PAPER-BASED MOIST-ELECTRIC GENERATORS FOR SCALABLE, DISPOSABLE, AND GREEN POWER GENERATION

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ABSTRACT

Our research presents a novel paper-based moist-electric generator (PMEG) for the Internet of Disposable Things (IoDT) that operates by harnessing ambient moisture. This disposable, eco-friendly power source is crafted from micropatternable hydrophilic paper, whose hygroscopicity is significantly enhanced with a blend of bacterial endospores and polyvinylpyrrolidone (PVP), a superhygroscopic polymer. The PMEG demonstrates remarkable electrical performance, producing a steady voltage of approximately 0.42 V at 90% relative humidity, with power densities reaching 2.3 μW/cm². Remarkably, it sustains a voltage of 0.2 V for over 60 hours even at a lower humidity of 40%. The integration of robust endospores, capable of swelling by up to 12% and withstanding environmental stresses, positions our PMEG as a sustainable and durable solution for powering IoDT devices.

KEYWORDS

Moist-electric generators; bacterial endospores; hydroscopic materials; energy harvesting; paper-based devices; Internet of Disposable Things

INTRODUCTION

Our research advances moist-electric generators (MEGs) as prime candidates for powering the Internet of Disposable Things (IoDT) [1], drawing on ambient environmental moisture to provide sustainable, cost-effective, and eco-friendly energy. These devices are particularly suited to IoDT applications given their minimalistic design and small footprint, which favor seamless integration into compact IoT devices. Nonetheless, traditional MEGs fall short for contemporary use due to limited efficiency, manufacturing complexities, and environmental concerns associated with their non-biodegradable inorganic substrates [2, 3].

We introduce an innovative MEG system, leveraging paper's innate hygroscopic properties as a substrate [4]. This system employs a straightforward fabrication method: a chromatography paper is patterned with wax printing and subsequent heat application, creating a defined moisture-absorptive region (Figures 1 & 2). Two screen-printed graphite electrodes encompass this region; the upper electrode features open windows to facilitate moisture uptake, while the lower electrode provides complete coverage, ensuring a stable moisture gradient propelled by the paper's capillarity (Figure 1b).

The novelty lies in augmenting the paper's hygroscopic capacity with a composite of *Bacillus subtilis* endospores embedded in a polyvinylpyrrolidone (PVP)

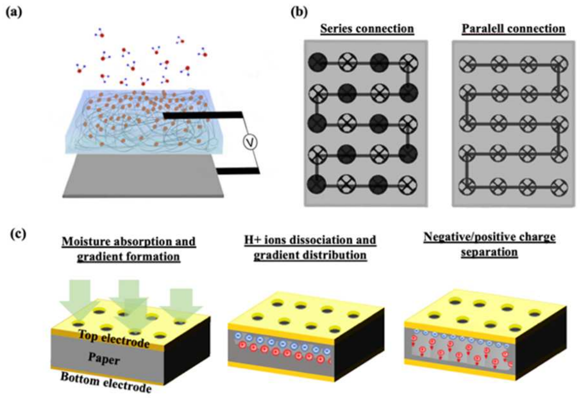

Figure 1: (a) A conceptual illustration of our proposed PMEG for energy harvesting. (b) Schematic diagram depicting the series and parallel connection of the PMEGs. (c) Schematic diagram showing the working mechanism of the moist-enabled power generation in the PMEG.

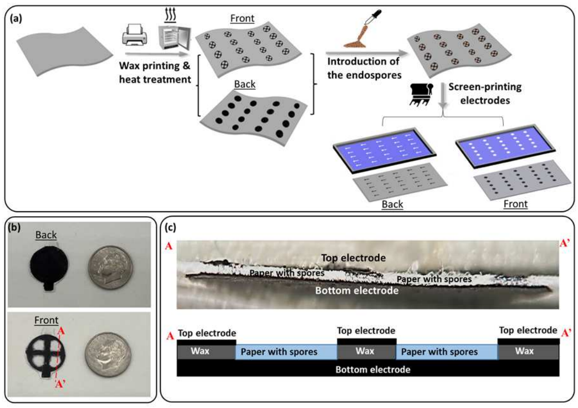

Figure 2: (a) Schematic of the fabrication process, (b) Photos of the front and back of the PMEG unit, (c) Photo and schematic diagram of the cross-section of the PMEG unit (A-A')

matrix. This combination not only bolsters moisture absorption due to the endospores' swelling capability [2] but also leverages their surface charge and proteinaceous functional groups [5]. These attributes aid in the dissociation of protons from water molecules, enhancing the ionization process and resulting in a more pronounced potential difference across the electrodes [6]. The interaction between the endospores' charged surfaces and the PVP further optimizes the moisture-to-electricity conversion efficiency, presenting a substantial leap forward in MEG technology for large-scale, environmentally-conscious applications [7].

Our MEG design promises a leap in performance, aligning with IoDT demands for environmentally responsible, scalable, and potent energy sources. The biological components introduce a groundbreaking approach to moisture electricity generation, setting a new standard for the design and integration of renewable power solutions in disposable electronics.

MATERIALS AND METHODS

Materials

Materials used in the study were sourced as follows: Grade 1 Whatman™ Filter Paper and polyvinylpyrrolidone (PVP) were obtained from Sigma-Aldrich. Graphite ink, product code E3449, was procured from Ercon Inc. The *Bacillus subtilis* strain 168 was supplied by the American Type Culture Collection (ATCC).

Cultivation and sporulation of *B. subtilis*

Bacterial cultures were initiated in Luria Broth (LB) with agitation at 50 rpm, incubated at 37°C for 24 hours. Subsequently, we induced sporulation on nutrient-limited agar plates in line with established methodologies [8, 9]. Mature spores were collected, centrifuged at 4000 rpm for four minutes, and resuspended in sterilized distilled water. A subsequent heat treatment at 80°C for 30 minutes was applied to eliminate any non-sporulated cells. The purified spores were then stored in sealed 15 mL tubes at 4°C for later experimental use.

Fabrication of PMEGs

A detailed electrode pattern was designed using AutoCAD software, and this blueprint was then transposed onto paper using a wax printer [10]. The imprinted design specified the top electrode dimensions as 4 cm by 0.4 cm. Graphite ink was utilized to construct the bottom electrode, measuring 1 cm by 2 cm, optimized for enhanced moisture absorption. Conductive graphite ink was meticulously applied to both electrodes to ensure consistent electrical conductivity throughout the device. The electrodes were screen-printed and a sacrificial mask was used to preserve the device's structural integrity and alignment. The device's architecture was specifically tailored to facilitate top-down moisture ingress, improving operational efficiency. To the paper, a mix of bacterial endospores and 6% PVP was added to enhance hygroscopic properties. Precise 20 µL droplets of the mixture were pipetted onto the system to achieve a homogeneous distribution across the cells.

RESULTS AND DISCUSSION

The microbial coating and structure were meticulously analyzed using Fourier-Transform Infrared Spectroscopy (FTIR) [5]. Samples underwent freeze-drying to ensure moisture did not affect the spectral data, isolating the microbial elements' contribution, as shown in Figure 3a. The spectrum highlights *B. subtilis* main molecular functions and vibrational bands, with crucial surface groups in the far-infrared range. Figure 3b contrasts this with a typical PVP spectrum for clarity. The combined sample's spectrum (Figure 3c) shows both PVP and endospore features, indicating successful integration of these materials.

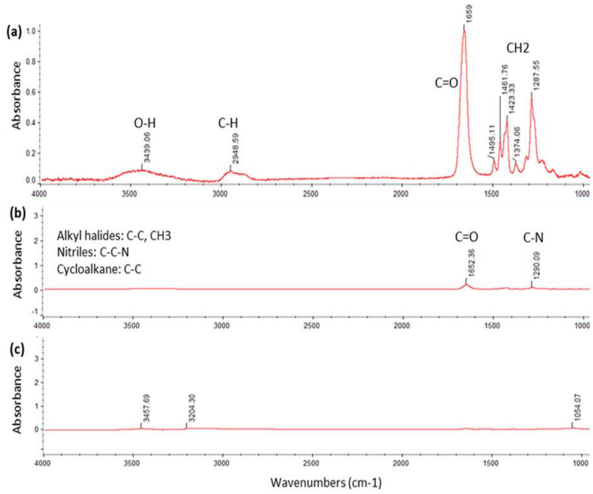

Figure 3: FTIR of (a) PVP, (b) Bacillus subtilis spores, and (c) the mixture of endospores and 6% PVP.

Every single fiber within the top paper reservoir undergoes a meticulous coating process. The top paper reservoir is coated with a mixture of endospores and PVP, ensuring each fiber is tightly encapsulated. This process, shown in Figure 4 via scanning electron microscopy (SEM), results in a coating that limits how deeply the mixture can penetrate the paper due to the diminishing capillary force. This creates a vertical moisture gradient within the paper depth.

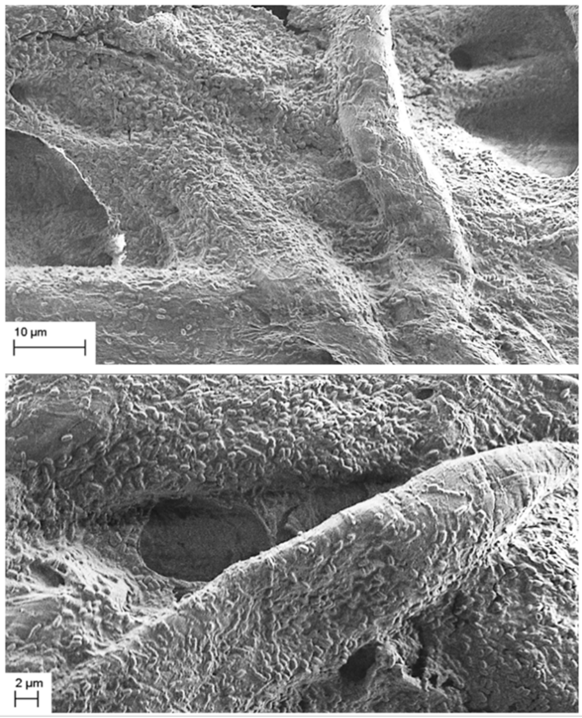

Figure 4: SEM images of the top paper reservoir with Bacillus subtilis endospores coating.

The inclusion of PVP, spores, and a combination of both PVP and spores has shown to significantly boost the voltage output of the PMEG, as depicted in Figure 5a.

However, a complete seal by the top and bottom electrodes prevents voltage generation (Figure 5b) [11, 12]. The output is moist-dependent, with higher relative humidity (RH) enhancing electrical output (Figure 6a). At 88.9% RH, the PMEG reaches a power density of 2.3 μW/cm^2, on par with an equivalently sized MFC, as demonstrated in Figure 6b.

But the capabilities PMEG do not end with a single unit [13, 14]. Its design allows for scalability within the confines of a single paper sheet [15, 16]. Connecting multiple units in series amplifies the electrical output, as seen in Figure 7a. A practical demonstration of this scalability is lighting a digital display with 20 PMEG units, using an external supercapacitor to channel the combined output, as depicted in Figure 7b. This illustrates the PMEG's potential and its practical adaptability.

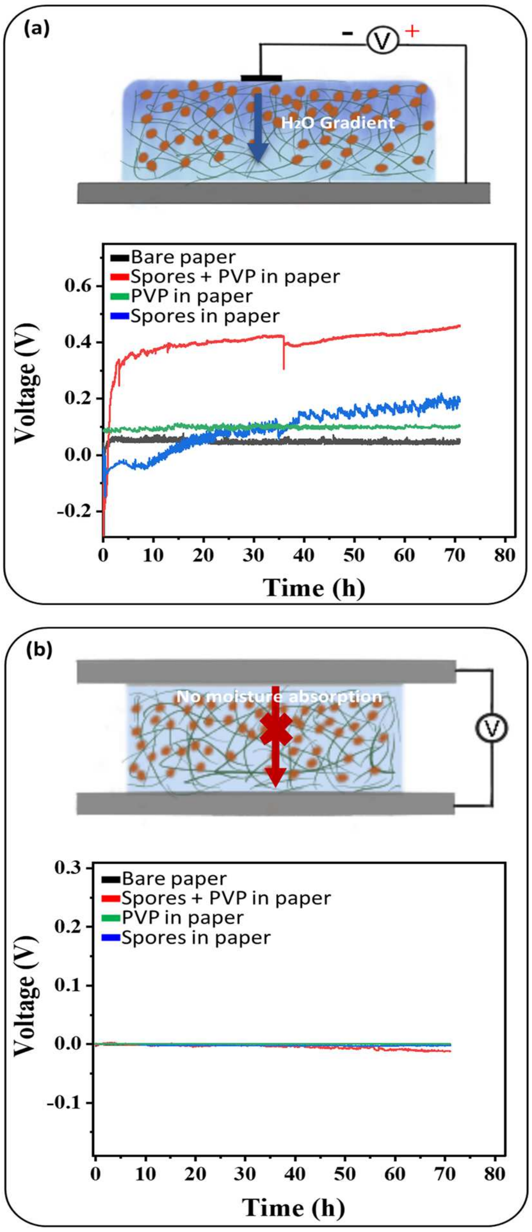

Figure 5: (a) Schematic diagram showing a vertical moisture gradient in our PMEG and its open circuit voltages as a function of time with different materials integrated in the PMEG. The PMEG with a mixture of spores and PVP generates the highest electrical output. (b) Schematic diagram of the PMEG with the top and bottom electrodes sealed and its open circuit voltages. No voltage is generated when the top part of the paper is completely covered by the electrode.

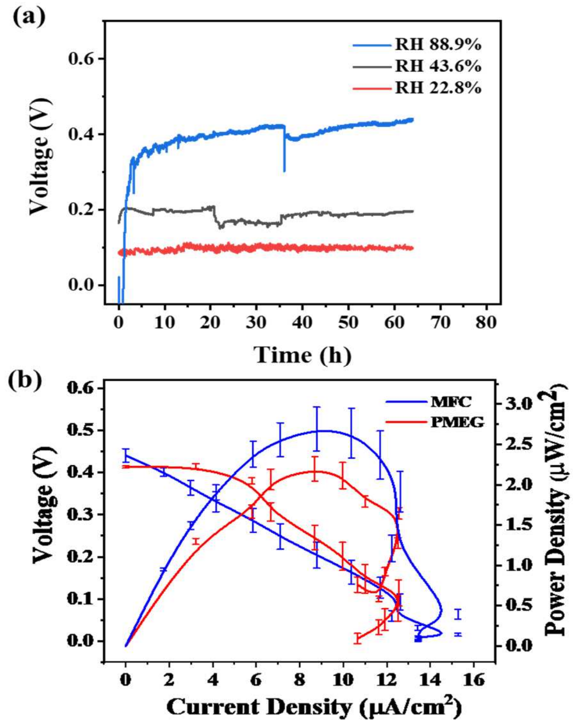

Figure 6: (a) The open circuit voltages generated from the single PMEG at different relative humidity (RH) conditions, (b) Output voltages and power densities as a function of current densities.

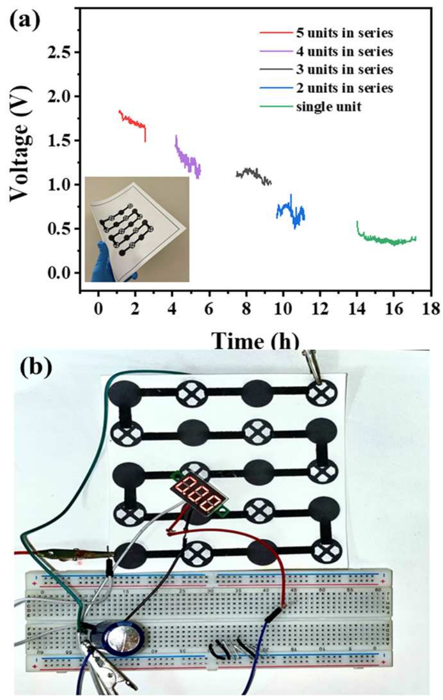

Figure 7: (a) Voltage output of a series of PMEG units with different serial numbers, and (b) a digital display powered by 20 PMEGs.

CONCLUSION

The findings presented herein detail the innovative integration of *Bacillus subtilis* endospores with a paper matrix, establishing a novel hygroelectric device for energy capture from environmental moisture. The developed MEG, constructed from paper, showcases a consistent voltage output of 0.42V and a maximum power density of 2.3μW/cm² at a relative humidity (RH) of approximately 90%. Remarkably, this generator sustains an output of 0.2V across a span exceeding 60 hours, even at a diminished RH of 40%. The strategic amalgamation of bacterial endospores with the highly hygroscopic PVP enhances the durability and operational efficacy of this power-generating system. The design's modularity permits the augmentation of electrical output by arranging multiple units in series or parallel on a singular sheet of paper. Advancing this concept, we have designed and crafted a compact device that generates electricity by leveraging atmospheric moisture. This research heralds the advent of an innovative hygroscopic material poised to revolutionize the field of moisture-driven energy devices.

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