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A New Paradigm on Waste to Energy Applying Hydrovoltaic Energy Harvesting Technology on Face Masks

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Abstract: The widespread use of single-use face masks during the recent epidemic has led to significant environmental challenges due to waste pollution. This study explores an innovative approach to address this issue by repurposing discarded face masks for hydrovoltaic energy harvesting. By coating the face masks with carbon black (CB) to enhance their hydrophilic properties, we developed mask-based hydrovoltaic power generators (MHPGs). These MHPGs were evaluated for their hydrovoltaic performance, revealing that different configurations and sizes of the masks affect their efficiency. The study found that MHPGs with smaller, more structured areas exhibited better energy output, with maximum open-circuit voltages reaching up to 0.39 V and short-circuit currents up to 65.6 μA. The integration of CB improved water absorption and transport, enhancing the hydrovoltaic performance. This research demonstrates the potential of converting waste face masks into a valuable energy source, aligning with circular economy principles and providing a sustainable solution to municipal waste. The findings highlight the feasibility of utilizing discarded masks in energy harvesting systems, offering both environmental benefits and a novel method for renewable energy generation. Therefore, this work provides a new paradigm for waste-to-energy (WTE) technologies and inspires further research into the use of unconventional waste materials for energy production.

Keywords: Energy harvesting; hydrovoltic generator; carbon black coating; face mask recycling; waste-to-energy(WTE)

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1. Introduction

An epidemic disease has drastically altered everyday life, leading to a significant increase in the use of personal protective equipment (PPE), especially face masks [1]. While face masks have been essential in curbing the spread of the virus, their widespread use has resulted in a substantial environmental challenge [2, 3]. The surge in demand for single-use face masks has exacerbated plastic pollution, as these masks are predominantly composed of non-biodegradable materials such as polypropylene [4-6]. This has created

a pressing need for innovative waste management solutions that not only mitigate environmental burdens but also repurpose waste into valuable resources.

Waste-to-energy (WTE) technologies have emerged as a promising avenue for addressing the dual challenges of waste management and renewable energy production. These technologies convert waste materials into usable energy forms, such as electricity, heat, and alternative fuel [7]. Traditional WTE methods include incineration, anaerobic digestion, and gasification, each with its own advantages and limitations [8, 9]. However, the quest for more sustainable and efficient technologies continues, with recent advancements exploring novel materials and processes for energy harvesting. One such novel approach is hydrovoltaic energy harvesting, which harnesses the energy from evaporating water to generate electricity [10, 11]. This method leverages the natural process of water evaporation, which is a continuous and abundant source of energy. By using different kinds of materials that facilitate the evaporation process, it is possible to create systems that convert this energy into electricity [12-14].

For example, Park, et al. [15] present a novel approach to sustainable energy generation using a leaf-inspired energy-harvesting foam (LIEHF) composed of polydimethylsiloxane integrated with conductive carbon materials. The LIEHF can produce an open-circuit voltage (V_{OC}) of 254 mV, a short-circuit current (I_{SC}) of 42 μA, and a power density of 1 μW cm^{-2} under standard sunlight conditions. A honeycomb-structured reduced graphene oxide (rGO) film was well demonstrated for generating electricity through water evaporation [16]. The innovative structure of the rGO film significantly enhances the evaporation-induced output power with its abundant interconnected microchannels providing a larger specific surface area and superior ion-exchange capacity. This generator was capable of stable performance over 240 hours, delivering a stable V_{OC} of approximately 0.83 V with a power density of 0.79 μW cm^{-2}. Additionally, typical bio-based materials such as wood can be chemically treated to achieve a highly porous structure [17]. Despite its current limitation of maintaining high voltage for only 2-3 hours, the wood power generator can produce a potential of up to 1.0 V and a power output of 1.35 μW cm^{-2}. Porous carbon film has also demonstrated the significant role of carbon materials in evaporation-driven flow, generating a sustainable voltage of approximately 1.0 V with a power density of approximately 8.1 μW cm^{-3} under ambient conditions [18]. The authors have highlighted further application potentials of the device, such as electrodeposition, water splitting, and pollutant degradation, making it low-cost and environmentally friendly.

In this work, we explored the potential of using discarded face masks as a key material in a hydrovoltaic energy harvesting system by investigating the feasibility and efficiency. The choice of discarded face masks is both timely and innovative. To date, there has been limited research on the use of face masks in energy harvesting applications. Most studies have focused on the environmental impact of face mask waste or their potential for recycling into new materials [19-22]. Given the sheer volume of face mask waste generated globally, repurposing these masks into an energy harvesting system addresses multiple issues simultaneously. It provides a method for reducing plastic pollution, offers a new source of renewable energy, and adds value to what would otherwise be considered waste. This aligns with the principles of a circular economy, where waste materials are reintegrated into the production cycle, minimizing waste and optimizing resource use. The significance of this research lies in its potential to provide a sustainable solution to a pressing environmental problem. By transforming discarded face masks into a source of renewable energy, this study not only addresses the issue of plastic pollution but also contributes to the diversification of energy sources.

2. Materials and Methods

2.1. Materials

Single-use disposable face masks were obtained as commercial products. Carbon black powder (CB) was obtained from Mitsubishi Chemical Co., Ltd., Japan. To uniformly disperse the CB in deionized (DI) water, cetyl trimethyl ammonium bromide (CTAB), purchased from Tokyo Chemical Industry Co., Ltd., Japan, was used. To fill the nanochannels with the ion solution for electricity generation, lithium chloride (LiCl, ≥ 99.98%) powders were purchased from Sigma-Aldrich Co., Ltd. An adhesive copper foil tape for electrode connection of the generators was purchased from Teraoka Seisakusho Co., Ltd., Japan.

2.2. Preparations of mask-based hydrovoltaic power generator (MHPG)

To prepare CB coating solution, 5.0 g of CB was dispersed in 800 ml of DI water with 10.0 g of CTAB. The CB solution was then mixed via sonication for 60 min to uniformly disperse. To fabricate mask-based hydrovoltaic power generators (MHPGs), single-use disposable face masks with eliminated the elastic ear loops and metal strips were dip-coated in the CB solution and then dried in a 90°C oven (SH Scientific Co., Ltd., Korea) for 2 hours. After that, two pieces of adhesive copper foil tape were connected to each end of the CB-coated face mask and MHPGs were eventually prepared. To investigate the characterizations of MHPGs, scanning field emission electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) (JSM-7100F, JEOL Co., Ltd., Japan), as well as Fourier-transform infrared spectroscopy (FT-IR, Spectrum Two, PerkinElmer Inc., USA) were utilized.

2.3. Electrical output performance by different features

Due to the hydrovoltaic generation performances are dependent on the generator heights, widths and thicknesses, different features and shapes of MHPGs were designated as summarized in Table 1. A typical deliquescent chemical, 3 M of lithium chloride (LiCl) solution, was used as liquid source of hydrovoltaic energy harvesting. The generation performances, including open-circuit voltage and short-circuit current curves, were measured using a Keithley 2400 source meter (Keithley Instruments, Inc., USA). at 23°C and a relative humidity of 40%.

Table 1. Different features and shapes of MHPGs designated from a piece of single-use face mask.

Types	Definitions	Sizes
MHPG-1	Original mask form	97 × 170 × 0.24 mm^3
MHPG-2	Equally cut in 2 pieces and put together	97 × 85 × 0.48 mm^3
MHPG-3	Equally cut in 3 pieces and put together	97 × 57 × 0.72 mm^3
MHPG-4	Cut in half of unfolded mask and roll together	75 mm × 1.47 mm^2

3. Results and Discussion

3.1. Characterizations of MHPGs

Single-use face masks for MHPGs were fabricated following the experimental process shown in Fig. 1a. In this work, four different features and shapes of MHPGs (*i.e.*, MHPG-1, MHPG-2, MHPG-3, and MHPG-4) were examined, as illustrated in Fig. 1b. The surface of the single-use face mask was observed to verify its disordered fibrous structure, with fiber diameters ranging from 20.0 to 23.5 μm, as shown in the SEM image (Fig. 1c). Due to the application of CTAB, a uniform distribution of CB on the mask surface was discovered. As shown in Fig. 1d, nano-sized CB powder aggregated on the polypropylene fibers, offering a larger specific surface area compared to the non-coated (raw) face mask. In the hydrovoltaic energy harvesting system, CB plays an important role in enhancing the hydrophilic characteristics within the microchannels of the face mask. With its abundant capillary structure and high surface-area-to-volume ratio, the face mask with CB permits better water absorption and transport abilities. Additionally, MHPGs exhibit good

flexibility, as they can be repeatedly bent and stretched back to their original shape without cracking or crumbling (Fig. 1e). Thus, the mechanical properties of MHPG further confirm its reliability as an energy harvesting device.

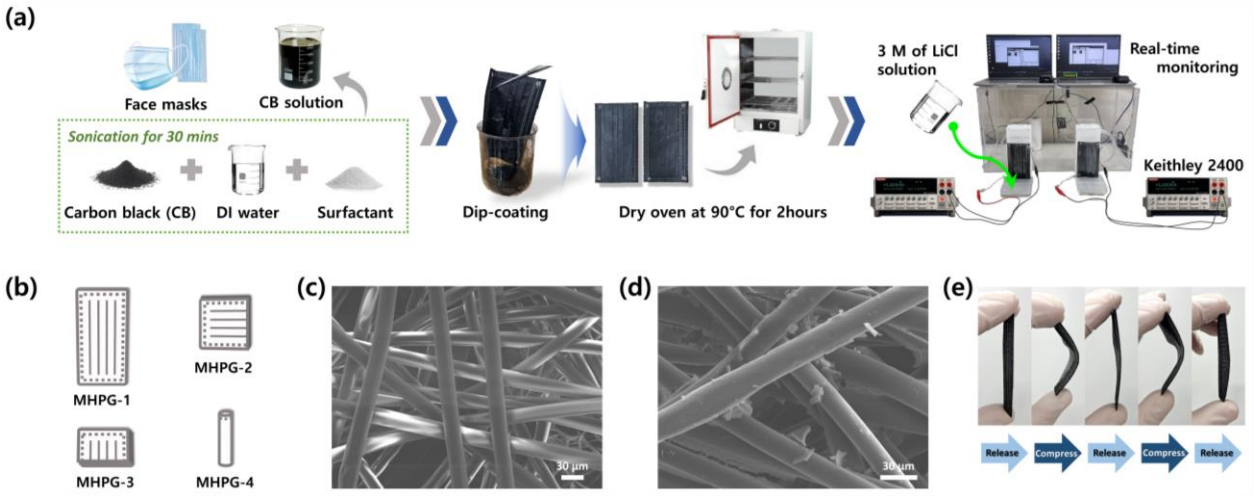


Figure 1. Fabrication of MHPG and its characterizations. **(a)** Schematic diagram of the MHPG preparation; **(b)** Four different types of MHPG designated from single face mask; The morphologies of **(c)** non-coated (raw) face mask and **(d)** CB-coated face mask (MHPG); **(e)** The mechanical stability and flexibility test of MHPG.

The surface modification of the face mask was further confirmed by FT-IR spectra. As shown in Fig. 2b, the absorption peak at 2950 cm^{-1} corresponding to the stretching vibration of carboxylic acid -OH was significantly enhanced due to the CB coating process on the mask surface. This can contribute to increasing the hydrophilic property of MHPG, ensuring a continuous water transport and evaporation for the energy harvesting. The absorption peak at 2917 cm^{-1} and the absorption peak at 2836 cm^{-1} on curves of both raw face mask and MHPG were respectively attributed to C-H alkane and C-H aldehyde. As signature peaks of polypropylene, the absorption peaks at 1453 cm^{-1} and 1375 cm^{-1} corresponding to the functional group of $-CH_3$ could be found on both curves. Additionally, there was an increasing absorption peak at 1167 cm^{-1} (C-O-C) attributed to carbon black powder on the surface of MHPG. The uniform distribution of CB on MHPG was clearly apparent with EDS patterns examined through Fig. 1c and 1d. According to Fig. 2c, it was evident that the element of carbon (C, red) is evenly dispersed on the surface of the face mask at the nanometer level due to the polypropylene composition of the mask filter. Although the additional carbon (C, red) from the CB is indistinguishable from the polypropylene microfibers, the well-distribution of CB can be verified by the presence of bromine (Br, green) owing to the mixture of CTAB in the CB solution (Fig. 2d).

3.2. Electrical performances by different features

Following the general energy harvesting principle and generation mechanism, the bottom electrode of MHPG was immersed in a liquid. In this work, a typical deliquescent chemical, the LiCl solution was applied rather than DI water. There are mainly four principal mechanisms for hydrovoltaic conversion including streaming potential, electron drag effect, pseudostreaming mechanism and ion gradient diffusion, and those mechanisms are known to co-exist simultaneously [23]. When water is deliberately injected or absorbed from the moist air into the hydrovoltaic energy harvesting generator, electrokinetic phenomena occur due to the movement of charged ions through a liquid electrolyte flowing over the capillary channel. At this moment, ion solutions such as sodium chloride (NaCl), calcium chloride ($CaCl_2$) and hydrochloric acid (HCl) can improve the electricity generation outputs better than DI water [24, 25]. Similar to the roots of plants, the water

is absorbed from one end of the MHPG follows the capillary channel (Fig. 3a). Water evaporation then occurs at the other end of the MHPG, generating electricity owing to the potential difference between the wet and dry sides.

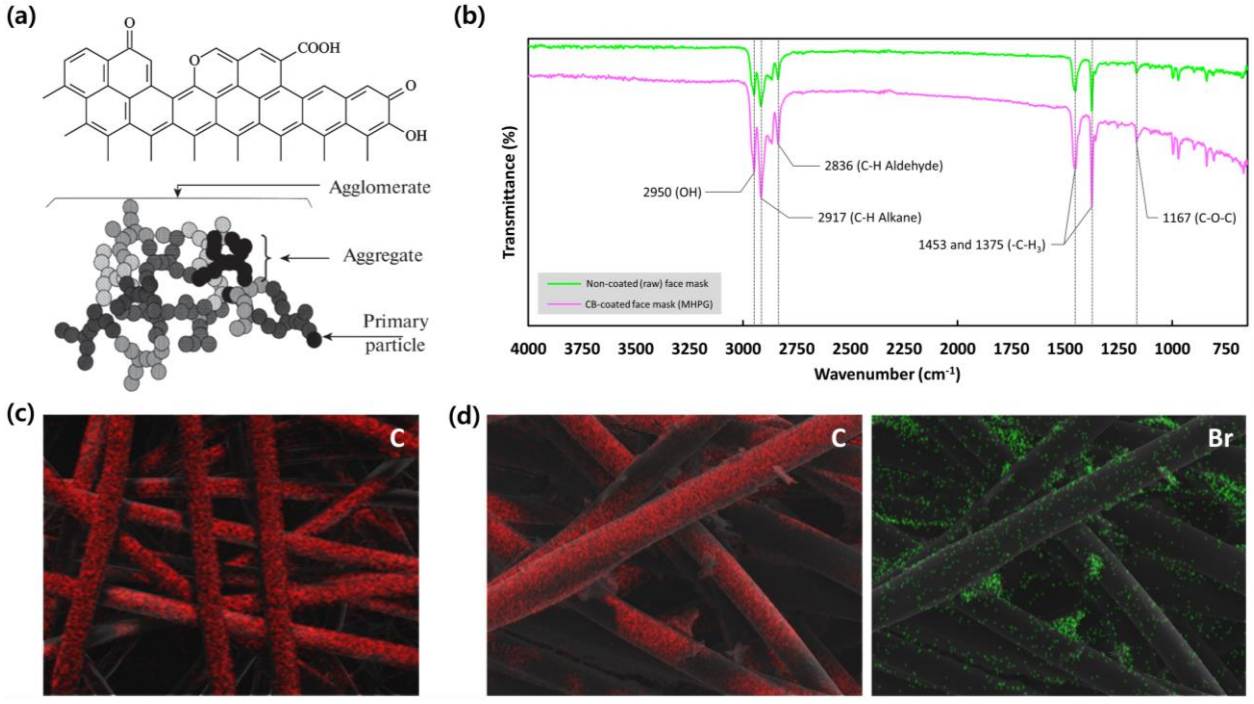


Figure 2. Surface modification of the MHPG. **(a)** The structure of carbon black (CB) and its agglomeration characteristics; **(b)** FT-IR spectroscopy comparing raw and CB-coated face masks; EDS patterns of **(c)** Carbon (C, red) in non-coated (raw) face mask and **(d)** Carbon (C, red) and bromine (Br, green) in CB-coated face mask.

Comparing the electricity output performances among four different generating devices (MHPG-1, MHPG-2, MHPG-3, and MHPG-4), the maximum V_{OC} values were 0.39, 0.31, 0.28, and 0.28 V, respectively (Fig. 3b) and the maximum I_{SC} values were 18.3, 32.7, 65.6, and 17.3 μA, respectively (Fig. 3c). Thus, the maximum power outputs of 7.1, 10.1, 18.4 and 4.8 μW per single unit of MHPG were achievable. The V_{OC} and I_{SC} values of MHPGs with varying configurations showed similar tendencies to those observed in previous studies. The voltage is generally proportional to the distance between the top and bottom electrodes and has a negative correlation with thickness [26]. Conversely, the current tends to increase linearly with the number of layers in the generator [27]. The mean electricity generation outputs for V_{OC} values were 0.32, 0.17, 0.19, and 0.05 V, and for I_{SC} values were 16.57, 15.59, 47.43, and 3.02 μA from MHPG-1, MHPG-2, MHPG-3, and MHPG-4, respectively. For a comprehensive evaluation of MHPG performances, the long-term generation stability of each device was assessed at 23°C and a relative humidity of 40% (Figs. 3d-3g). The generation outputs of V_{OC} and I_{SC} from MHPGs quickly increased due to the maximum wet differences between two ends of MHPGs. After reaching peak generation efficiencies, both V_{OC} and I_{SC} gradually decreased and stabilized to consistent generation ranges as the MHPGs became fully wetted and maintained a continuous water supply and evaporation. Although each MHPG exhibited different tendencies in terms of maximum electricity output, efficiency change gradient and stable output range, the results provided sufficient insight into the generation efficiency characteristics of various MHPG types for further development. The electricity generation output from MHPGs can be further enhanced by connecting the devices in series or parallel, similar to commercial batteries. For instance, in the case of MHPG-1, V_{OC} of 1.51 V and I_{SC} of 83.4 μA were achieved by connecting five MHPGs in series (Fig. 3h) and parallel (Fig. 3i), respectively.

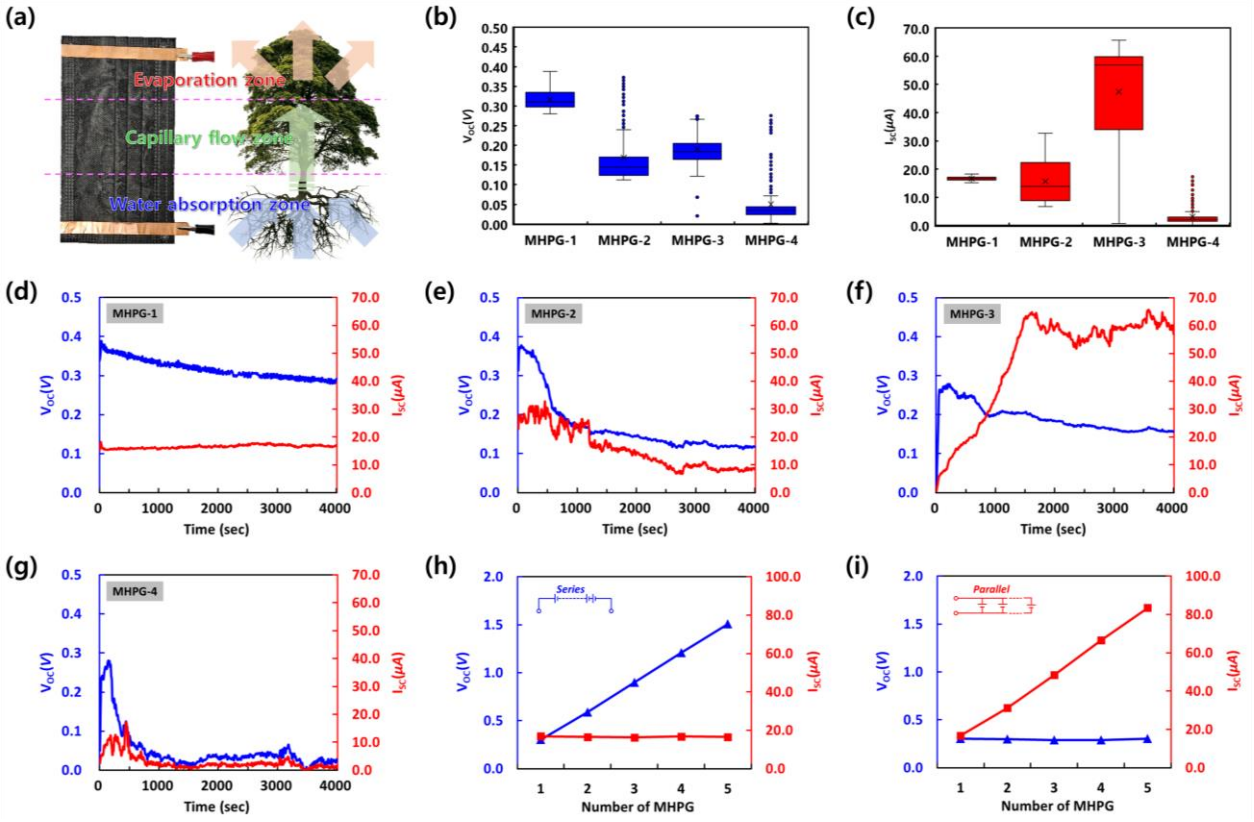


Figure 3. Operation principal of MHPG and its electricity generation performances. **(a)** Schematic representation comparing the MHPG and plant transpiration; **(b)** Open-circuit voltage (V_{oc}) and **(c)** Short-circuit current (I_{sc}) distributions of different types of MHPGs; Long-term generation performances of **(d)** MHPG-1; **(e)** MHPG-2; **(f)** MHPG-3 and **(g)** MHPG-4; Output voltages and currents of MHPG-1 connected **(h)** in series and **(i)** parallel.

3.3. Discussion and Future perspectives

This study explored the feasibility of repurposing discarded face masks for hydrovoltaic energy harvesting, presenting a novel approach to addressing both plastic waste and energy generation challenges. The results demonstrated that face masks, modified with carbon black (CB), can effectively generate electricity through the hydrovoltaic mechanism. Following the research outcomes and findings, further implications can be discussed for both energy harvesting technology and environmental sustainability perspectives (Fig. 4).

The hydrovoltaic generation output performance of the MHPGs varied with the different configurations examined. MHPG-1, which retained the original mask form, exhibited a maximum open-circuit voltage (V_{OC}) of 0.39 V and a short-circuit current (I_{SC}) of 18.3 μA. In contrast, MHPG-2 and MHPG-3, which involved cutting and reassembling the mask into smaller sections, showed improved performance with maximum I_{SC} values of 32.7 μA and 65.6 μA, respectively. MHPG-4, which involved rolling the mask, had the lowest output, suggesting that the configuration significantly affects the efficiency of the hydrovoltaic energy harvesting outputs. The variation in performance can be attributed to the differences in the exposure of the mask material to the electrolyte and the evaporation surface area. MHPG-3, which had a smaller but more structured area, allowed for better exposure and interaction with the electrolyte, enhancing the overall ion transport and energy conversion efficiency. This aligns with the principle that smaller, well-defined channels can improve fluid dynamics and, consequently, the electrokinetic phenomena involved in hydrovoltaic energy generation.

The long-term stability of MHPGs was evaluated by monitoring the voltage and current outputs over extended periods. The results indicated that while the initial performance was high, there was a gradual decrease in V_{OC} and I_{SC} as the devices became fully wetted and reached a steady-state condition. This behavior reflects the inherent limitations of hydrovoltaic energy harvesting systems, where continuous exposure to moisture and evaporation can affect the material properties and performance over time. Despite this, the MHPGs demonstrated promising potential for sustainable energy generation. The ability to convert discarded face masks into functional energy-harvesting devices addresses two critical issues: reducing plastic waste and providing a renewable energy source. By integrating these masks into energy-harvesting systems, we not only mitigate the environmental impact of plastic pollution but also contribute to the development of low-cost, eco-friendly energy solutions.

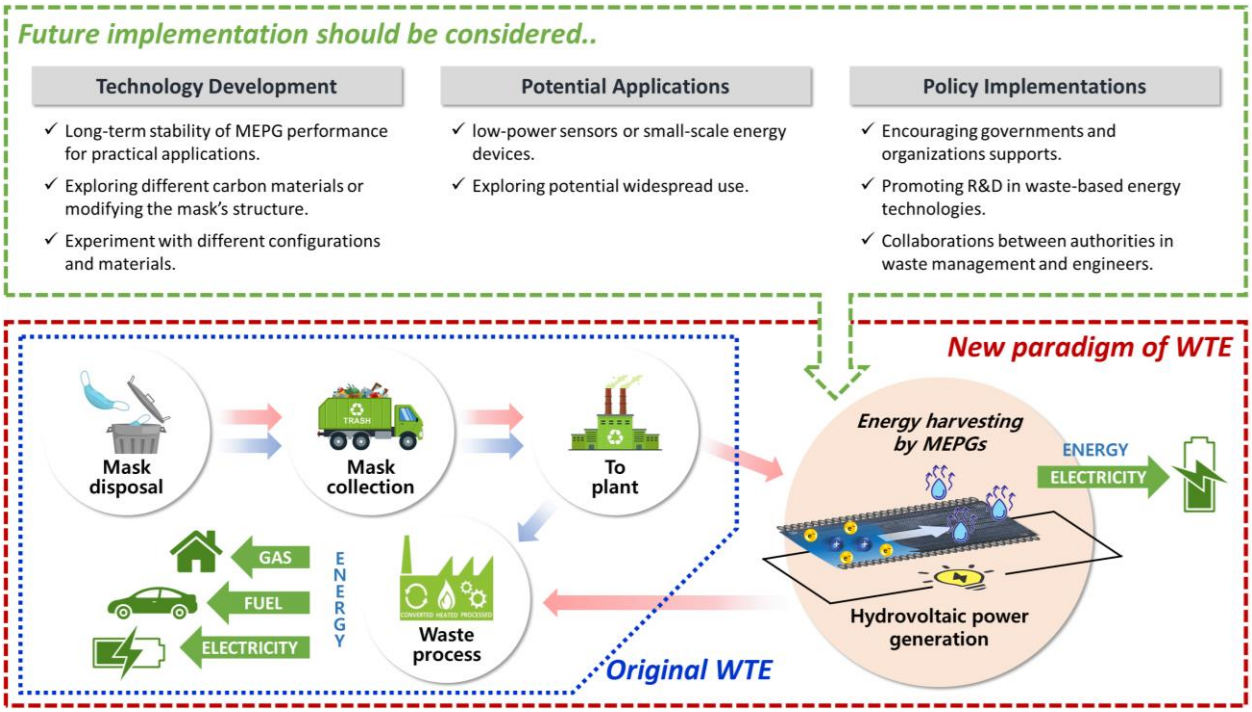


Figure 4. Perspectives on waste-to-energy paradigm with hydrovoltaic energy harvesting mechanism and its implication for future implementations.

By integrating the principles of WTE with hydrovoltaic energy harvesting, a dual benefit can be achievable by mitigating plastic waste and generating renewable energy. This approach aligns with the ultimate goals of the WTE paradigm of transforming waste into valuable resources while minimizing environmental impact. The innovative use of face masks, a common and problematic waste stream, illustrates how waste-to-energy principles can be adapted to emerging technologies and materials. The repurposing of discarded face masks into MHPGs demonstrates how resource efficiency can be enhanced by using existing waste streams. Face masks, primarily composed of polypropylene, are not biodegradable and contribute significantly to plastic pollution. By transforming these masks into functional energy-harvesting devices, we effectively reduce the environmental burden of plastic waste and create a new resource for energy production. The integration of waste-to-energy principles with hydrovoltaic energy harvesting technology has several policy and practical implications. Thus, the scalability of MHPGs and their integration into existing waste management systems could be further explored.

4. Conclusions

This study presents a novel approach to repurposing discarded face masks as components in hydrovoltaic energy harvesting systems. By coating face masks with carbon black (CB), we significantly enhanced their ability to absorb and transport water, resulting in improved hydrovoltaic performance. The results indicate that different configurations of the masks impact their energy output, with a maximum open-circuit voltage (V_{OC}) of 0.39 V and a short-circuit current (I_{SC}) of 65.6 μA. Furthermore, four different generating devices (MHPG-1, MHPG-2, MHPG-3, and MHPG-4) presented average voltages of 0.32, 0.17, 0.19, and 0.05 V, respectively, and average currents for MHPG-1 to 4 were 16.57, 15.59, 47.43, and 3.02 μA, respectively. The integration of these waste materials into energy-harvesting devices not only addresses the growing problem of municipal waste pollution but also contributes to the development of sustainable and low-cost energy solutions. The successful application of waste face masks in this context aligns with the principles of a circular economy, offering a dual benefit of reducing environmental impact and generating renewable energy. Future research should focus on optimizing the design and scalability of these systems to maximize their practical applications and benefits. This approach represents a significant step towards innovative waste management and energy production strategies, paving the way for further advancements in sustainable technologies.

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