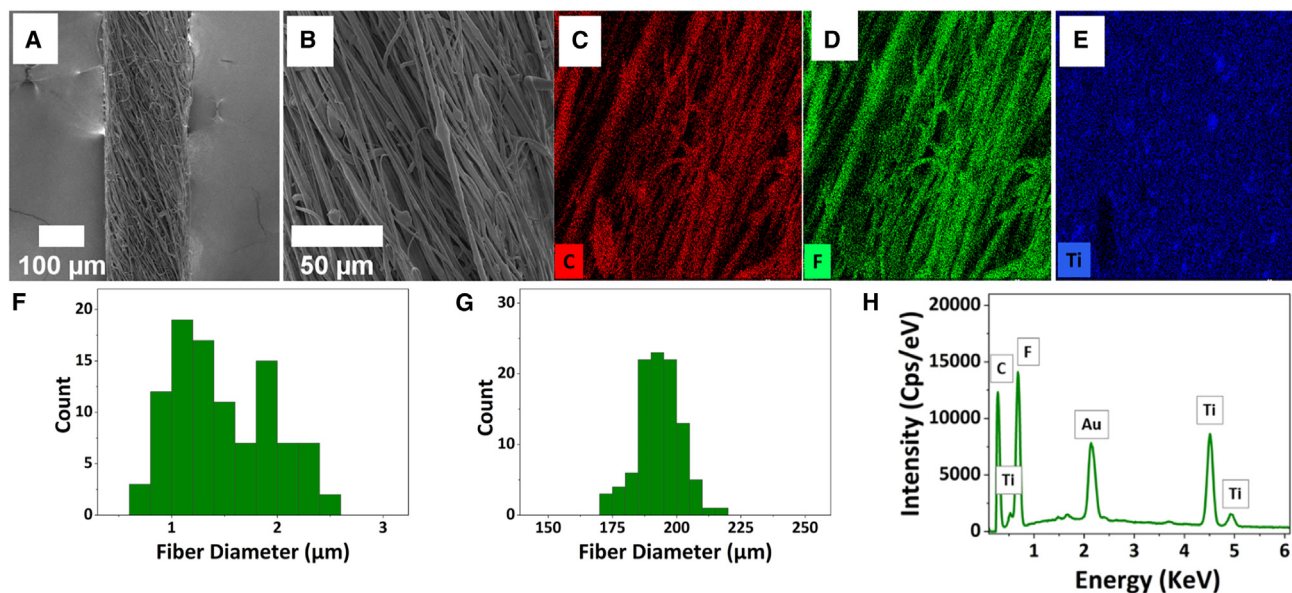


Figure 2. Characterization of yarns

(A and B) SEM micrographs of PVDF-TiO₂ yarn.

(C–E) EDX mapping of PVDF-TiO₂ yarn.

(F) Fiber diameter distribution.

(G) Yarn diameter distribution.

(H) EDX spectra from PVDF-TiO₂ yarn.

nanoparticles. Au is present on the EDX spectra due to the Au coating applied for SEM imaging.

Wettability

Wettability is a fundamental determinant in the efficacy of fog water harvesting systems.⁴⁵ The hydrophobicity of surfaces is essential for removing fog droplets after they collect and coalesce on the surface. This property ensures the maintenance of discrete droplets, a critical factor for optimizing the water harvesting efficiency. Hydrophobic surfaces, by minimizing surface adhesion, facilitate superior droplet removal with increased water yield.⁴⁶ Conversely, hydrophilic surfaces play an equally vital role in fog harvesting, promoting the efficient utilization of fog by facilitating the spread and adherence of water droplets.⁴⁷ The inherent property of hydrophilic surfaces to encourage droplet coalescence enhances the capture efficiency of fog water harvesting systems when integrated with a hydrophobic gradient. The integration of a wettability gradient, encompassing both hydrophobic and hydrophilic regions, emerges as a promising strategy for optimizing fog water collection.⁴⁸ This gradient strategically leverages the strengths of both surface types, allowing for efficient droplet capture.⁴⁵ The controlled transition between hydrophobic and hydrophilic regions enhances the overall collection efficiency, offering a dynamic and adaptable approach to fog harvesting. In this study, the static contact angle of water on the PVDF harp is $149^\circ \pm 3.1^\circ$, and the static contact angle of water on the PVDF-TiO₂ harp is $146^\circ \pm 4.9^\circ$. These values are comparable to those of our previous studies, in which a PVDF mesh contact angle was 147° and the addition of TiO₂ into the mesh resulted in a contact angle of 145° .² Although the intrinsic contact angle of TiO₂ is very low ($\sim 30^\circ$), this does not lower the contact angle of the blended PVDF-TiO₂ yarns since the majority of the surface is PVDF.⁴⁹

The flexibility of the harp construction allows the collector to be entirely hydrophobic, fully hydrophilic, or patterned with alternating hydrophobic and hydrophilic sections (Figure 3A). It is also feasible for future work to prepare a yarn with mixed wettability in the same yarn with alternating directional wettability.⁵⁰ This tunability ensures optimal performance in various environmental conditions, making fog water collection systems more efficient and adaptable, particularly in water-scarce regions. Figure 3B illustrates UV irradiation on PVDF-TiO₂ fibers for photoinduced hydrophilicity, a phenomenon stemming from the photocatalytic properties of TiO₂.⁵¹ The resultant catalytic activity generates hydroxyl radicals, transforming the surface from hydrophobic to hydrophilic. Based on our previous studies, PVDF-TiO₂ maintains hydrophilicity in air after several days.² The surface can resort back to hydrophobicity with the addition of heat. The external stimulus can be used as a control to determine which yarns in a fog collector are hydrophobic or hydrophilic. The yarns can be tailored and dynamically controlled to exhibit diverse wettability profiles. For the alternating wettability gradient, every other yarn contained TiO₂, making the wettability switch simple under UV light. Figure 3C illustrates the complete harp setup prior to fog harvesting experimentation. The yarns were exposed to UV light for different durations to determine the change in wettability (Figure 3D). After 4 h of UV irradiation, the fibers exhibit complete wetting. A non-wetting surface can be restored by maintaining the yarns at 60°C for 2 h, highlighting the potential for controlled and reversible wettability. This process is repeatable, with only a 6% decrease from the first measurement to the last, demonstrated within a 10 cycle wettability switch in Figure 3E.

Fog water collection

The chemical composition, surface geometry, harp construction, roughness, and wettability of electrospun yarns emerge as critical factors, highlighting their significance within the water collection experiment.⁵² Although harp construction plays a critical role in optimizing fog water collection, it was optimized based on the best practices from the existing literature.²⁹ The yarn diameter influences the surface area available for droplet formation and collection. Thinner yarns increase the surface area, which enhances the collection rate. The length of the harp also increases the total surface area; however, this can also lead to severe wire tangling.⁵³ In our study, we decided on the constant diameter of approximately 190 μm for PVDF-TiO₂ combined with a constant length to precisely monitor the water collection rate influenced by the changes in wettability. Lastly, the pitch between the yarns determines how effectively the fog interacts with the collection surface. Too much airflow, where fog in the airstreams flows through the harp, will also result in fog going straight through the collector and no water collection.⁵⁴ In this study, we select a 90° angle, as it is the most common in the literature, thus providing the easiest platform to compare with other results. In the absence of UV irradiation, discrete droplets populate the harps. Notably, UV irradiation induces rapid spreading of water droplets on the harp's surface. The responsiveness of the electrospun harps to UV irradiation introduces a dynamic element to fog water harvesting. The photoresponsive harps undergo a change to become hydrophilic, enhancing their ability to capture droplets, which has historically been difficult for hydrophobic surfaces. Conversely, where droplet capture is less critical, the electrospun mesh can be manipulated to revert to a hydrophobic state under heat, maximizing droplet shedding. Since the harps can be set to have completely hydrophobic, hydrophilic, or alternating wettability, the water harvesting was run on all the surface options for comparison (see Figure 4).

UV-irradiated PVDF-TiO₂ or hydrophilic harps exhibit comparable water collection rates with non-irradiated or hydrophobic harps, even though the droplet-surface interaction is entirely different for the two surfaces (Figure 4A). When the air is highly

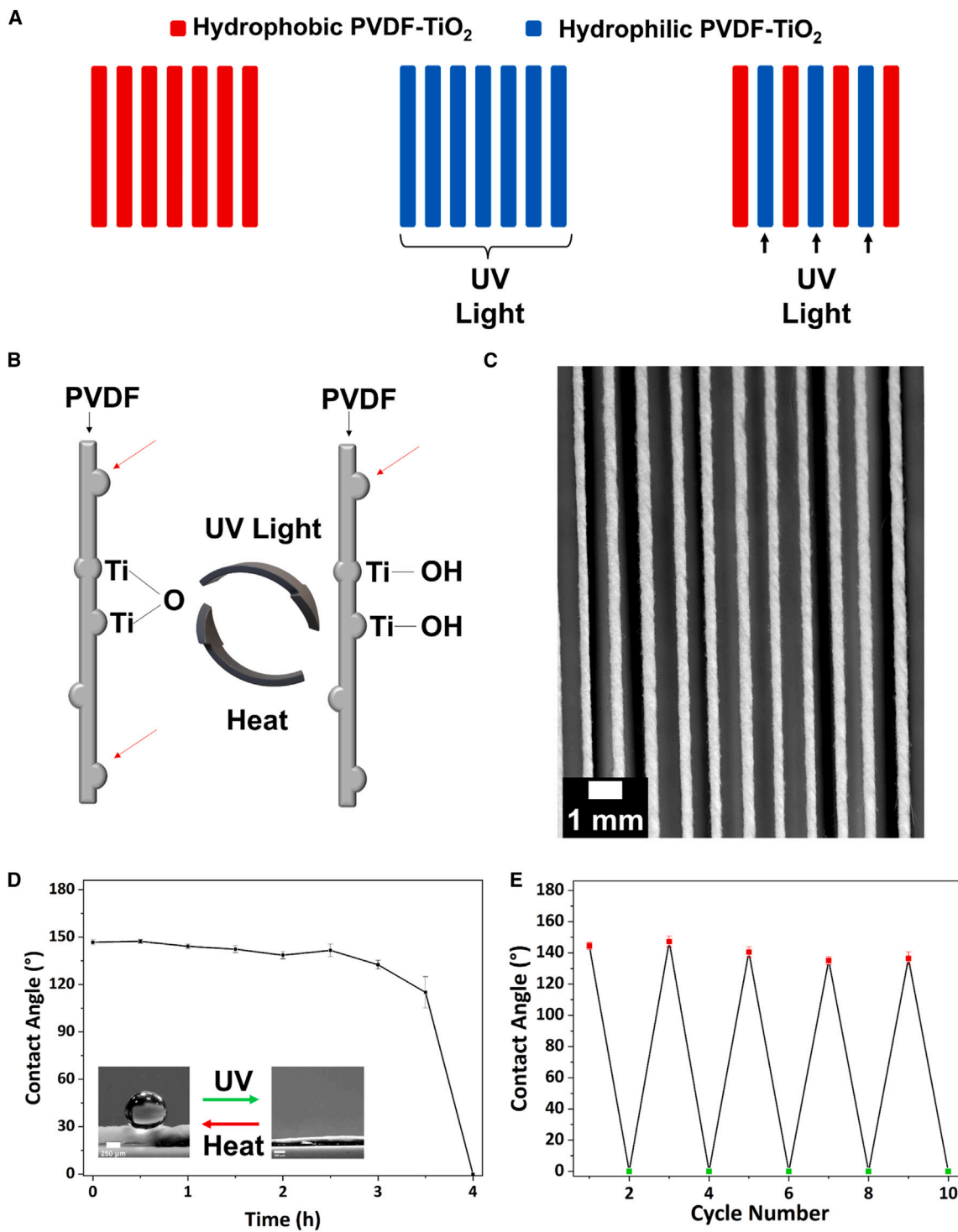


Figure 3. Wetting characteristics of yarns

(A) Schematic illustration of the three different wetting characteristics of PVDF-TiO₂ yarns: fully hydrophobic, fully hydrophilic, and alternating.

(B) The mechanism of the conversion process of wettability of PVDF-TiO₂ fibers. TiO₂ agglomerates are indicated with red arrows.

(C) Image of completed harp prior to fog harvesting with 1 mm scale bar.

(D) Water contact angle under UV irradiation.

(E) Cycling between hydrophobic and hydrophilic with the addition of UV irradiation followed by heat.

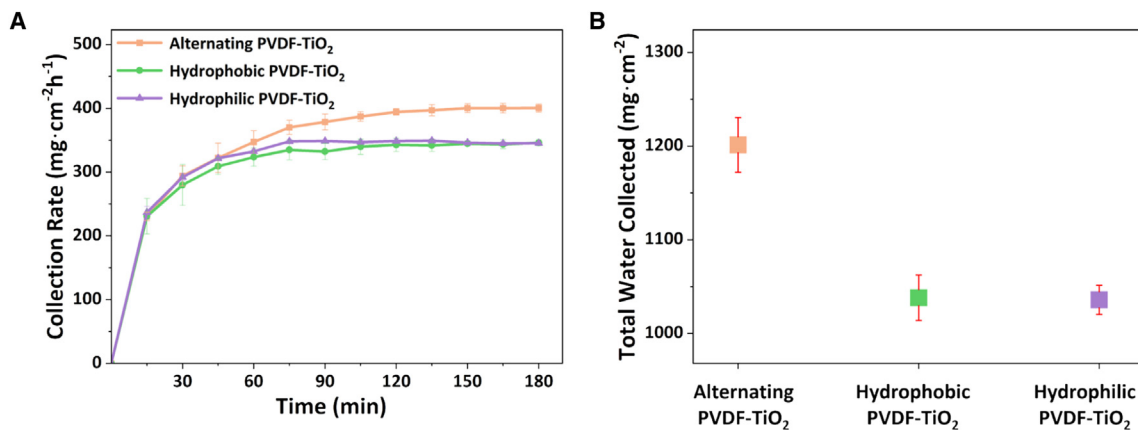


Figure 4. Water collection

(A) Results of water collection rate of all three wetting possibilities of harps: hydrophobic PVDF-TiO₂, hydrophilic PVDF-TiO₂, and alternating hydrophobic and hydrophilic PVDF-TiO₂.

(B) Comparison of total water collected after 3 h.

saturated with fog, there is competition between the rapid formation of droplets and shedding at high humidity levels, making the initial wettability difference negligible. After 3 h of fog water harvesting, the hydrophobic and hydrophilic PVDF-TiO₂ harps have a water collection rate of 346 ± 4.8 mg and 345 ± 1.8 mg cm⁻² h⁻¹, respectively. The results shown here are similar to our previous results of PVDF harps in the same fog conditions of 365 mg cm⁻² h⁻¹.¹⁴ This demonstrates that physical TiO₂ nanoparticles have very little effect on the water collection rate of PVDF harps. On the other hand, the alternating PVDF-TiO₂ variant attains the highest water collection rate of 400 ± 6.4 mg cm⁻² h⁻¹ (see Figure 4B). All water collection tests were run in triplicate, showing small standard deviations between each experiment. Even after 9 h of water collection testing, the collection rate did not decrease, demonstrating that no structural damage was present that would affect the fog water harvesting results. Table 1 illustrates several existing reports on fog water collection using commonly used materials. Other groups have taken advantage of a wettability gradient or patterned wettability surface to improve droplet capture and droplet shedding. Yin et al.³¹ added polytetrafluoroethylene (PTFE) nanoparticles on a copper mesh to construct a hybrid superhydrophobic-hydrophilic surface for water collection. By introducing wetting and non-wetting regions, Lee et al.⁴² were able to achieve a fog harvesting rate of 209 mg cm⁻² h⁻¹ when constructing a cylindrical double structural system. Additionally, other researchers have shown that adding patterned wettability with control of the surface topography can increase water collection compared to non-optimized surfaces.^{55–57} By changing the collection shape to wires, Yang et al.⁵⁸ were able to construct a wettability gradient to induce fog capture on the top of the wires and induce droplet shedding as the droplets grow with size. Zhu et al. created a Janus fabric with a water collection rate of 225 mg cm⁻² h⁻¹.⁴⁸ Another research group used ultraslippery patterning mixed with hydrophilic surfaces for efficient fog harvesting of 160 mg cm⁻² h⁻¹.⁵⁹ Another example of patterned wettability for fog capture is demonstrated by Sun et al., in which they used superhydrophobic sticky paper with holed, smooth aluminum alloy as the hydrophilic region to obtain a fog capture rate of 363 mg cm⁻² h⁻¹.⁶⁰ Besides patterned wettability, groups have discovered multiple uses of fog-harvester materials to improve capture efficiency while providing additional functionalities. A bifunctional fog harvester was addressed to show an alternative method of water collection while decontaminating the collected water.⁶¹

Table 1. Summary of fog water collection rate for various materials based on the listed references

Material class	Processing methodology	Water harvesting performance ($\text{mg cm}^{-2} \text{h}^{-1}$)	Reference
Copper mesh	nanoparticle deposition by femtosecond laser	203	Yin et al. ³¹
Hydrogel	dip immersion and cylindrical structuring	209	Lee et al. ⁴²
Carbohydrate polymer	spin coating	91	Shi et al. ⁵⁵
Glass-PFDS	patterned wettability with laser ablation	7	Wang et al. ⁵⁶
Titanium alloy	laser grid texturing	416	Liu et al. ⁵⁷
Aluminum wires	patterned immersion	46	Yang et al. ⁵⁸
PVDF-TiO ₂ yarns	electrospinning	400	current work

An alternating wettability gradient proves to be a highly efficient configuration for fog water harvesting, primarily due to its ability to capitalize on the distinct advantages of hydrophobic and hydrophilic surfaces. In this configuration, the hydrophobic regions are critical in preventing premature coalescence by repelling water droplets and facilitating their faster movement. As droplets traverse the hydrophobic sections, they eventually fall from the force of gravity and roll down the surface. The strategically positioned wet hydrophilic regions then come into contact with the rolling drop on the hydrophobic region, as shown in the [supplemental information \(Figure S2\)](#). Since the wettability gradient is neighboring yarns, the interplay of wettability comes during droplet shedding on the hydrophobic yarn and facilitates water removal of the hydrophilic yarn. This interplay between the two regions is shown in a high-speed video in [Video S1](#), where the droplet can be seen rolling down the hydrophobic yarn and coming into contact with the hydrophilic yarn, increasing the total volume of removed water. The electrospun yarns are porous and contain porous fibers; because of this, the hydrophilic yarns are swollen with water during fog water capture and exhibit larger fiber diameters compared to the hydrophobic yarns, which do not retain water. This dynamic relationship ensures that the droplets, once repelled by the hydrophobic regions, are efficiently captured and consolidated by the adjacent hydrophilic segments, removing even more water. Hence, although the total water collected from the hydrophobic and hydrophilic harps are almost identical, the alternating PVDF-TiO₂ harp collected 16% more water after 3 h ([Figure 4B](#)). The alternating PVDF-TiO₂ harp had a total fog water collection of $1,201 \pm 19.2 \text{ mg cm}^{-2}$. By utilizing an alternating wettability gradient, the described water harvester demonstrates increased water collection compared to conventional wetting harps. This innovative approach enhances water harvesting efficiency and introduces a novel method for creating wettability gradients using UV irradiation and electrospinning.

Overall, we advanced fog water harvesting using electrospun yarns with an alternating wettability gradient. The integration of PVDF and TiO₂, coupled with dynamic control over wettability, presents a versatile and efficient approach to fog water capture. The water collection experiments highlight the improved water capture rate of the alternating wettability gradient harps. While both hydrophobic and hydrophilic harps exhibited similar water collection rates, the alternating PVDF-TiO₂ harp outperformed them, achieving a remarkable rate of $400 \pm 6.4 \text{ mg cm}^{-2} \text{h}^{-1}$, which represents a 16% increase in water collection compared to the harps without a wettability gradient. The alternating wettability gradient harps also introduces a tunable

and responsive process. The scalability of the PVDF-TiO₂ harp for practical applications is highly promising. The electrospinning process used to produce the PVDF-TiO₂ yarns is both stable and reliable, as demonstrated by the successful production of several meters of yarn for experimental purposes. This is crucial in arid regions of the world because there is an urgent need to provide alternative clean water globally.⁶² This stability indicates that the process can be extended to larger scales without compromising the material's quality. To engineer the harp at a meter scale, the same experimental setup can be used to produce additional yarn. The main requirement for scaling up is to increase the quantity of yarn produced, which can be achieved by extending the duration of the electrospinning process. The design of the harp itself is inherently flexible; it can be easily extended to accommodate more yarn and cover larger areas. This scalability makes the PVDF-TiO₂ harp a viable option for large-scale water collection applications, providing an efficient solution for practical, real-world deployment.⁶² Importantly, the here-presented methodology is transferrable to various materials and technologies, making this approach applicable beyond PVDF. This study demonstrates electrospun yarns with alternating wettability gradients as a viable and efficient fog water collector that is able to help in current water shortage challenges.

EXPERIMENTAL PROCEDURES

Materials and electrospinning

25 wt % TiO₂ nanoparticles (Sigma-Aldrich, UK, particle size <100 nm) were added to dimethylacetamide (Sigma-Aldrich, UK) and acetone (Sigma-Aldrich, UK) in a 1:1 ratio. The solution was sonicated for 1 h in an ultrasonic bath (Bandelin, Sonorex, Germany). Then, 24 wt % of PVDF (Sigma-Aldrich, UK, $M_w = 350,000 \text{ g mol}^{-1}$) was added to the above mixture for a final concentration of 24 wt %. The solution was stirred at 400 rpm for 4 h on a hot plate set to 50°C (IKA RCT basic, Staufen, Germany).

The electrospinning process was conducted using a TechNOVA (ESVY-100, MicroNano Tools, Canada) electrospinner with a climate control system. The PVDF fiber yarns were produced by applying a voltage of +8 kV to one 19G stainless needle and a voltage of -9 kV to the other 19G stainless needle, which were both set to a 12 cm distance from the collector. The chamber's environmental conditions were kept at $T = 22^\circ\text{C}$ and a relative humidity of 50%. The flow rate for both pumps was set to 0.08 mL min^{-1} . The collecting mandrel was held at a constant rotating speed of 12 rpm, and the vortex speed was held constant at 400 rpm. The harps were heated in an oven at 60°C (Pol-eko Aparatura, Poland) for 2 h.

Material characterization

A scanning electron microscope (Merlin Gemini II, ZEISS, Germany) was employed to analyze the surface morphologies of the electrospun samples. Before observations, the samples were coated with an 8 nm Au layer for SEM imaging using a rotary pump sputter coater (Q150RS, Quorum Technologies, UK). The fiber and yarn diameters were measured using the SEM micrographs with ImageJ software (1.53k, NIH, USA). The average fiber diameter values were calculated from 100 measurements, and the error was based on the standard deviation with OriginLab (2022, USA) software. The chemical composition of the fibers was analyzed using FTIR spectroscopy (Nicolet, iS-5, USA) and on Al substrates using EDX (Bruker Quantax 800). The wettability was measured by placing and imaging 3 μL volume droplets of deionized water (Spring 5UV purification system, Hydrolab, Poland) on the electrospun yarns. Wettability tests were conducted using a digital camera interfaced with a macro-lens (EOS 700D, EF-s 60 mm, Canon, Japan) and repeated seven times. The contact angles were measured on a vertically placed yarn and analyzed using a contact angle

plug-in on ImageJ software. High-speed imaging was conducted during fog water collection (Chronos CR14–1.0, Krontech, Canada, 3,381 fps and $400 \times 1,000$ pixels).

Water harvesting experimental setup

The water harvesting performance of the as-prepared samples was evaluated with a lab-built experimental apparatus, including a commercial humidifier (Setii, AH900, Poland) and a chamber ($50 \times 60 \times 40$ cm). The humidifier produced the fog at a rate of 400 mL h^{-1} and a velocity of 2 m s^{-1} . The harps (60 cm^2) were fixed to two steel stands and placed vertically 7 cm away from the humidifier. The harps were attached to 3D-printed in-house holders consisting of 30 individual yarns. Two holders were set 10 cm apart and finely tuned using adjustable nuts on a threaded rod. The teeth on the 3D-printed holders were spaced 1.05 mm apart and had a total length of 15 cm. A flowmeter (SOLE Uni-T, China) was used to measure the fog flow rate, and the chamber was held above 95% relative humidity during experiments. Fog water collection was conducted in a custom-built environmental chamber specifically designed for this study at an ambient air temperature of $26^\circ\text{C} \pm 2^\circ\text{C}$. The experiments were conducted thrice, and the collected fog water was measured at 15 min intervals for 3 h. The wettability switch of the harps from hydrophobic to hydrophilic was conducted in a UV chamber for 2 h. UV irradiation for the wettability switch was performed in the air by 6 parallel UV lamps (9 W, 285 nm) at 4 cm from the electrospun samples. To revert back to the initial hydrophobic state, the harp samples were placed in an oven at 60°C for 2 h.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Urszula Stachewicz (ustachew@agh.edu.pl).

Materials availability

This study did not generate new unique materials.

Data and code availability

All data from this study are available from the lead contact.

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AUTHOR CONTRIBUTIONS

Conceptualization, U.S. and G.P.; methodology, G.P. and P.K.S.; validation, G.P., P.K.S., and U.S.; formal analysis, G.P. and P.K.S.; investigation, G.P. and P.K.S.; resources, U.S.; data curation, G.P. and P.K.S.; writing – original draft, G.P. and U.S.; writing – review & editing, P.K.S., S.N., and U.S.; visualization, G.P.; supervision, U.S. and S.N.; project administration, U.S.; funding acquisition, G.P., S.N., and U.S.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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REFERENCES

- Gigliotti, M., Schmidt-Traub, G., and Bastianoni, S. (2019). The Sustainable Development Goals. *Encyclopedia of Ecology* 4, 426–431. <https://doi.org/10.1016/B978-0-12-409548-9.10986-8>.
- Parisi, G., Szewczyk, P.K., Narayan, S., and Stachewicz, U. (2023). Photoresponsive electrospun fiber meshes with switchable wettability for effective fog water harvesting in variable humidity conditions. *ACS Appl. Mater. Interfaces* 15, 40001–40010. <https://doi.org/10.1021/acsmami.3c07044>.
- Shan, H., Li, C., Chen, Z., Ying, W., Poredoš, P., Ye, Z., Pan, Q., Wang, J., and Wang, R. (2022). Exceptional water production yield enabled by batch-processed portable water harvester in semi-arid climate. *Nat. Commun.* 13, 5406. <https://doi.org/10.1038/s41467-022-33062-w>.
- Parker, A.R., and Lawrence, C.R. (2001). *Water Capture by a desert beetle*. *Nature* 414, 33–34.
- Regalado, C.M., and Ritter, A. (2016). The design of an optimal fog water collector: A theoretical analysis. *Atmos. Res.* 178–179, 45–54. <https://doi.org/10.1016/j.atmosres.2016.03.006>.
- Wang, X., Zeng, J., Yu, X., Liang, C., and Zhang, Y. (2019). Water harvesting method via a hybrid superwetttable coating with superhydrophobic and superhydrophilic nanoparticles. *Appl. Surf. Sci.* 465, 986–994. <https://doi.org/10.1016/j.apsusc.2018.09.210>.
- Jiang, Y., Machado, C., and Park, K.C.K. (2023). From capture to transport: A review of engineered surfaces for fog collection. *Droplet* 2, 1–23. <https://doi.org/10.1002/dro2.55>.
- Knapczyk-Korczak, J., Ura, D.P., Gajek, M., Marzec, M.M., Berent, K., Bernasik, A., Chiverton, J.P., and Stachewicz, U. (2020). Fiber-Based Composite Meshes with Controlled Mechanical and Wetting Properties for Water Harvesting. *ACS Appl. Mater. Interfaces* 12, 1665–1676. <https://doi.org/10.1021/acsmami.9b19839>.
- Wang, J., Guo, Y., Pan, G., Li, Y., Zhang, Y., Yu, H., Zhao, M., Zhao, G., Tang, G., and Liu, Y. (2022). Hybrid wettability surfaces with hydrophobicity and hydrophilicity for fog harvesting. *Colloids Surf. A Physicochem. Eng. Asp.* 650, 129555. <https://doi.org/10.1016/j.colsurfa.2022.129555>.
- Knapczyk-Korczak, J., and Stachewicz, U. (2021). Biomimicking spider webs for effective fog water harvesting with electrospun polymer fibers. *Nanoscale* 13, 16034–16051. <https://doi.org/10.1039/d1nr05111c>.
- Cao, M., Xiao, J., Yu, C., Li, K., and Jiang, L. (2015). Hydrophobic/Hydrophilic Cooperative Janus System for Enhancement of Fog Collection. *Small* 11, 4379–4384. <https://doi.org/10.1002/smll.201500647>.
- Xu, J., Li, T., Yan, T., Wu, S., Wu, M., Chao, J., Huo, X., Wang, P., and Wang, R. (2021). Ultrahigh solar-driven atmospheric water production enabled by scalable rapid-cycling water harvester with vertically aligned nanocomposite sorbent. *Energy Environ. Sci.* 14, 5979–5994. <https://doi.org/10.1039/d1ee01723c>.
- Li, T., Yan, T., Wang, P., Xu, J., Huo, X., Bai, Z., Shi, W., Yu, G., and Wang, R. (2023). Scalable and efficient solar-driven atmospheric water harvesting enabled by bidirectionally aligned and hierarchically structured nanocomposites. *Nat. Water* 1, 971–981. <https://doi.org/10.1038/s44221-023-00150-0>.
- Parisi, G., Szewczyk, P.K., Narayan, S., Ura, D.P., Knapczyk-Korczak, J., and Stachewicz, U. (2024). Multifunctional Piezoelectric Yarns and Meshes for Efficient Fog Water Collection, Energy Harvesting, and Sensing. *Small Science* 4. <https://doi.org/10.1002/ssmc.202400021>.
- Xue, J., Wu, T., Dai, Y., and Xia, Y. (2019). Electrospinning and electrospun nanofibers: Methods, materials, and applications. *Chem. Rev.* 119, 5298–5415. <https://doi.org/10.1021/acs.chemrev.8b00593>.
- Yu, Y., Cui, W., Song, L., Liao, Q., Ma, K., Zhong, S., Yue, H., and Liang, B. (2022). Design of Organic-Free Superhydrophobic TiO₂ with Ultraviolet Stability or Ultraviolet-Induced Switchable Wettability. *ACS Appl. Mater. Interfaces* 14, 9864–9872. <https://doi.org/10.1021/acsmami.1c24083>.
- Szewczyk, P.K., Busolo, T., Kar-Narayan, S., and Stachewicz, U. (2023). Wear-Resistant Smart Textiles Using Nylon-11 Triboelectric Yarns. *ACS Appl. Mater. Interfaces* 15, 56575–56586. <https://doi.org/10.1021/acsmami.3c14156>.
- Moradi, A., Szewczyk, P.K., and Stachewicz, U. (2023). Bridging a Gap in Thermal Conductivity and Heat Transfer in Hybrid Fibers and Yarns via Polyimide and Silicon Nitride Composites. *Small* 19, e2305104–e2305110. <https://doi.org/10.1002/smll.202305104>.
- Busolo, T., Szewczyk, P.K., Nair, M., Stachewicz, U., and Kar-Narayan, S. (2021). Triboelectric Yarns with Electrospun Functional Polymer Coatings for Highly Durable and Washable Smart Textile Applications. *ACS Appl. Mater. Interfaces* 13, 16876–16886. <https://doi.org/10.1021/acsmami.1c00983>.
- Szewczyk, P.K., Berniak, K., Knapczyk-Korczak, J., Karbowniczek, J.E., Marzec, M.M., Bernasik, A., and Stachewicz, U. (2023). Mimicking natural electrical environment with cellulose acetate scaffolds enhances collagen formation of osteoblasts. *Nanoscale* 15, 6890–6900. <https://doi.org/10.1039/d3nr00014a>.
- Szewczyk, P.K., Kopacz, M., Krysiak, Z.J., and Stachewicz, U. (2024). Oil-Infused Polymer Fiber Membranes as Porous Patches for Long-Term Skin Hydration and Moisturization. *Macromol. Mater. Eng.* 309, 1–8. <https://doi.org/10.1002/mame.202300291>.
- Elshennawy, A.A., Abdelaal, M.Y., Hamed, A.M., and Awad, M.M. (2023). Evaluating Mesh Geometry and Shade Coefficient for Fog Harvesting Collectors. *Water Resour. Manage.* 37, 6107–6126. <https://doi.org/10.1007/s11269-023-03644-4>.
- Huang, G., Xu, H., Jin, Y., Huo, L., Zhao, J., and Li, Z. (2021). Electrospun Janus fabrics with directional water transport property for efficient water collection. *Mater. Lett.* 289, 129424. <https://doi.org/10.1016/j.matlet.2021.129424>.
- Knapczyk-Korczak, J., Szewczyk, P.K., and Stachewicz, U. (2021). The importance of nanofiber hydrophobicity for effective fog water collection. *RSC Adv.* 11, 10866–10873. <https://doi.org/10.1039/d1ra00749a>.
- Knapczyk-Korczak, J., Zhu, J., Ura, D.P., Szewczyk, P.K., Gruszczyński, A., Benker, L., Agarwal, S., and Stachewicz, U. (2021). Enhanced Water Harvesting System and Mechanical Performance from Janus Fibers with Polystyrene and Cellulose Acetate. *ACS Sustain. Chem. Eng.* 9, 180–188. <https://doi.org/10.1021/acssuschemeng.0c06480>.
- Knapczyk-Korczak, J., Szewczyk, P.K., Ura, D.P., Berent, K., and Stachewicz, U. (2020). Hydrophilic nanofibers in fog collectors for increased water harvesting efficiency. *RSC Adv.* 10, 22335–22342. <https://doi.org/10.1039/d0ra03939j>.
- Knapczyk-Korczak, J., Szewczyk, P.K., Ura, D.P., Bailey, R.J., Bilotti, E., and Stachewicz, U. (2020). Improving water harvesting efficiency of fog collectors with electrospun random and aligned Polyvinylidene fluoride (PVDF) fibers. *Sustainable Materials and Technologies* 25, e00191. <https://doi.org/10.1016/j.susmat.2020.e00191>.
- Shi, W., Anderson, M.J., Tulkoff, J.B., Kennedy, B.S., and Boreyko, J.B. (2018). Fog harvesting with harps. *ACS Appl. Mater. Interfaces* 10, 11979–11986. <https://doi.org/10.1021/acsmami.7b17488>.

29. Kowalski, N.G., Shi, W., Kennedy, B.S., and Boreyko, J.B. (2021). Optimizing fog harps. *ACS Appl. Mater. Interfaces* 13, 38826–38834. <https://doi.org/10.1021/acsmi.1c08995>.
30. Kowalski, N.G., and Boreyko, J.B. (2022). Dynamics of fog droplets on a harp wire. *Soft Matter* 18, 7148–7158. <https://doi.org/10.1039/d2sm00674j>.
31. Yin, K., Du, H., Dong, X., Wang, C., Duan, J.A., and He, J. (2017). A simple way to achieve bioinspired hybrid wettability surface with micro/nanopatterns for efficient fog collection. *Nanoscale* 9, 14620–14626. <https://doi.org/10.1039/c7nr05683d>.
32. Parisi, G., and Narayan, S. (2021). Using a fluorine-free copper mesh with dynamically tunable wetting properties for high-flux separation of oil-water mixtures. *Journal of Water Process Engineering* 44, 102365. <https://doi.org/10.1016/j.jwpe.2021.102365>.
33. Song, J., Shi, R., Bai, X., Algadi, H., and Sridhar, D. (2023). An overview of surface with controllable wettability for microfluidic system, intelligent cleaning, water harvesting, and surface protection. *Adv. Compos. Hybrid Mater.* 6, 22. <https://doi.org/10.1007/s42114-022-00603-2>.
34. Parisi, G., and Narayan, S. (2022). A fluorine-free customizable membrane using sintered copper for oil/water and surfactant-stabilized water-in-oil emulsion separation. *Chemical Engineering and Processing - Process Intensification* 181, 109165. <https://doi.org/10.1016/j.cep.2022.109165>.
35. Qu, M., Liu, L., Liu, Q., Li, J., Yang, C., Yang, X., Li, K., Liu, X., and He, J. (2021). Highly stable superamphiphobic material with ethanol-triggered switchable wettability for high-efficiency on-demand oil–water separation. *J. Mater. Sci.* 56, 2961–2978. <https://doi.org/10.1007/s10853-020-05418-4>.
36. Parisi, G., Lopez, A., and Narayan, S. (2023). A dynamically responsive surface with switchable wettability for efficient evaporation and self-cleaning abilities. *ACS Appl. Eng. Mater.* 1, 408–416. <https://doi.org/10.1021/acsaenm.2c00097>.
37. Parisi, G., Wang, X., Hwang, Y., and Narayan, S. (2024). Assessing the Performance of a Thermoresponsive Liquid-Based Smart Windows for Building Thermal Regulation through Outdoor Experimentation and Computational Modeling. *Adv. Sustain. Syst.* 1–12. <https://doi.org/10.1002/advs.202400237>.
38. Dong, P., Huang, Z., Nie, X., Cheng, X., Jin, Z., and Zhang, X. (2019). Plasma enhanced decoration of nc-TiO₂ on electrospun PVDF fibers for photocatalytic application. *Mater. Res. Bull.* 111, 102–112. <https://doi.org/10.1016/j.materresbull.2018.11.007>.
39. Liu, H., Zhang, L., Huang, J., Mao, J., Chen, Z., Mao, Q., Ge, M., and Lai, Y. (2022). Smart surfaces with reversibly switchable wettability: Concepts, synthesis and applications. *Adv. Colloid Interface Sci.* 300, 102584. <https://doi.org/10.1016/j.cis.2021.102584>.
40. Li, H., Zhang, Z., Ren, Z., Chen, Y., Huang, J., Lei, Z., Qian, X., Lai, Y., and Zhang, S. (2023). A quadruple biomimetic hydrophilic/hydrophobic Janus composite material integrating Cu(OH)₂ micro-needles and embedded bead-on-string nanofiber membrane for efficient fog harvesting. *Chem. Eng. J.* 455, 140863. <https://doi.org/10.1016/j.cej.2022.140863>.
41. Guo, Y., Li, Y., Zhao, G., Zhang, Y., Pan, G., Yu, H., Zhao, M., Tang, G., and Liu, Y. (2023). Patterned hybrid wettability surfaces for fog harvesting. *Langmuir* 39, 4642–4650. <https://doi.org/10.1021/acs.langmuir.2c03432>.
42. Lee, S.J., Ha, N., and Kim, H. (2019). Superhydrophilic-Superhydrophobic Water Harvester Inspired by Wetting Property of Cactus Stem. *ACS Sustain. Chem. Eng.* 7, 10561–10569. <https://doi.org/10.1021/acssuschemeng.9b01113>.
43. Karbownik, J.E., Berniak, K., Knapczyk-Korczak, J., Williams, G., Bryant, J.A., Nikoi, N.D., Banzhaf, M., de Cogan, F., and Stachewicz, U. (2023). Strategies of nanoparticles integration in polymer fibers to achieve antibacterial effect and enhance cell proliferation with collagen production in tissue engineering scaffolds. *J. Colloid Interface Sci.* 650, 1371–1381. <https://doi.org/10.1016/j.jcis.2023.07.066>.
44. Galiano, F., Song, X., Marino, T., Boerrigter, M., Saoncella, O., Simone, S., Faccini, M., Chaumette, C., Dioli, E., and Figoli, A. (2018). Novel photocatalytic PVDF/Nano-TiO₂ hollow fibers for Environmental remediation. *Polymers* 10, 1–20. <https://doi.org/10.3390/polym10101134>.
45. Yu, Z., Li, S., Liu, M., Zhu, R., Yu, M., Dong, X., Sun, Y., and Fu, S. (2022). A dual-biomimetic knitted fabric with a manipulable structure and wettability for highly efficient fog harvesting. *J. Mater. Chem. A Mater.* 10, 304–312. <https://doi.org/10.1039/d1ta08295g>.
46. Azeem, M., Noman, M.T., Petru, M., Shahid, M., Khan, M.Q., and Wiener, J. (2022). Surface wettability of vertical harps for fog collection. *Surface. Interfac.* 30, 101842. <https://doi.org/10.1016/j.surfint.2022.101842>.
47. Guo, J., Huang, W., Guo, Z., and Liu, W. (2022). Design of a Venation-like Patterned Surface with Hybrid Wettability for Highly Efficient Fog Harvesting. *Nano Lett.* 22, 3104–3111. <https://doi.org/10.1021/acs.nanolett.2c00488>.
48. Zhu, R., Liu, M., Hou, Y., Zhang, L., Li, M., Wang, D., Wang, D., and Fu, S. (2020). Biomimetic Fabrication of Janus Fabric with Asymmetric Wettability for Water Purification and Hydrophobic/Hydrophilic Patterned Surfaces for Fog Harvesting. *ACS Appl. Mater. Interfaces* 12, 50113–50125. <https://doi.org/10.1021/acsmi.0c12646>.
49. Sakai, N., Fujishima, A., Watanabe, T., and Hashimoto, K. (2003). Quantitative evaluation of the photoinduced hydrophilic conversion properties of TiO₂ thin film surfaces by the reciprocal of contact angle. *J. Phys. Chem. B* 107, 1028–1035. <https://doi.org/10.1021/jp022105p>.
50. Dai, X., Sun, N., Nielsen, S.O., Stogin, B.B., Wang, J., Yang, S., and Wong, T.-S. (2018). Hydrophilic directional slippery rough surfaces for water harvesting. *Sci. Adv.* 4, eaa0919–10. <https://doi.org/10.1126/sciadv.aag0919>.
51. Balaur, E., MacAk, J.M., Taveira, L., and Schmuki, P. (2005). Tailoring the wettability of TiO₂ nanotube layers. *Electrochem. Commun.* 7, 1066–1070. <https://doi.org/10.1016/j.elecom.2005.07.014>.
52. Wu, J., Zhang, L., Wang, Y., and Wang, P. (2017). Efficient and anisotropic fog harvesting on a hybrid and directional surface. *Adv. Mater. Interfaces* 4, 1–7. <https://doi.org/10.1002/admi.201600801>.
53. Shi, W., van der Sloop, T.W., Hart, B.J., Kennedy, B.S., and Boreyko, J.B. (2020). Harps Enable Water Harvesting under Light Fog Conditions. *Adv. Sustain. Syst.* 4, 1–10. <https://doi.org/10.1002/advs.202000040>.
54. Shi, W., De Koninck, L.H., Hart, B.J., Kowalski, N.G., Fugaro, A.P., Van Der Sloop, T.W., Ott, R.S., Kennedy, B.S., and Boreyko, J.B. (2020). Harps under heavy fog conditions: Superior to meshes but prone to tangling. *ACS Appl. Mater. Interfaces* 12, 48124–48132. <https://doi.org/10.1021/acsmi.0c12329>.
55. Shi, Z., Liu, L., Chen, H., Tang, C., Yu, J., and Fan, Y. (2024). Preparation of Janus film for fog water collection via layer-by-layer assembling of nanocellulose and nanochitin on PLA. *Carbohydr. Polym.* 323, 121369. <https://doi.org/10.1016/j.carbpol.2023.121369>.
56. Wang, Y., Zhou, Y., Han, P., Qi, G., Gao, D., Zhang, L., Wang, C., Che, J., Wang, Y., and Tao, S. (2024). Improved Water Collection from Short-Term Fog on a Patterned Surface with Interconnected Microchannels. *Environ. Sci. Technol.* 58, 3812–3822. <https://doi.org/10.1021/acs.est.3c09504>.
57. Liu, S., Sun, C., Zhang, K., Geng, Y., Yu, D., and Wang, C. (2024). Fog collection efficiency of superhydrophobic surfaces with different water adhesion prepared by laser grid texturing. *Opt. Laser Technol.* 172, 110523. <https://doi.org/10.1016/j.optlastec.2023.110523>.
58. Yang, D., Ramu, A.G., and Choi, D. (2024). Multifunctional integrated pattern for enhancing fog harvesting water unidirectional transport in a heterogeneous pattern. *NPJ Clean Water* 7, 20. <https://doi.org/10.1038/s41545-024-00317-6>.
59. Qi, B., Yang, X., and Wang, X. (2022). Ultraslippery/hydrophilic patterned surfaces for efficient fog harvest. *Colloids Surf. A Physicochem. Eng. Asp.* 640, 128398. <https://doi.org/10.1016/j.colsurfa.2022.128398>.
60. Sun, R., Zhao, J., Liu, C., Yu, N., Mo, J., Pan, Y., and Luo, D. (2022). Design and optimization of hybrid superhydrophobic–hydrophilic pattern surfaces for improving fog harvesting efficiency. *Prog. Org. Coat.* 171, 107016. <https://doi.org/10.1016/j.porgcoat.2022.107016>.
61. Gao, S., and Wang, Z. (2023). Capture fog for clean water. *Nat. Sustain.* 6, 1514–1515.
62. Vass, P., Szabó, E., Domokos, A., Hirsch, E., Galata, D., Farkas, B., Démuth, B., Andersen, S.K., Vigh, T., Verreck, G., et al. (2020). Scale-up of electrospinning technology: Applications in the pharmaceutical industry. *WIREs Nanomedicine and Nanobiotechnology* 12, e1611. <https://doi.org/10.1002/wnan.1611>.