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Evaporation-Driven Electricity Generation Using Nanocarbon-Coated Fabrics

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ABSTRACT

The growing environmental impact of fossil fuel consumption highlights the need for renewable and eco-friendly energy sources. In this study, we investigated evaporation-driven electricity generation using fabrics coated with nanocarbon materials, carbon black (CB), multi-walled carbon nanotubes (MWCNTs), and graphene nanoplatelets (GNPs). When a water droplet was introduced onto one side of the coated fabric, capillary-driven ion transport through the nanocarbon coating generated a measurable voltage. CB-coated fabric produced the highest and most sustained voltage, reaching a peak of 0.308 V at 100 s and remaining measurable up to 2000 s. MWCNT-coated fabric produced a peak voltage of 0.080 V with a response duration of approximately 500 s. GNP-coated and uncoated bare fabrics showed negligible voltage responses over a 250 s measurement period. As a proof-of-concept demonstration, four CB-coated fabric pieces were connected in series, producing a combined voltage of 2.252 V that was sufficient to power a battery-free pocket calculator. These results indicate that CB-coated fabrics have potential as a simple and low-cost platform for evaporation-driven electricity generation.

Keywords: Water cycle; evaporation; capillary flow; nanocarbons; coating; electricity generation

INTRODUCTION

As the impacts of fossil fuel usage intensify global warming and climate change, the need for renewable energy and eco-friendly energy source has become increasingly clear (1). Although solar power, wind power, and hydropower represent leading clean energy sources, building the large-scale infrastructure needed to use them widely remains a significant challenge (2-4). This motivates the exploration of simpler, small-scale approaches to renewable energy generation. Water evaporation, a continuous process driven entirely by solar energy, remains an underexplored source for electricity generation.

Evaporation is driven by surface molecules overcoming intermolecular forces to transition into the vapor phase. In porous materials, this process induces capillary flow as water is continuously drawn through the pore network to replace evaporated molecules (5, 6). In aqueous systems, dissolved ions, primarily H^+ (H_3O^+) and OH^-, are transported along this capillary flow path. The directional movement of these ions through the negatively charged surfaces of a conductive coating generates a streaming potential, driving a corresponding electron flow through the conductive network and producing a measurable electrical current (7).

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Three material properties are critical for effective evaporation-driven electricity generation: electrical conductivity, surface area, and coating stability. Electrical conductivity is essential to support electron flow. Although uncoated bare fabric has a porous structure that supports capillary flow, it cannot generate measurable electricity due to its insulating nature. High surface area enhances ion transport at the material interface, while coating stability ensures uniform coverage of the fabric fibers and maintains the integrity of the conductive network. Nanocarbon materials are strong candidates for this application because they are highly conductive, possess large surface areas, and their negatively charged surfaces facilitate ion transport near the material interface (8).

In this study, we coated fabrics with three nanocarbon materials, carbon black (CB), multi-walled carbon nanotubes (MWCNTs), and graphene nanoplatelets (GNPs), and evaluated their performance in evaporation-driven electricity generation. We hypothesize that fabrics coated with nanocarbon materials will generate measurable voltage during evaporation-driven capillary flow, and that the magnitude and duration of this voltage will differ among materials depending on their conductivity, surface area, and coating uniformity.

METHODS AND MATERIALS

Materials

In this study, we used carbon black (CB, KB Chemical, CAS No.1333-86-4), graphene nanoplatelets (GNP, Sigmaaldrich, SKU900413), multi-walled carbon nanotubes (MWCNT, Sigmaaldrich, SKU755125), Sodium dodecylbenzenesulfonate (DDBS, Sigmaaldrich, SKU289957), conical tubes (BioLab, SPL50050), glass vials (LK Lab, Model 986541), a tip sonicator(Sonics US, Model Vibracell VCX500), and fabric pieces (Chungage, S-001). Ultrapure deionized (DI) water (18.2 MΩ·cm resistivity) was obtained from a Direct-Q3 system (Millipore Inc.) and used throughout all experiments.

Methods

To prepare the CB coating solution, a 10 wt% surfactant solution was first prepared by mixing DDBS with tertiary distilled water. Then, 0.03 g, (2.5 mmol) of CB was added into a conical tube, followed by 1.5 g (0.43 mmol) of the prepared surfactant solution and 13.47 g (747 mmol) of DI water to make a total mass of 15 g. The GNP and MWCNT coating solutions were prepared using the same method and mass ratios.

After preparation, the coating solutions were transferred into 20 mL glass vials. The ultrasonic disperser tip was cleaned by running it in a vial containing DI water. Each coating solution was then processed for 10 minutes using the tip sonicator, with the tip cleaned between each sample.

After sonication, the solutions were allowed to cool and transferred back into their respective conical tubes. Each fabric piece (2.5 × 1.5 cm) was dipped completely into the coating solution for approximately 10 seconds. Additional loading of carbon materials was achieved by filtering the coating solution through the fabric. Coated fabrics were then dried in an oven at 80°C for 4 hours. Coating uniformity was assessed visually; uniform coatings appeared as homogeneous coloration across the fabric surface, while non-uniform coatings showed patchy or streaked discoloration.

All experiments were conducted indoors at approximately 23°C and 55% relative humidity. To minimize the effect of ambient airflow on evaporation, measurements were performed inside an enclosed cage. After drying, alligator clip electrodes were attached approximately 2 cm apart at both ends of each coated fabric piece, as shown in Figure 1. A single droplet of DI water (approximately 30 μL), dispensed using a 1 mL pipette, was introduced adjacent to one electrode to initiate capillary flow across the fabric surface toward

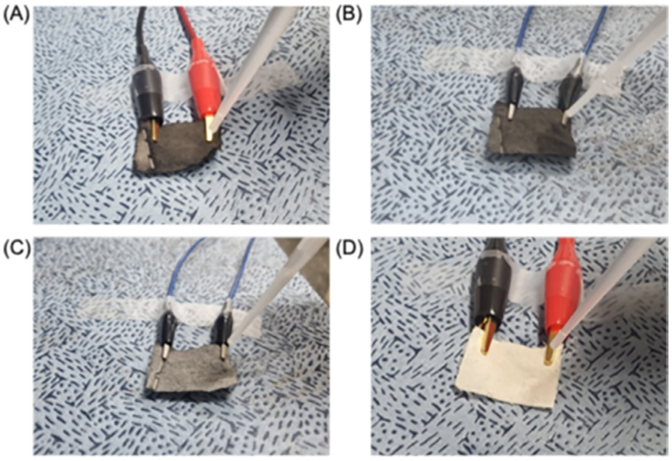

Figure 1. ***Fabric samples with attached electrodes.*** *Carbon-coated and bare fabric specimens with electrodes fixed at both ends: (A) CB-, (B) MWCNT-, (C) GNP-coated, and (D) uncoated (bare) fabric. A 1 mL pipette is used to introduce a single water droplet (approximately 30 μL) adjacent to one electrode on the right side of each sample.*

the opposite electrode. The opposite electrode was connected to the positive terminal of the potentiostat. For the control condition, the same procedure was applied to an uncoated bare fabric. Open-circuit voltage (the voltage measured when no external current flows) and short-circuit current (the current measured when the two electrodes are directly connected) of individual fabric samples were measured using a potentiostat (Ivium-n-stat). The measured voltage and current were shown in Figure 2 and Figure 3. The combined voltage output of the series configuration was measured using a digital multimeter (Hioki CARD HiTESTER 3244-60). Electrical conductivity of the coated fabrics was measured using a four-point probe system (AIT CMT-SR1000N Sheet Resistance System). For the control condition, the same procedure was applied to an uncoated bare fabric.

RESULTS AND DISCUSSION

Three carbon materials, such as CB, MWCNT, and GNP, were applied onto fabric pieces and compared against an uncoated bare fabric as a control, to investigate how the choice of carbon material influences the voltage generation. Each fabric was connected to a circuit via electrodes on both ends, and a single water droplet was introduced adjacent to one electrode to initiate capillary flow and evaporation across the surface. The voltage and current generated by the carbon-coated fabrics were measured over time (Figure 2 and Figure 3). The results showed clear difference depending on the coating materials.

Among all samples, CB demonstrated the best overall performance in terms of both peak voltage and sustained output duration, reaching a peak voltage of 0.308 ± 0.021 V at 100 s and remaining measurable over 2000 s. The current of CB was stable at approximately 0.135 μA throughout the measurement period. MWCNT-coated fabric also generated measurable outputs, with a peak voltage of 0.080 ± 0.022 V and a peak current of approximately 0.825 μA, but both decayed rapidly, returning to near baseline within 500 s. Despite exhibiting a higher electrical conductivity (3.5×10^{-2} S/m) than CB (3.5×10^{-4} S/m), MWCNT produced a lower voltage. This may be because when a material conducts electricity too well, the ions moving through it lose their energy too quickly to generate a measurable voltage. In contrast, the moderate conductivity of CB allows ions to move steadily in one direction, producing a higher and more sustained voltage output. From a practical standpoint, CB therefore demonstrates superior overall performance, as consistent and sustained energy output is more relevant to real-world applications than transient peak values. GNP-coated and uncoated

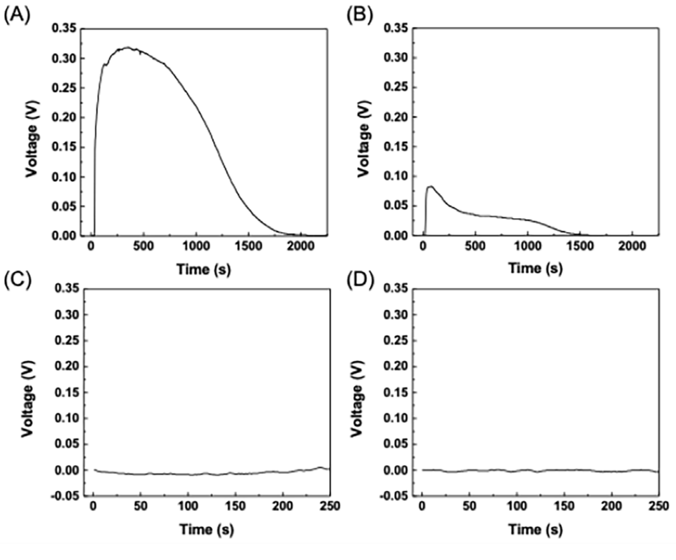

Figure 2. Voltage generated over time for different fabric samples. *Voltage output measured as a function of time for (A) CB-, (B) MWCNT-, (C) GNP-coated, and (D) bare fabric. A representative trial is shown for each material.*

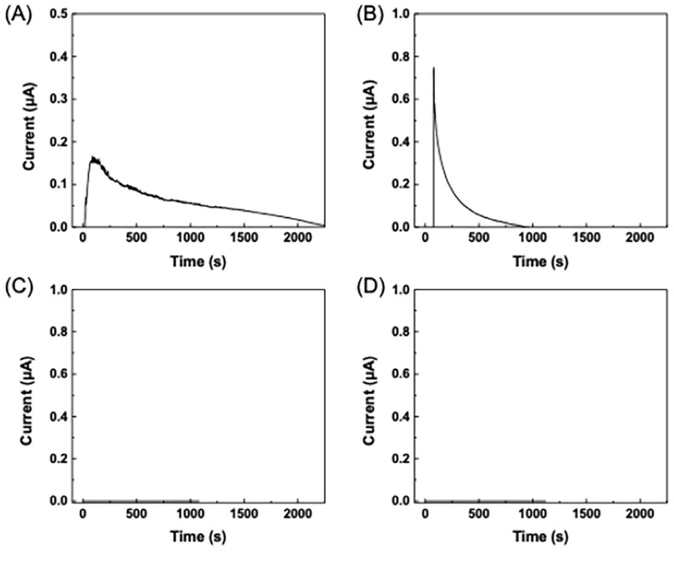

Figure 3. Current generated over time for different fabric samples. *Current output measured as a function of time for (A) CB-, (B) MWCNT-, (C) GNP-coated, and (D) bare fabric. A representative trial is shown for each material.*

bare fabrics remained close to 0 V throughout the measurement period, showing no noticeable voltage or current response. The estimated upper bound of power output, calculated as $P_{est} = V \times I$, was approximately 42 nW for CB and 66 nW for MWCNT at peak values. As voltage and current were measured independently, these values represent upper bound estimates rather than true maximum power output.

GNP-coated fabric showed no measurable electrical conductivity under the same coating conditions, as confirmed by four-point probe measurements. Consequently, GNP-coated and uncoated bare fabrics both produced negligible voltage and current responses throughout the measurement period, confirming that a functional conductive network is essential for evaporation-driven voltage generation.

The differences in voltage generation can be explained by the electrokinetic properties of each material. When a water droplet is introduced, it spreads across the fabric surface through capillary action. As evaporation proceeds, dissolved ions in the water are directionally transported along the capillary flow path through the negatively charged nanocarbon coating. This directional ion movement generates a streaming potential, which drives a corresponding electron flow through the conductive nanocarbon network, producing a measurable voltage (8, 9). This mechanism is consistent with previously reported evaporation-driven hydrovoltaic systems, in which streaming potential arising from directional ion transport through charged nanomaterials has been identified as the primary electricity generation mechanism (8, 9)

The electrical conductivity of the coated fabrics, measured using a four-point probe, was 3.5×10^{-4} S/m for CB and 3.5×10^{-2} S/m for MWCNT. GNP-coated fabric showed no measurable conductivity under the same coating conditions, consistent with its negligible voltage output.

To further explore the potential of CB-coated fabric, four pieces were connected in series. Surprisingly, the combined voltage was enough to power a battery-free calculator (Figure 4A). To measure the exact voltage output, a digital multimeter was connected to the same setup, which showed a reading of 2.252 V (Figure 4B). This was notably higher than simply multiplying the single-piece peak voltage by four, though the exact reason for this is unclear and may be due to variations in experimental conditions. These results suggest that the output of CB-coated fabric can be scaled up, and that it has real potential as a small-scale power source.

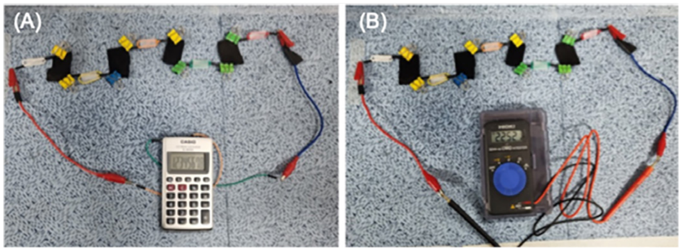

Figure 4. *Demonstration of scaled voltage generation from CB-coated fabric connected in series. (A) Four CB-coated fabric pieces (2.5 × 1.5 cm each) connected in series, with 3-4 water droplets introduced sequentially onto each fabric, successfully powering a battery-free pocket calculator. (B) Combined voltage of 2.252 V measured using a digital multimeter.*

To further explore the scalability of CB-coated fabric, four pieces were connected in series. The four CB-coated fabrics connected in series produced a combined voltage of 2.252 V, which exceeded the theoretical sum of 1.312 V based on single-fabric peak values. This result serves as a proof-of-concept demonstration that connecting multiple CB-coated fabric units in series can increase the combined voltage output. In the series configuration, 3-4 water droplets were introduced sequentially onto each fabric, providing a greater total water supply than the single-droplet condition used in individual measurements, which may have contributed to the higher combined output. The series configuration successfully powered a battery-free pocket calculator (working voltage: 1.5 V), as confirmed by activation of the display and operations (9).

CONCLUSION

This study demonstrated that nanocarbon-coated fabrics can generate measurable evaporation-driven electricity through capillary-driven ion transport. Among the materials tested, CB-coated fabric produced the highest and most sustained voltage of 0.308 ± 0.021 V over 2000 s, along with a stable short-circuit current of approximately 0.135 µA. Although MWCNT-coated fabric generated a higher peak current, its rapid decay and instability limit its practical utility compared to CB. GNP-coated and bare fabrics produced negligible output, confirming that a functional conductive network is essential for voltage generation. When four CB-coated fabrics were connected in series, a combined voltage of 2.252 V was achieved, sufficient to power a battery-free pocket calculator, demonstrating the scalability of this approach. These results suggest that CB-coated fabrics represent a simple, low-cost, and scalable platform for evaporation-driven electricity generation, with potential utility in low-power applications that can make use of the natural water cycle as an energy source.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

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