Peer Review File

Small-Scale Water Energy Harvesting for Sustainably-Powered Distributed Electronics

Corresponding Author: Professor Dong-Myeong Shin

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

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Dear Professor Shin,

Thank you again for submitting your manuscript "Small-Scale Water Energy Harvesting: Pathways to Ubiquitous Sustainable Power for Distributed Electronics" to Communications Materials. We have now received reports from 3 reviewers and, based on their comments, we have decided to invite a revision of your work. You will find the reviewers' reports below. While they find your work of interest, they have raised important points which must be addressed in a revised manuscript.

To allow us to move forward with your work, we also ask that you edit your manuscript according to the attached table. **Please read this document carefully as we will be unable to further assess your revised paper until these important points are addressed.**

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We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

John Plummer, PhD
Chief Editor
orcid.org/0000-0003-4824-8497
Communications Materials

Reviewers' comments:
Reviewer #1 (Remarks to the Author):

This manuscript is a comprehensive review of small-scale water-based energy harvesting technologies aimed at powering distributed electronics and IoT devices. It covers an extensive range of energy transduction mechanisms-mechanical, thermal, and water-mediated processes, across all forms of water. The authors synthesize a large body of literature to highlight state-of-the-art materials and designs that convert rain, humidity, river currents, wave motion, and even snow/ice into usable electrical energy for micro-scale applications. Overall, the manuscript's focus and contribution lie in providing a timely, in-depth overview of this rapidly evolving field, outlining how ubiquitous water in the environment can be tapped to realize sustainable, maintenance-free power for distributed electronic devices. Thus, I support its acceptance for publication after minor revisions.

1. While the coverage is comprehensive, Sections 3.2.3 and 3.2.4 (triboelectric and droplet-driven mechanisms) contain substantial repetition of working principles such as contact electrification, electrostatic induction, and AC/DC output characteristics. I suggest condensing these sections by reducing repeated mechanism descriptions and focusing more on comparative insights between representative device architectures and performance metrics.
2. Several acronyms are used without clear definition at first appearance (e.g., WT-TENG in Section 3.2.3, corresponding to Figure 11d), and terminology is occasionally inconsistent (e.g., "water energy harvesting" vs. "water energy harvestings"). In addition, a few phrases are non-standard or awkward (e.g., "system's perspectivity," "maintenance-light"), and some long sentences could be simplified to improve fluency and clarity.
3. The "Summary and Future Challenges" section contains valuable insights but is somewhat lengthy and diffuse. I recommend a more concise synthesis that explicitly prioritizes the key bottlenecks, such as long-term material stability, intermittent output and power management, scalability, and lack of standardized evaluation, and more clearly links these challenges to future research opportunities.

Reviewer #2 (Remarks to the Author):

The authors present a comprehensive review of small-scale water energy harvesting technologies, covering water forms (gaseous, liquid, ice/snow), transduction mechanisms (e.g., phase-change-induced capillary flow, electromagnetic, piezoelectric, triboelectric), state-of-the-art advances in materials and device design, and diverse applications (power sources, self-powered sensors, wearables). The review also outlines future research directions to bridge laboratory innovation and real-world deployment. However, the manuscript exhibits ambiguities in performance comparison, insufficient mechanistic elaboration, gaps in practical validation, and lack of systematic analysis on key challenges, which affect its depth and guidance for the field.

1. Referring to hydrovoltaic technology (Chem. Soc. Rev., 2022, 51, 4902-4927), what is the core distinction between the reviewed small-scale water energy harvesting and this hydrovoltaic technology in terms of energy conversion fundamentals, water-material interaction mechanisms and targeted water forms? Beyond common advantages, what unique technical merits does TENG-based harvesting offer over it specifically regarding adaptation to ultra-low energy density water sources, response to intermittent water supply and integration with flexible devices?

2. Table 1 compares energy transduction mechanisms but lacks explicit clarification of the standardized test conditions (e.g., ambient humidity, water flow velocity, temperature gradient, salinity) across different studies. This makes direct performance comparison unreliable. Could the authors supplement a standardized test condition framework or a sensitivity analysis to illustrate how environmental factors influence the reported energy density and efficiency?

3. For the "ion concentration gradient" mechanism, the review mentions "ion depletion issues" but provides limited discussion on effective mitigation strategies (e.g., ion replenishment designs, material regeneration technologies) and their long-term performance. Could the authors elaborate on recent progress in addressing ion depletion and provide quantitative data on the operational lifespan of relevant devices?

4. Hybrid systems (e.g., moist-thermoelectric generators, MTEG) are highlighted as a future direction, but the synergistic mechanism between complementary transduction modules (e.g., humidity-responsive layers and thermoelectric units) and optimization methods for interface charge transfer and energy coupling are not sufficiently detailed. Could the authors elaborate on the design principles and performance enhancement mechanisms of hybrid systems?

5. The application section on self-powered sensors lacks long-term performance data from practical deployments (e.g., continuous operation time, signal stability under complex environmental interference). Could the authors supplement field test results from specific scenarios?

6. Energy management systems (e.g., micro-energy storage devices, impedance matching circuits) are only briefly mentioned in future directions, with insufficient discussion on their compatibility with low-power output from small-scale water energy harvesters. Could the authors elaborate on the current status and challenges of energy conditioning and storage technologies tailored for such harvesters?

7. For wearable device applications, biocompatibility and wear comfort (e.g., breathability, skin irritation) of materials are not mentioned. Could the authors supplement research advances in biocompatible materials and their safety test results (e.g., cytotoxicity tests)?

8. The review proposes "standardized evaluation" as a future direction but does not identify the core standardized metrics that are currently lacking (e.g., energy density measurement methods, environmental stability evaluation systems). Could the authors list priority metrics for standardization to guide future research and industrialization?

9. Hybrid solar-water energy harvesting systems are briefly introduced, but the energy distribution strategy and complementary working modes (e.g., switching mechanisms between sunlight and rainfall) are not elaborated. Could the authors supplement design principles and performance optimization methods for such hybrid systems?

All in all, I would like to give a major revision chance for this manuscript.

Reviewer #3 (Remarks to the Author):

This manuscript provides a comprehensive, well-organized, and timely review of small-scale water energy harvesting technologies. It successfully bridges fundamental transduction mechanisms, state-of-the-art materials and device architectures, and diverse applications—from self-powered sensors to wearable systems. The review is thorough, logically structured, and richly supported with recent references and illustrative figures.
1.Sections 3.1–3.3 thoroughly describe examples but could benefit from more comparative critique. For instance, in Table 1, some power density ranges span several orders of magnitude. Adding a brief commentary on what factors lead to such variability (e.g., material choices, testing conditions, scaling effects) would provide deeper insight.
2.Section 4 covers many applications but could be more structured. Subdividing "4.4 Other Applications" into thematic areas (e.g.,

environmental remediation, corrosion protection, hybrid systems) might improve flow and readability.
3。The reference list is extensive and up-to-date. A quick check for very recent breakthroughs in this area such as：(Advanced Materials. 18 (2025), 2505613. https://doi.org/10.1002/adma.202505613; J. Adv. Manuf. Sci. Technol. 4 (2024), 2024005. https://doi.org/10.51393/j.jamst.2024005; ACS Appl. Mater. Interfaces 16 (2024), 32249. https://doi.org/10.1021/acsami.4c04251; Nano Energy 129 (2024), 110056. https://doi.org/10.1016/j.nanoen.2024.110056; Adv. Mater. Technol. 2400554. https://doi.org/10.1002/admt.202400554; Applied materials today 41 (2024), 102492. https://doi.org/10.1016/j.apmt.2024.102492)should be commented.

Version 1:

Decision Letter:

Dear Professor Shin,

Thank you again for submitting your manuscript "Small-Scale Water Energy Harvesting for Sustainably-Powered Distributed Electronics" to Communications Materials. We have now received reports from 1 reviewers, which are copied below. Based on their comments, we are delighted to accept your Review for publication.

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Best regards,

John Plummer, PhD
Chief Editor
orcid.org/0000-0003-4824-8497
Communications Materials

Reviewers' comments:
Reviewer #2 (Remarks to the Author):

The authors have revised the work accordingly. The work has been highly improved.

As a new journal, we would greatly appreciate any comments you have about your experience at Communications Materials. I hope that we have been able to meet your expectations and look forward to working with you again in the future.

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Reviewer #1

This manuscript is a comprehensive review of small-scale water-based energy harvesting technologies aimed at powering distributed electronics and IoT devices. It covers an extensive range of energy transduction mechanisms-mechanical, thermal, and water-mediated processes, across all forms of water. The authors synthesize a large body of literature to highlight state-of-the-art materials and designs that convert rain, humidity, river currents, wave motion, and even snow/ice into usable electrical energy for micro-scale applications. Overall, the manuscript's focus and contribution lie in providing a timely, in-depth overview of this rapidly evolving field, outlining how ubiquitous water in the environment can be tapped to realize sustainable, maintenance-free power for distributed electronic devices. Thus, I support its acceptance for publication after minor revisions.

> **Our response**: We sincerely thank the reviewer for the positive and encouraging assessment of our manuscript. We are grateful for the recognition of the manuscript's scope, timeliness, and contribution in synthesizing recent advances in small-scale water-based energy harvesting technologies for distributed electronics and IoT applications. Below is the point-by-point response to address each comment in detail.

1. While the coverage is comprehensive, Sections 3.2.3 and 3.2.4 (triboelectric and droplet-driven mechanisms) contain substantial repetition of working principles such as contact electrification, electrostatic induction, and AC/DC output characteristics. I suggest condensing these sections by reducing repeated mechanism descriptions and focusing more on comparative insights between representative device architectures and performance metrics.

> **Our response**: We thank the reviewer for this helpful and constructive suggestion. We agree that these two sections contained overlapping descriptions of fundamental working principles. In response, we have revised these sections to reduce redundancy. We have revised Section 2.2.2 and reorganized the manuscript structure by integrating the droplet-driven mechanisms related to triboelectric transduction originally discussed in Section 3.2.4 into the direct-contact mode subsection of Section 3.2.3. The specific revisions are detailed below:
>
> 2.2.2 Droplet-driven mechanisms
>
> Multiple mechanisms have been proposed for droplet-based energy harvesting. One representative approach, analogous to triboelectric transduction, relies on CE and electrostatic induction[177]. As illustrated in Figure 3e, in these systems electrical output is generated through interfacial processes that occur as droplets approach, spread on, and detach from dielectric surfaces such as polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), or polydimethylsiloxane (PDMS)[177,178]. Upon contact, interfacial charge transfer is initiated at the liquid–solid interface due to atomic-scale overlap of electron clouds, leading to the formation of an EDL that subsequently governs electrostatic induction during droplet motion[172]. This process establishes an uneven charge distribution, with the dielectric surface becoming negatively charged while the droplet acquires an equal positive charge. Upon detachment, the interfacial equilibrium is disrupted, and the induced potential difference drives electrons to flow through the external circuit, producing a transient alternating current (AC) output.
>
> 3.2.3 Triboelectric transduction

To overcome this limitation, researchers have proposed spherical[313] or UFO-shaped[311,312] encapsulated triboelectric nanogenerators. Unlike tubular designs, these multidimensional encapsulations allow the internal liquid to flow freely in three-dimensional space, enabling effective energy harvesting under external forces from arbitrary directions. In addition, researchers also studied the continuous flow of water within the pipes. Munirathinam et al. designed a single-electrode tubular TENG that utilizes the continuous flow of tap water to achieve sustainable energy generation[314] (Figure 11e). The results showed that as the flow rate increased from 0 to 2.5 L·min⁻¹, both the output voltage and current rose correspondingly. This enhancement was attributed to the higher flow velocity allowing more charged water molecules to enter and leave the PTFE surface per unit time, thereby inducing a greater amount of charge on the electrode.

As another form of small-scale water, droplets are also well suited for energy harvesting based on triboelectric transduction[53,57,60,242,315.] Lin et al. were the first to use the principle of TENGs to harvest mechanical energy from water droplets via a combination of contact electrification and electrostatic induction57. In their design, when a droplet impacts an electrode surface coated with a PTFE film, an instantaneous charge transfer occurs at the solid–liquid interface, generating an alternating electrical signal through the external circuit (Figure 11f). Experimental results showed that a single droplet could generate approximately 9.3 V of voltage and 17 μA of current, corresponding to a power density of about 20 $mW \cdot m^{-2}$. Building upon this foundation, researchers systematically investigated the influence of dielectric layer thickness[316], ionic concentration[63,317], and surface chemical properties on the charge-transfer dynamics[64,65,290,318], while developing various structural designs to more efficiently capture and convert the kinetic and interfacial energy carried by droplets. However, due to the inherent characteristics of conventional TENGs, which primarily generate AC signals, they are not directly compatible with wearable electronic devices that require direct current (DC) power sources, thereby limiting their practical applications[173,319]. To overcome this limitation, Zhou et al. proposed a switchable TENG (s-TENG) based on the dielectric breakdown effect[58]. In this design, a microscale air gap was introduced between the FEP triboelectric layer and the ITO electrode (Figure 11g). By regulating the surface charge density and electric field intensity, localized air ionization occurs once the electric field exceeds the dielectric strength of air, triggering breakdown discharge and inducing unidirectional electron flow. Through this mechanism, a self-rectified DC output was achieved without the need for an external rectification circuit. Experimental results demonstrated that the device reached a rectification ratio of ≈133 and an energy conversion efficiency of about 26%, maintaining stable DC output under low-frequency (0.8–2.5 Hz) and random mechanical excitations. Furthermore, to better adapt to the needs of flexible and wearable electronics, Yang et al. developed a highly stretchable PTFE particle–reinforced droplet-based TENG[59] (Figure 11h). The device was fabricated by embedding PTFE microparticles in a flexible Ecoflex substrate and combining it with liquid-metal electrodes, which significantly improved both mechanical flexibility and hydrophobic stability while maintaining excellent electrical conductivity. Even under a 500% strain, the device retained over 80% of its output performance, demonstrating outstanding mechanical robustness and environmental adaptability.

3.2.4 Other droplet-driven mechanisms

In addition to triboelectric transduction, a range of alternative mechanisms has been explored for harvesting energy from droplets[53,60,62,186,327-331]. Xu et al. proposed a droplet-based electricity generator (DEG) with a bulk-effect transistor-like architecture[60]. In this design, a conductive electrode (such as aluminum) was placed on the surface of the dielectric layer, enabling conversion of interfacial charge induction into a bulk effect and thereby achieving significant current amplification (Figure 13a). Experimental results showed that the output voltage increased to 143.5 V, the current reached 270 μA, and the power density was approximately 2600 times that of conventional interfacial TENGs, sufficient to light up more than 400 commercial LEDs simultaneously. Building on this, researchers systematically analyzed how factors such as droplet impact position[187,332], dielectric material type[327-329], and layer thickness[60,186] affect the bulk-effect droplet electricity generator's output performance. Meanwhile, Wu et al.[61] employed high-speed imaging synchronized with electrical signal measurements to construct an electrohydrodynamic model describing the interaction between droplet impact and surface charging (Figure 13b). Combined with an equivalent RC circuit analysis, this approach quantitatively described the energy conversion process and revealed the coupling relationship between droplet impact dynamics and electrical response[61].

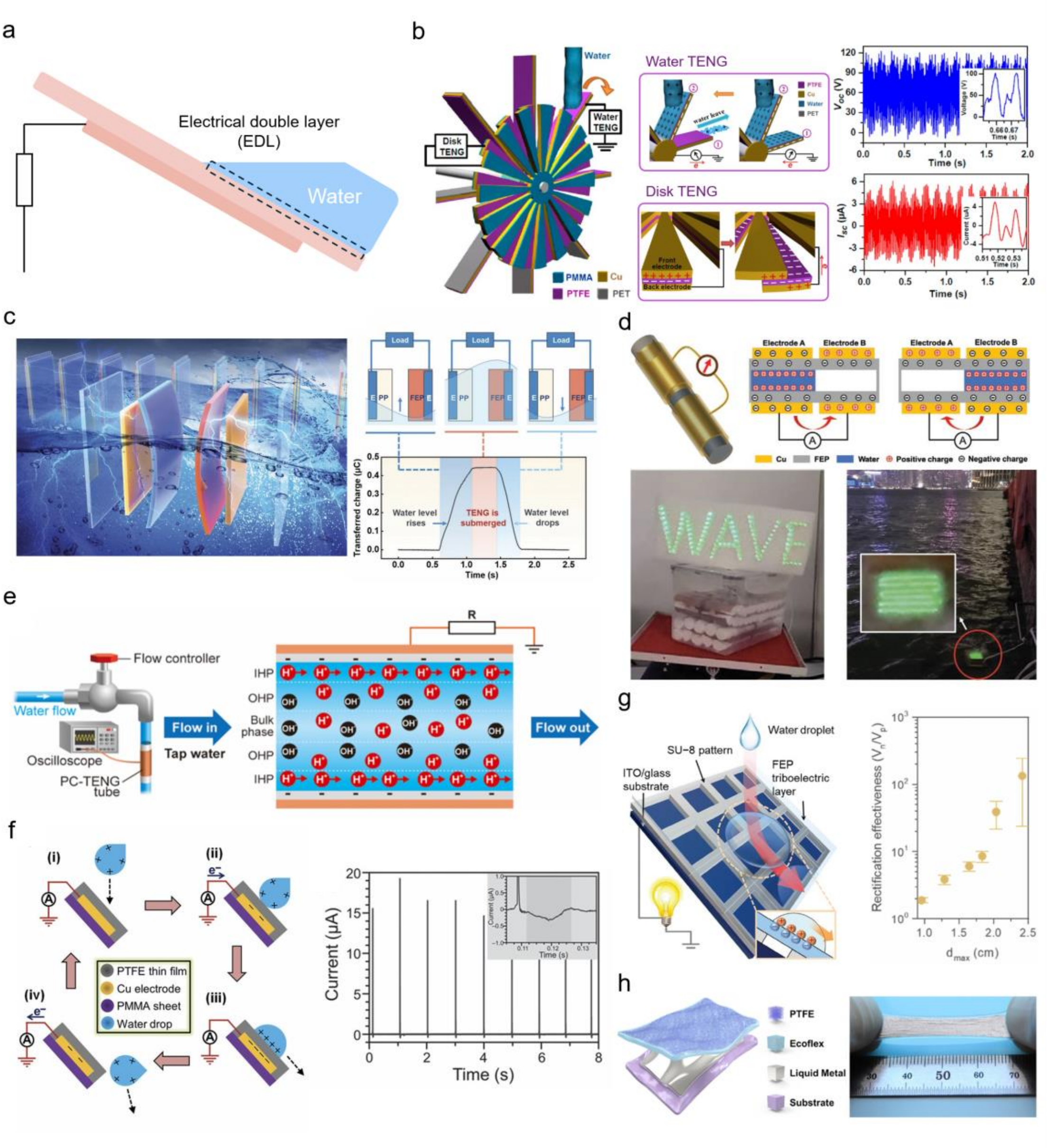

Figure 11. Energy harvesting from water flow and droplets via triboelectric transduction. (a) Schematic of the direct contact mode triboelectric transduction, where liquid contact with the solid surface induces contact electrification. **(b)** Structural diagram of the hybrid device(left), schematic of the operational mechanisms for the water-based TENG and disk-based TENG component in the hybrid system(center), and the voltage (V_{oc}) and current (I_{sc}) versus time curve for the disk-TENG(right). Reproduced with permission from ref.[56]. Copyright 2014 ACS Nano. **(c)** Exploded diagram of the DE-TENG(left),with a schematic illustrating water level variations relative to the device and corresponding transferred charge during a single operational cycle(right). Reproduced with permission from ref.[308]. Copyright 2023 Advanced

Energy Materials. **(d)** Diagram of a water-tube-based triboelectric nanogenerator (WT-TENG) and its operational mechanism(top). The 'WAVE' pattern demonstrates WT-TENG powering 103LEDs in seesaw mode, and water waves lighting up 150 LEDs in Victoria Harbor, Hong Kong(bottom). Reproduced with permission from ref.[49]. Copyright 2021 Advanced Energy Materials. **(e)** Schematic showing the operating mechanism of the PC-TENG tube, which relies on the formation and modulation of the electrical double layer (EDL). Reproduced with permission from ref.[314]. Copyright 2022 Nano Energy. **(f)** Operating mechanism of the water TENG, where triboelectricity generation is primarily generated through contact electrification(left), and the output current produced by water TENG from water droplet, with a fixed volume of 30μL and falls from a height of 90cm(right). Reproduced with permission from ref.[57]. Copyright 2014 Advanced Materials. **(g)** Schematic diagram of switchable TENGs featuring adjustable air gaps between the triboelectric layer and electrode, enabling control over the direction of electron flow(left), and the rectification efficiency varies with maximum spreading diameters(right). Reproduced with permission from ref.[58]. Copyright 2024 Small. **(h)** Schematic illustration(left), and photo of its stretch state(right) of SH-TENG. Reproduced with permission from ref.[59]. Copyright 2023 Nano Energy.

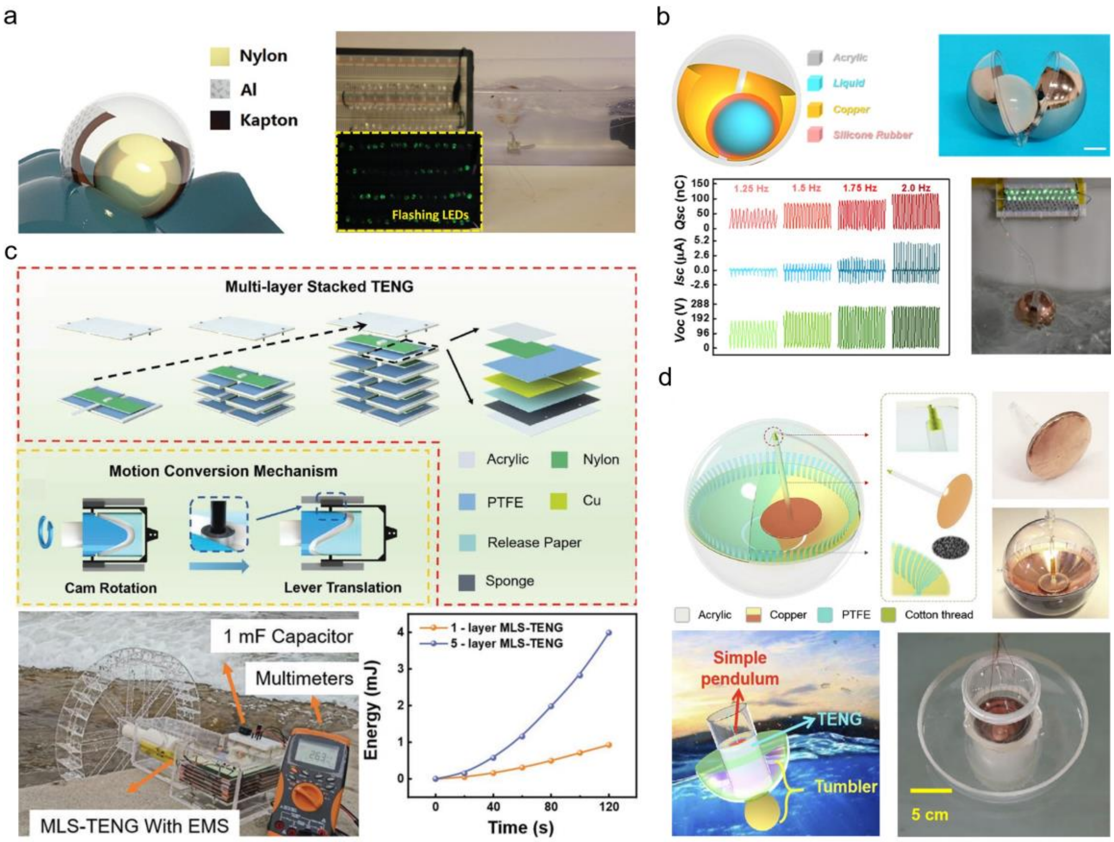

Figure 12. Energy harvesting from indirect-contact mode of water via triboelectric transduction. (a) Schematic of the freestanding-triboelectric-layer-based nanogenerator (RF-TENG) enclosed rolling Nylon ball(left). Photograph displays 70 green LEDs powered by the rocking TENG within a wave system(right). Reproduced with permission from ref.[320]. Copyright 2015 Advanced Energy Materials. **(b)** Structural schematic of soft-contact model spherical triboelectric nanogenerator (SS-TENG) featuring a flexible rolling sphere, along with a photograph of a SS-TENG (scalar bar = 1.5cm) (top), with a typical electrical output waveforms of the SS-TENG and LEDs illuminated by the SS-TENG submerged in water(bottom). Reproduced with permission from ref.[158]. Copyright 2019 Nano Energy. **(c)** Schematic of a single TENG and multilayer stacking process and the conversion of cam rotation into lever translation. Reproduced with permission from ref.[45]. Copyright 2023 Advanced

Functional Materials. **(d)** Schematic diagram of P-TENG components (top). Reproduced with permission from ref.[301]. Copyright 2019 Nano Energy. And photograph of the pendulum triboelectric layer and the fully assembled P-TENG device(bottom). Reproduced with permission from ref.[159]. Copyright 2021 Joule.

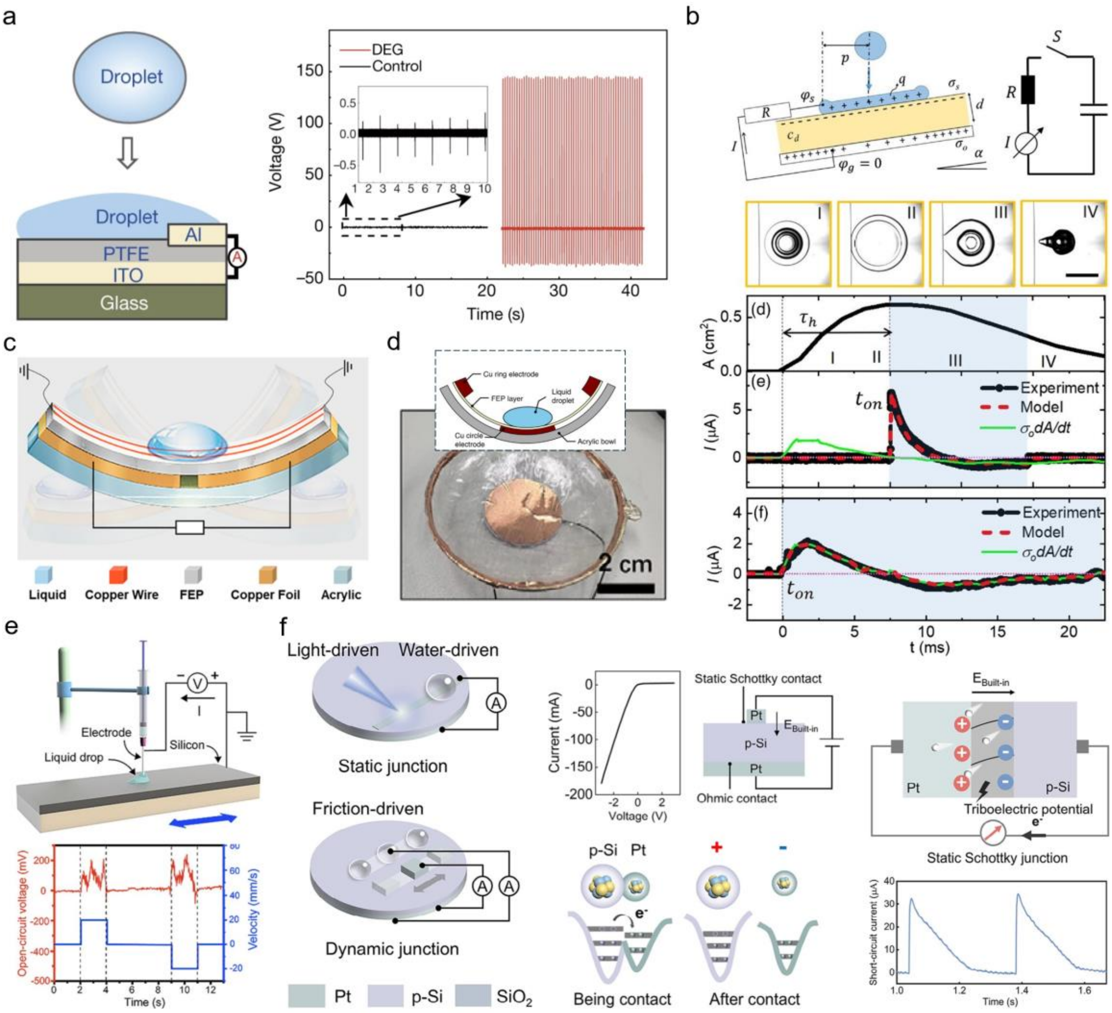

Figure 13. Energy harvesting from water flow and droplets via non triboelectric transduction. (a) Schematic diagram of the DEG(left), and comparison of the output current generated by the DEG(red) with that of a control device(black) under continuous impact of individual droplets(right). Reproduced with permission from ref.[60]. Copyright 2020 Nature. **(b)** High-speed camera imaging and electrical signal measurement capturing the interaction between droplet impact and surface charging. Reproduced with permission from ref.[61]. Copyright 2020 Physical Review Letters. **(c)** Schematic illustration of the Droplet-Based (DB-TENG) unit. Reproduced with permission from ref.[50]. Copyright 2021 ACS Nano. **(d)** Schematic diagram (top) and optical image (bottom) of the floating-droplet-activated electricity generator (FDEG). Reproduced with permission from ref.[52]. Copyright 2025 Device. **(e)** Experimental setup for the tribovoltaic measurement along with the external circuit schematic(left), and the open-circuit voltage generated by DI water droplet slides on a P-type silicon wafer (0.1Ω·cm) at a speed of 20mm/s, with a static contact diameter of 2.5mm(right). Reproduced with permission from ref.[53]. Copyright 2020 Nano Energy. **(f)** Schematic illustration of a static M-S junction activated by light and water, alongside a dynamic M-S junction driven by sliding friction(left). Current -Voltage characteristics of a static Schottky MSM structure and electron cloud potential model depicting the electron transfer process from

sliding state to separated state(center). Carrier transport behavior within the static MSM structure, governed by triboelectric potential and positive current response of MSM structure from impinging water droplet. Reproduced with permission from ref.[62]. Copyright 2025 Advanced Materials.

2. Several acronyms are used without clear definition at first appearance (e.g., WT-TENG in Section 3.2.3, corresponding to Figure 11d), and terminology is occasionally inconsistent (e.g., "water energy harvesting" vs. "water energy harvestings"). In addition, a few phrases are non-standard or awkward (e.g., "system's perspectivity," "maintenance-light"), and some long sentences could be simplified to improve fluency and clarity.

Our response: We thank the reviewer for pointing out these important issues regarding acronym and language clarity. We have carefully revised the manuscript to ensure that all the acronyms, terminology, and phrases have been clearly defined and standardized as follows:

2. Forms of water and energy transduction mechanisms

This section explores the forms of water and transducers that are employed in the fields of small-scale water energy harvesting technologies, highlighting their operational principles, advantages, and limitations. Comparison of energy transduction mechanisms for small-scale water energy harvesting is summarized in **Table 1**[14,17-65] and **Table 2**[14,17-65].

2.2.1.3.1 Electron Transfer

Furthermore, when liquid solutions containing ions, such as ordinary water or rainwater, come into contact with solid surfaces, an EDL is formed.

2.2.2 Droplet-driven mechanisms

Multiple mechanisms have been proposed for droplet-based energy harvesting. One representative approach, analogous to triboelectric transduction, relies on CE and electrostatic induction[177]. As illustrated in Figure 3e, in these systems electrical output is generated through interfacial processes that occur as droplets approach, spread on, and detach from dielectric surfaces such as polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), or polydimethylsiloxane (PDMS)[177,178]. Upon contact, interfacial charge transfer is initiated at the liquid–solid interface due to atomic-scale overlap of electron clouds, leading to the formation of an EDL that subsequently governs electrostatic induction during droplet motion[172]. This process establishes an uneven charge distribution, with the dielectric surface becoming negatively charged while the droplet acquires an equal positive charge. Upon detachment, the interfacial equilibrium is disrupted, and the induced potential difference drives electrons to flow through the external circuit, producing a transient alternating current (AC) output.

3.1.3 Thermoelectric harvesting

Steam-driven thermoelectric harvesting exploits a temperature differential between a vapor source and a cooler reservoir to drive Seebeck-effect conversion of heat into electricity[106,107].

3.2.3 Triboelectric transduction

Wu et al. encapsulated deionized water inside an FEP tube and wound two copper electrodes side-by-side on the outer surface of the tube, forming a water-tube-based TENG (WT-TENG)[49] (Figure 11d).

4.2.1 Self-powered physical sensors

By attaching it to plant surfaces, a self-powered agricultural system was constructed. This WB-TENG does not affect the plant leaf surface and thus does not affect its transpiration and growth. Simultaneously, by harnessing wind-induced vibrations and raindrop impacts experienced by the plant, the WB-TENG can continuously harvest ambient mechanical energy and provide a stable power supply for wireless sensors around the plant, enabling real-time monitoring of key agricultural parameters such as soil moisture, light intensity, and temperature.

4.3 Self-powered wearable devices

5. Outlook

Overall, small-scale water energy harvesting is transitioning from proof-of-concept demonstrations to practical, system-level solutions. Success requires simultaneous progress in materials innovation, multiscale understanding of coupled transport, adaptive multimodal architectures, integrated energy conditioning, and manufacturable processes validated by standardized protocols. When materials selection, device architectures, power management electronics, and application requirements are considered within an integrated design framework, small-scale energy harvesters can deliver reliable, low-maintenance power for distributed sensing, autonomous soft robotic systems, and other self-sustaining technologies.

Table 1. Comparison of energy transduction mechanisms for small-scale water energy harvesting.

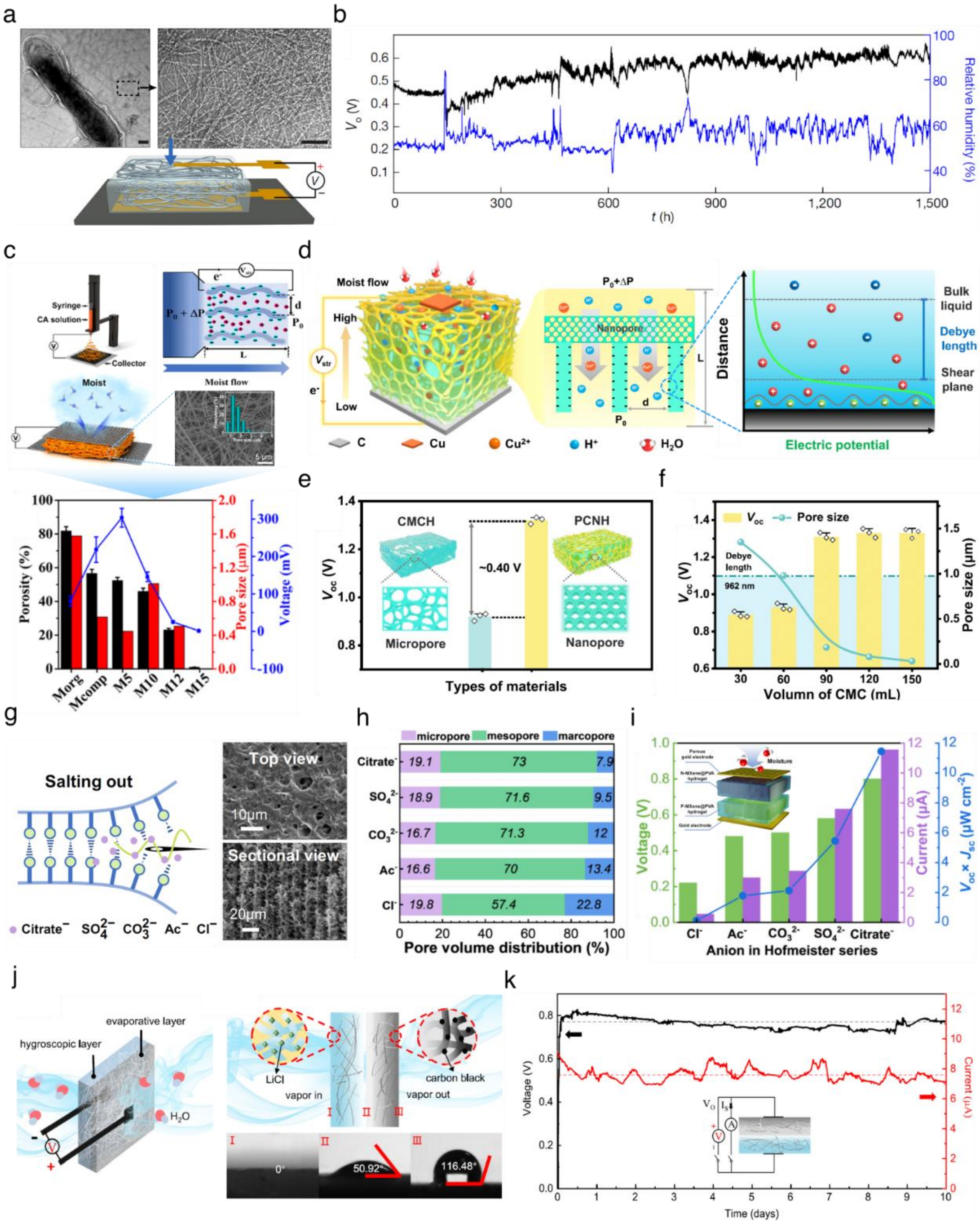

Figure 5. Energy harvesting driven by moisture and steam based on phase change induced capillary flow

(j) Schematic of the self-sustained electricity generator (SSEG) (left), and side view diagram illustrating the device structure with different contact angles for hygroscopic layer(I), the inner side(II) and outer side(III) of the evaporative layer are shown (right).

3. The "Summary and Future Challenges" section contains valuable insights but is somewhat lengthy and diffuse. I recommend a more concise synthesis that explicitly prioritizes the key bottlenecks, such as long-term material stability, intermittent output and power management, scalability, and lack of standardized evaluation, and more clearly links these challenges to future research opportunities.

Our response: We thank reviewer's comment. We have revised and condensed this section to provide a more concise synthesis that explicitly prioritizes the key bottlenecks limiting the field. In the revised version, we identify long-term material stability, intermittent output and power management, scalability of device architectures, and the lack of standardized evaluation protocols as the four primary challenges, in line with the reviewer's recommendation. Moreover, the revised text now clearly links each challenge to corresponding future research opportunities.

5. Outlook

Small-scale water energy harvesting encompasses a broad class of transduction strategies that convert local environmental stimuli—mechanical (triboelectric, piezoelectric), thermal (thermoelectric, thermo-osmotic), and water-mediated (sorption, evaporation, capillarity, ionic streaming)—into usable electrical power. These approaches target distributed low-power applications such as wearable and implantable electronics, autonomous sensors, and soft robotics, where wired power or bulky batteries are impractical. Recent progress has demonstrated functional devices based on hygroscopic ionic membranes, photothermal evaporators coupled to TE/thermo-osmotic elements, nanocomposite hydrogels for moisture-driven ionic generation, and microstructured tribo/piezo interfaces that produce burst power for intermittent loads. Key approaches include engineered material chemistries that sustain ionic gradients, hierarchical porosity for rapid fluid and heat transport, multifunctional composites that combine conductivity with mechanical compliance, and scalable fabrication routes (printing, roll-to-roll, laser patterning) that permit gradient and geometry control. Despite the extensive work that has been conducted on small-scale water energy harvesting, several bottlenecks are yet to be overcome before the translation of laboratory demonstrations into field-ready modules:

(i) Many hygroscopic functional materials suffer from performance degradation caused by repeated humidity cycling, salt crystallization, mechanical fatigue, or biofouling. Future research should develop materials-by-design strategies that balance ion dissociation and selective transport with controlled water retention, mechanical resilience, and biocompatibility, for example through polyelectrolytes, zwitterionic chemistries, nanofiller-reinforced networks (e.g., MXenes, rGO, SiO_2), and dynamic or supramolecular bonding for self-healing and fatigue tolerance.

(ii) Water-based harvesters generate low-frequency, pulsed, or environment-dependent outputs that are poorly matched to the steady power requirements of electronics. Therefore, the adaptive and hybrid architectures that reconcile burst power with continuous energy supply, including multimodal platforms that combine complementary mechanisms (e.g., hygroscopic ionic layers with thermoelectric modules, or triboelectric interfaces coupled to microstorage) should be focused on in the future.

(iii) Without efficient power management, a substantial fraction of harvested energy is lost before reaching the load, particularly given the low-amplitude, high-impedance, and often intermittent output characteristics of small-scale water energy harvesters. Based on this, future research should co-design harvesters with ultra-low-loss power electronics, impedance-matched interfaces, and microscale buffers (e.g., microcapacitors, thin-film batteries, and hybrid microsupercapacitors) that are specifically tailored to low-frequency, pulsed energy inputs. In addition, energy-aware control strategies—such as event-driven operation, duty-cycled sensing, and adaptive load management—are needed to minimize standby losses and enable energy-neutral sensing and local processing under realistic environmental conditions.

(iv) Scalability and manufacturability also constitute a major challenge. Many reported devices rely on bespoke fabrication processes or fragile architectures that are difficult to translate into industry. Multimaterial additive printing, roll-to-roll deposition, laser-patterned gradient writing, and solution processing can be considered for future research, which can translate laboratory concepts to volume production as well as retain gradient and geometry control. Post-fabrication tuning methods (laser or thermal writing) can also be considered to optimize devices without complex process chains.

(v) The lack of standardized metrics currently hinders meaningful comparison among harvesting technologies, as performance is often reported under disparate environmental conditions and timescales. To address this issue, several priority metrics should be standardized. First, electrical output normalized by device area or volume is recommended to enable comparison across different architectures. Second, key test conditions—including humidity (e.g., 10–90%), temperature (e.g., 25 °C), flow velocity, and droplet parameters—should be explicitly specified and standardized. Finally, durability metrics, such as time to a defined level of performance degradation under controlled aging and environmental cycling, are needed to assess long-term stability.

Overall, small-scale water energy harvesting stands at a transition from proof-of-concept demonstrations to practical, system-level solutions. Success requires simultaneous progress in materials innovation, multiscale understanding of coupled transport, adaptive multimodal architectures, integrated energy conditioning, and manufacturable processes validated by standardized protocols. When materials selection, device architectures, power management electronics, and application requirements are considered in an integrated design framework, small-scale energy harvesters can deliver reliable and low-maintenance power for distributed sensing, autonomous soft robotic systems, and other self-sustaining technologies.

Reviewer #2

The authors present a comprehensive review of small-scale water energy harvesting technologies, covering water forms (gaseous, liquid, ice/snow), transduction mechanisms (e.g., phase-change-induced capillary flow, electromagnetic, piezoelectric, triboelectric), state-of-the-art advances in materials and device design, and diverse applications (power sources, self-powered sensors, wearables). The review also outlines future research directions to bridge laboratory innovation and real-world deployment. However, the manuscript exhibits ambiguities in performance comparison, insufficient mechanistic elaboration, gaps in practical validation, and lack of systematic analysis on key challenges, which affect its depth and guidance for the field

> **Our response**: We sincerely thank the reviewer for the thorough and constructive evaluation of our manuscript, as well as for recognizing its comprehensive coverage of water forms, energy transduction mechanisms, materials and device advances, and application scenarios. We particularly appreciate the reviewer's insightful comments regarding performance comparison, mechanistic clarity, practical validation, and the need for a more systematic discussion of key challenges. We have carefully considered all the reviewer's comments and have revised the manuscript accordingly to address these concerns. We believe these revisions will enhance the depth and clarity of the review, and we are grateful to the reviewer for comments that helped us improve the manuscript to better meet the high standards of *Communications Materials*.

1. Referring to hydrovoltaic technology (Chem. Soc. Rev., 2022, 51, 4902-4927), what is the core distinction between the reviewed small-scale water energy harvesting and this hydrovoltaic technology in terms of energy conversion fundamentals, water-material interaction mechanisms and targeted water forms? Beyond common advantages, what unique technical merits does TENG-based harvesting offer over it specifically regarding adaptation to ultra-low energy density water sources, response to intermittent water supply and integration with flexible devices?

> **Our response**: We appreciate the reviewer's valuable comments and the opportunity to clarify the relationship between our review and the referenced work on hydrovoltaic technology. While both reviews address water-enabled electricity generation, they are organized around different scopes and perspectives. Our review is structured around the forms of water and a broad range of energy-transduction mechanisms within small-scale application contexts. In contrast, the hydrovoltaic technology review primarily focuses on a specific interfacial energy-conversion paradigm, namely direct electricity generation in materials driven by water–material interactions. Accordingly, our intent is to situate them within a wider landscape of small-scale water energy harvesting strategies. Beyond hydrovoltaic, interface-governed electricity generation, our review considers additional scenarios in which water serves as a mechanical, thermal, or coupled driving source to sustain or enhance electrical output. These include flow- or pressure-driven operation (e.g., electromagnetic turbine rotation or oscillatory flows), water-borne thermal driving enabled by heating/cooling and phase-change environments (such as geothermal gradients and snow- or ice-mediated thermal differentials), as well as thermally induced solvent or ion fluxes under steam-associated conditions. From this perspective,

the review aims to provide a cross-mechanism benchmarking framework that facilitates comparison across fundamentally different transduction routes under shared small-scale water harvesting constraints. In response, we have added a dedicated paragraph in the section 2 to explicitly distinguish the scope and conceptual framework of this review from hydrovoltaic energy conversion.
For the second comment, TENG-based water harvesting exhibits several technical features that complement hydrovoltaic approaches, particularly in deployment-relevant scenarios. First, TENGs are highly responsive to ultra-low energy-density water sources because contact electrification and electrostatic induction are sensitive to localized and weak mechanical stimuli (e.g., individual droplets, small-amplitude undulation, or microflows), enabling detectable output even at single-event scales. Second, TENGs are naturally compatible with intermittent water supply, as their energy conversion is event-driven rather than dependent on sustained gradients; recent device architectures have further demonstrated stable DC output under low-frequency and stochastic excitations, which is relevant for nonstationary water availability in practical environments. Third, TENGs are well suited for flexible and wearable integration owing to their reliance on soft and stretchable polymeric materials. In response to the reviewer's comment, we have emphasized these three technical advantages of TENG-based harvesting in Section 2.2.1.3 of the revised manuscript.

1. Introduction

In light of these opportunities and challenges, this review provides a comprehensive overview of the rapidly growing field of small-scale water-energy harvesting technologies. Compared with recent reviews on hydrovoltaic technology, which primarily focus on electricity generation driven by water–material interfacial interactions under quasi-static conditions[13], this review adopts a broader framework organized around different forms of water and the mechanical, thermal, and multiphysical driving forces they provide, enabling cross-mechanism comparison within small-scale water energy harvesting. Beginning with an analysis of water forms and energy transduction mechanisms, this review critically evaluate cutting-edge technologies through the lenses of material innovation, device architecture, and interfacial design. These advancements are further contextualized within their potential applications, spanning energy storage systems, real-time environmental sensing, and next-generation wearable electronics. Lastly, we conclude by summarizing the key challenges that remain and offering perspectives on future research directions, including high-performance interface design, long-term reliability, system integration, and standardized evaluation, with the aim of providing guidance for the further advancement of this field.

2.2.1.3 Triboelectric transduction

Since 2012, when Wang's group first reported energy harvesting through the interaction of two solid materials, extensive research has been conducted in the field of triboelectric nanogenerator (TENG) with laboratory experiments achieving power densities in the µW–mW range[157]. The triboelectric effect describes the process by which charges are generated and separated at the interface of two dissimilar materials upon contact and subsequent separation (Figure 3c and 3d). Subsequent separation or relative motion induces a flow of current through an external circuit[49,158-162]. In hydromechanical applications, TENGs can be actuated by flapping motion[159,163] or sliding surfaces driven by fluid forces. Unlike the traditional electromagnetic induction effect, the triboelectric effect mainly uses interface physical processes to achieve energy conversion[157], and therefore shows unique advantages in the collection of decentralized and microscale water flow[164,165] and water wave energy[166,167]. In water energy harvesting, TENGs are particularly effective for ultra-low energy-density and intermittent water sources, as contact electrification and electrostatic induction are highly sensitive to weak mechanical stimuli[168,169]. Their polymer-based architectures further enable straightforward integration with flexible and wearable devices[170,171]. The underlying mechanism of the triboelectric transductions can be attributed to the processes of contact electrification (CE) and electrostatic induction.

2. Table 1 compares energy transduction mechanisms but lacks explicit clarification of the standardized test conditions (e.g., ambient humidity, water flow velocity, temperature gradient, salinity) across different studies. This makes direct performance comparison unreliable. Could the authors supplement a standardized test condition framework or a sensitivity analysis to illustrate how environmental factors influence the reported energy density and efficiency?

Our response: We appreciate the reviewer's valuable comments. In response to this comment, Table 1 has been revised to explicitly report the "operating/test conditions" and "main performance contributors" utilized to evaluate each energy harvesting transduction mechanism. These new sets of columns have been added to summarize the key environmental parameters and experimental design factors that critically govern the conversion of the corresponding water energy into electrical output. By providing these mechanism-specific test conditions alongside the reported performance metrics, this addition facilitates an intuitive understanding of how each mechanism harnesses water-mediated stimuli to generate electrical energy, as well as promoting the association of other information with mechanisms in the table (device size, and energy density). The pros and cons. that were originally in Table 1 are separately summarized in Table 2, as the editorial policy in Communication Materials allows the single-page table only.

Table 1. Comparison of energy transduction mechanisms for small-scale water energy harvesting.

Table 2. Advantages and disadvantages of energy transduction mechanisms for small-scale water energy harvesting.

Table 1. Comparison of energy transduction mechanisms for small-scale water energy harvesting.

Mechanisms	Water forms	Operating/test conditions	Main performance contributors	Device size† (cm^2)	Energy density* ($\mu W/cm^2$)	Ref.
Phase-change–induced capillary flow	Gas, Liquid	➢ Humidity control - arid to humid air ➢ Direct water stream ➢ - soak one side of the device in water	➢ Wettability ➢ Continuous water uptake dynamics	0.25 - 30	0.0063-101	17-21
Ion concentration gradient	Gas	➢ Humidity control ➢ - arid to humid air	➢ Wettability ➢ Ion flux dynamics in active layer	0.01 - 25	0.0184-110	14, 21-24
Thermoelectric harvesting	Gas, Liquid, Solid (Snow/Ice)	➢ Temperature gradient - solar-driven steam ➢ - aboveground/subgrade	➢ Thermal coupling ➢ Optical/thermal properties	~10-200	~10-500	25-28
Thermo-osmotic and thermoelectro-kinetic conversion	Gas, Liquid	➢ Temperature gradient - water steam ➢ - hot/chilly water sinks	➢ Ionic Seebeck coefficient ➢ Soret-driven ionic migration	~0.09-1	~0.00008 -5	29-32
Electromagnetic transduction	Gas, Liquid	➢ Flow velocity - vapor or water flow	➢ Rate of magnetic flux change ➢ Flow induced rotation speed	30-700	0.09 - 4	33-38
Piezoelectric transduction	Liquid, Solid	➢ Mechanical oscillation - vortex in fluid - falling water droplets	➢ Strain amplitude ➢ Piezoelectric coupling	~0.13-0.5	0.0001-0.005	39-44
Triboelectric transduction	Gas, Liquid,Solid (Snow/Ice)	➢ Directional water flow - rotation of wheel - passing tap water ➢ Water wave - reciprocation of tube - rolling sphere ball	➢ Contact-separation dynamics ➢ Contact area	~0.03-200	~0.00005-1060	45-56
Droplet-driven mechanisms	Liquid	➢ Collision of droplet - impact & sliding droplet on device ➢ Motion of droplet - oscillating droplet in device on wave	➢ Wetting dynamics ➢ Droplet sliding dynamics	1-20	0.01863-~2.6×10^5	50-53, 57-65

† Unit for electromagnetic transduction is cm^3.

* Unit for electromagnetic transduction is $\mu W/(L\cdot min^{-1})$. Power (μW) measured under flow rate ($L\cdot min^{-1}$) conditions.

Table 2. Advantages and disadvantages of energy transduction mechanisms for small-scale water energy harvesting.

Mechanisms	Water forms	Advantages	Disadvantages	Ref.
Phase-change–induced capillary flow	Gas, Liquid	➢ Continuous energy input from the ambient ➢ Low cost ➢ Versatile material selection	➢ Environmental sensitivity ➢ Limited durability and power density ➢ Limited efficiency in non-optimized channels	17-21
Ion concentration gradient	Gas	➢ Continuous energy input from ambient ➢ Simple design and flexible ➢ Scalable through series or parallel connection.	➢ Environmental sensitivity ➢ Low Efficiency ➢ Depletion of ion concentration gradient over time	14, 21-24
Thermoelectric harvesting	Gas, Liquid, Solid	➢ High Reliability ➢ Low Maintenance	➢ Low Conversion Efficiency ➢ Cost	25-28
Thermo-osmotic and thermoelectro-kinetic conversion	Gas, Liquid	➢ Range of Material ➢ Flexibility ➢ High adhesive ➢ Self-Healing ➢ Small and Lightweight	➢ Stability and Durability ➢ Limited Power Output	29-32
Electromagnetic transduction	Gas, Liquid	➢ Easily retrofit and Modularization ➢ Long lifetime ➢ Wide power range	➢ Flow threshold behavior ➢ Noise/cavitation ➢ Environmental durability issues	33-38
Piezoelectric transduction	Liquid, Solid	➢ Low sensitivity to environment ➢ Compactness and Structural Simplicity ➢ Material Versatility	➢ Low power output ➢ Electrical Impedance Matching problem	39-44
Triboelectric transduction	Gas, Liquid,Solid(Snow/Ice)	➢ Material Versatility ➢ Long term stability ➢ Wide range of application scenarios ➢ Fast response time ➢ Low cost	➢ Electrical Impedance Matching problem ➢ High Internal Impedance ➢ Environmental Sensitivity ➢ Instant output power	45-56
Droplet-driven mechanisms	Liquid	➢ Material Versatility ➢ Long term stability ➢ Fast response time ➢ Low cost	➢ Limited Frequency Response ➢ Difficulty of maintaining the same output every drop ➢ Instant output power	50-53, 57-65

3. For the "ion concentration gradient" mechanism, the review mentions "ion depletion issues" but provides limited discussion on effective mitigation strategies (e.g., ion replenishment designs, material regeneration technologies) and their long-term performance. Could the authors elaborate on recent progress in addressing ion depletion and provide quantitative data on the operational lifespan of relevant devices?

Our response: We appreciate the reviewer for this insightful suggestion. In the revised manuscript, we have added some new content in Section 3.1.2 to discuss the ion gradient depletion issues of MEGs and highlight representative recent mitigation strategies and their long-term performance. The added content shows as follows:

Section 3.1.2. Ion concentration gradient

Zhang et al.[87] proposed a laminated structure that comprising a cation-selective Nafion membrane sandwiched between hydrogels with disparate LiCl concentrations (4M/0.01M) (Figure 6g), which can establish a Li^+ gradient and selective Li^+ diffusion, enabling directional cation migration. Additionally, Kim et al.[85] employed Marangoni-assisted gelation to fabricate a LiBr-rich-to-lean gradient from the top to the bottom of the Fumion FAA-3 hydrogel (FAA gel) (Figure 6h). By synchronizing this gradient with the direction of water flow, their MEG delivered a current density 15-fold higher than that of pure FAA gel under 80% RH (Figure 6i). Even under conditions of limited moisture, the device can still generate electricity through its inherent salt concentration gradient.

The power generation duration of ion concentration gradient-based MEGs typically ranges from seconds to days[12,15-22]. However, a key challenge is that the ion gradient progressively weakens or even dissipates entirely as directional ion migration continues. This results in saturation of the water content and substantial decay in electrical output, thereby limiting the long-term operational stability[14,17-24]. Recently, various effective mitigation strategies have been proposed to address this issue. One notable approach is the previously mentioned construction of dual-sided moisture exposure architecture, which consists of an absorption layer and an evaporation layer. This design can generate a persistent, running-water circle, thereby counteracting the depletion of the ion concentration gradient[222,246]. As reported by Tan et al.[222], MEGs based on this structure can produce a continuous voltage of 0.78 V and a current of 7.5 μA (25°C, 60% RH) for more than 10 days. Another strategy is based on ionic diode rectification, which selectively filters ions using negatively charged or positively charged nanochannels. It allows ions to migrate in one direction while substantially suppressing reverse diffusion, thereby maintaining an asymmetric charge distribution over extended periods of operation. Zhang et al.[212] implemented an ionic diode–type hybrid membrane composed of carbon nanotubes (CNT) and anodic aluminium oxide (AAO) in MEGs, forming a PN-junction-like built-in electric field and thus enabling selective ion separation and steady-state unidirectional ion transport. The resulting devices can generate continuous electrical output for at least one month. Building upon this strategy, Fu et al.[247] further integrated electrode regulation to develop a durable MEG that combines directional ion transport with interfacial charge management, enabling continuous power generation for up to 1240 h under ambient humidity. In this design, redox-active electrodes were employed to consume accumulated ions via ion intercalation or redox reactions, rather than allowing passive charge buildup, thereby effectively suppressing electrostatic screening and current decay. Moreover, Duan et al.[248] proposed a photocatalysis-assisted ion gradient reconstruction strategy by introducing a photocatalytic layer beneath the moisture-absorption layer. Under light illumination, photogenerated charge carriers drive the hydrogen evolution reaction, consuming accumulated H^+ ions and releasing H_2, thereby reconstructing the ion gradient and extending continuous current output to 650 h.

4. Hybrid systems (e.g., moist-thermoelectric generators, MTEG) are highlighted as a future direction, but the synergistic mechanism between complementary transduction modules (e.g., humidity-responsive layers and thermoelectric units) and optimization methods for interface charge transfer and energy coupling are not sufficiently detailed. Could the authors elaborate on the design principles and performance enhancement mechanisms of hybrid systems?

Our response: We sincerely thank the reviewer for this insightful comment. Following the reviewer's suggestion, we have revised the manuscript in section 4.1.1 to explain on the synergistic mechanisms and energy coupling principles within the MTEG system to show why the hybrid system is advanced. We believe these additions provide a much clearer theoretical framework for the observed performance. The revised text is as follows:

4.1.1 Static water energy harvesting

To further enhance energy-harvesting efficiency, researchers proposed an integrated moist–thermoelectric generator (MTEG) that couples thermoelectric and moisture-electric conversion for efficient recovery of steam energy[29,339-341]. The core design principle of such systems lies in the spatial and functional synchronization of thermal and moisture gradients to minimize internal impedance and maximize carrier flux. Yang et al. addressed the challenge of underutilized waste-steam energy in industrial environments by developing a flexible MTEG that employs a polymer electrolyte copolymer membrane (PAMPS/PSSS) as the core functional layer[29] (Figure 15e). The hybrid performance enhancement mechanism is based on a synergistic enhancement loop between the temperature gradient (ΔT) and the moisture gradient (ΔRH). On the one hand, high-humidity conditions induce extensive water adsorption, promoting the dissociation of functional groups (-SO3H) and increasing the concentration of mobile ions. This provides a significantly higher density of charge carriers for the Soret-effect-driven thermodiffusion, thereby amplifying the thermoelectric output. On the other hand, the established ΔT accelerates localized water evaporation and transport dynamics, which, in turn, sustain and widen the ΔRH. This cyclic synergy ensures a continuous supply of carriers and a sustained driving force. Consequently, this "1 + 1 > 2" synergistic energy-conversion effect resulted in an open-circuit voltage of 1.81 V and a power density of 4.75 $\mu W \cdot cm^{-2}$ under a ΔT of 15 K and a ΔRH of 60%, far exceeding that of conventional single-function TEG or MEG systems.

5. The application section on self-powered sensors lacks long-term performance data from practical deployments (e.g., continuous operation time, signal stability under complex environmental interference). Could the authors supplement field test results from specific scenarios?

Our response: We thank the reviewer's comment. In the revised manuscript, we have added some long-term test results for the application to highlight the reliability of the self-powered sensors using the small-scale water energy nanogenerators.

4.2.1 Self-powered physical sensors

By attaching it to plant surfaces, a self-powered agricultural system was constructed. This WB-TENG does not affect the plant leaf surface and thus does not affect its transpiration and growth. Simultaneously, by harnessing wind-induced vibrations and raindrop impacts experienced by the plant, the WB-TENG can continuously harvest ambient mechanical energy and provide a stable power supply for wireless sensors around the plant, enabling real-time monitoring of key agricultural parameters such as soil moisture, light intensity, and temperature. The biocompatibility and the reliability of the WB-TENG have also been investigated. After 55 days under moderate sunlight and in an indoor environment, new leaves and roots have grown, indicating that the device does not affect the plant's normal growth. The output voltage of the WB-TENG shows only a slight difference (~500V to ~450V) after long-term testing. Furthermore, Zhang et al. constructed a self-powered humidity sensor (SPHS) using MEG to enable real-time monitoring of humidity in agricultural environments[353] (Figure 17b). This device employs a PSS/PVA/LiCl electrolyte membrane, which has strong hygroscopic capacity, as its core functional layer. It drives water-molecule adsorption and directional ion diffusion along the ambient humidity gradient, coupled with a metal-air redox reaction, thereby generating a stable DC signal without an external power source. Experimental results show that the sensor's response range covers 33–91% RH, with the output current increasing from 2.6 μA to 76.1 μA, exhibiting excellent linearity ($R^2 = 0.988$) and high sensitivity to changes in ambient humidity. The researchers further integrated this device with a wireless transmission module and auxiliary sensors, such as temperature/light intensity, to construct a long-term, operationally robust agricultural microenvironment monitoring system, demonstrating its broad application potential in precision agriculture, smart farmland management, and maintenance-free IoT sensor networks. The device undergoes a long-term reliability test in a high-humidity environment (91%) to demonstrate its capability in an agricultural environment, achieving an average short-circuit current (I_{sc}) of more than 75 μA for 10000s.

By utilizing the instantaneous response characteristics of TENG to external mechanical stimuli, its output electrical signal can not only be used for energy harvesting, but also as a sensitive indicator of changes in distance[283], speed[291,368], or position[369]. Zhang et al. proposed a self-powered water level sensor based on a tubular liquid-solid TENG (LST-TENG)[370] (Figure 17c). This device uniformly distributes multiple sets of copper electrodes on the outer wall of a PTFE tube. The rise and fall of water within the tube induces charge transfer at the liquid-solid interface, enabling water level detection without an external power source. Research shows that when the water level crosses different electrode regions, the rate of change of the open-circuit voltage (dV_{OC}/dt) exhibits corresponding positive peaks or negative troughs. These characteristic signals correspond one-to-one with the electrode distribution and can serve as accurate indicators of water level. Based on this principle, they applied the LST-TENG to ship draft monitoring, achieving a water level identification accuracy of 10 mm resolution, approximately ten times higher than traditional measuring tapes. Furthermore, the system maintains stable output under different salinity levels (0–35 $mg \cdot mL^{-1}$) and different water level change frequencies, demonstrating excellent environmental adaptability and practical application potential. LST-TENG also shows stable long-term results, with the output voltage peak remain stable (~12V) before and after 2000 cycles at a frequency of 0.9Hz. Moreover, Yang et al. developed a grounded electrode-based droplet generator (EG-DEG) [371] (Figure 17d). Unlike traditional single-electrode DEG, the EG-DEG employs a three-electrode structure: two strip-shaped upper electrodes deposited on a PTFE surface are grounded, while the bottom GSEC electrode is connected to a current amplifier. As a droplet slides along the device surface, it sequentially crosses the two upper electrodes, generating two clearly distinguishable current pulses. By measuring the time interval between these two pulses and combining it with the known electrode spacing, the EG-DEG can achieve millisecond-level measurement of the average droplet sliding velocity, thus enabling high-precision monitoring of droplet dynamics. To further verify its application potential, the authors integrated the EG-DEG into a liquid pipeline to achieve real-time monitoring of fluid flow velocity. As continuous liquid flows through the device, the resulting periodic disturbances generate a stable AC signal, and the frequency of the signal pulses increases with the flow velocity. Therefore, by analyzing the frequency of the output signal, the EG-DEG can quantitatively monitor the fluid flow velocity within the pipeline without any external power supply. The stable current output(~6.5uA) of the EG-DEG during continuous water droplet impinging for 10000 cycles shows the repeatability and reliability of the device in water droplet energy harvesting. Furthermore, Chen et al.

proposed a self-powered Triboelectric Microfluidic Sensor (TMS), further expanding the application scenarios of sensing based on small-scale water energy[372] (Figure 17e). This device utilizes the contact electrification and electrostatic induction signals generated when droplets or bubbles pass through the PTFE triboelectric interface in a microchannel to achieve real-time fluid monitoring without an external power source. Experiments show that the TMS can cover a wide dynamic range for liquids (~3–95 μL/s) and gases (~7–280 μL/s), and the output signal exhibits a good linear relationship with the flow rate. More importantly, this sensor demonstrates high application potential in real-world scenarios, such as for monitoring intravenous infusion drip rates and detecting airflow in industrial pipelines, realizing a power-free, low-cost, and easily integrated microfluidic monitoring solution.

4.2.3 Self-powered biomedical sensors

The amplitude and charge characteristics of this signal exhibit discernible shifts depending on the ionic strength, pH, specific gravity, viscosity, and pathological components of the urine. In experimental data, normal urine samples typically showed low charge output, while pathological samples containing glucose, protein, or high ion concentrations exhibited significantly enhanced voltage and current signals due to differences in conductivity and interfacial contact characteristics. Through systematic comparative experiments, the researchers successfully identified passive electrical signals associated with various physiological abnormalities, including diabetes, proteinuria, and electrolyte imbalances. The device was then exposed to a toxic experimental environment for more than 270 days and consistently performed, demonstrating its long-term reliability even in extreme conditions.

6. Energy management systems (e.g., micro-energy storage devices, impedance matching circuits) are only briefly mentioned in future directions, with insufficient discussion on their compatibility with low-power output from small-scale water energy harvesters. Could the authors elaborate on the current status and challenges of energy conditioning and storage technologies tailored for such harvesters?

Our response: We thank the reviewer for this important comment. In the revised manuscript, we have expanded the discussion of energy management systems to better address their compatibility with the low-power, intermittent, and high-impedance output of small-scale water energy harvesters.

5. Outlook

(iii) Without efficient power management, a substantial fraction of harvested energy is lost before reaching the load, particularly given the low-amplitude, high-impedance, and often intermittent output characteristics of small-scale water energy harvesters. Based on this, future research should co-design harvesters with ultra-low-loss power electronics, impedance-matched interfaces, and microscale buffers (e.g., microcapacitors, thin-film batteries, and hybrid microsupercapacitors) tailored to low-frequency, pulsed energy inputs. In addition, energy-aware control strategies—such as event-driven operation, duty-cycled sensing, and adaptive load management—are needed to minimize standby losses and enable energy-neutral sensing and local processing under realistic environmental conditions.

7. For wearable device applications, biocompatibility and wear comfort (e.g., breathability, skin irritation) of materials are not mentioned. Could the authors supplement research advances in biocompatible materials and their safety test results (e.g., cytotoxicity tests)?

Our response: We thank the reviewer's comment. For the wearable device, which may contact the skin and breathing system, it is important to study the biocompatibility of the materials. We have added some common materials safety tests in the section 4.3.

4.3 Self-powered wearable devices

By integrating multiple BSNG units with a wireless transmission module, the researchers demonstrated multi-point underwater motion monitoring, capable of capturing joint movements during swimming in real time. The system also enables practical underwater safety functions: when used in conjunction with an energy storage module, the BSNG embedded in a diving suit can power a wireless distress signal transmitter and remotely activate warning lights. As the self-powered wearable device will have the chance to contact with the skin, the safety performance of the materials is one of the important fields need to be study. Some common TENG materials had been studies on the biocompatibility, such as (GO)PANI, Yan et al. with the using of the mouse fibroblast cell line L929[391], a commonly used cell to test the cytotoxicity. MTT colorimetric assay, a method to test the cell viability and proliferation is done to test the cytocompatibility of the samples, which shown the survival rate on the (GO)PANI is 5% higher than GO after 96h, reaching 95%, showing a high biocompatibility. Another commonly used material, polydimethylsiloxane(PDMS) and polyvinylidene fluoride(PVDF) are also studied by Li et al.[392] With the PDMS and PVDF nanogenerators implanted inside female mice for six months. Histological analysis of the skin, muscles and tissue, blood and serum test had been done to test the biocompatibility and with no signs of toxicity or incompatibility were observed.

8. The review proposes "standardized evaluation" as a future direction but does not identify the core standardized metrics that are currently lacking (e.g., energy density measurement methods, environmental stability evaluation systems). Could the authors list priority metrics for standardization to guide future research and industrialization?

Our response: We sincerely thank the reviewer for this insightful comment. We have revised the manuscript to identify some priority metrics which are recommended to be standardized for small-scale water energy harvesting technologies as follows:

5. Outlook

(v) The lack of standardized metrics currently hinders meaningful comparison among harvesting technologies, as performance is often reported under disparate environmental conditions and timescales. To address this issue, several priority metrics should be standardized. First, electrical output normalized by device area or volume is recommended to enable comparison across different architectures. Second, key test conditions—including humidity (e.g., 10–90%), temperature (e.g., 25 °C), flow velocity, and droplet parameters—should be explicitly specified and standardized. Finally, durability metrics, such as time to a defined level of performance degradation under controlled aging and environmental cycling, are needed to assess long-term stability.

9. Hybrid solar-water energy harvesting systems are briefly introduced, but the energy distribution strategy and complementary working modes (e.g., switching mechanisms between sunlight and rainfall) are not elaborated. Could the authors supplement design principles and performance optimization methods for such hybrid systems?

Our response: We thank the reviewer for this comment. In the revised manuscript, we have expanded the discussion of hybrid solar–water energy harvesting systems by providing clearer design principles and outlining key strategies for system optimization. We have also incorporated additional mechanisms relevant to these hybrid systems, thereby enriching the discussion of current technological approaches in solar–water energy harvesting.

4.4.3 Solar-water energy harvesting hybrid system

To further expand the application scenarios of small-scale water-energy harvesters, researchers have begun to explore hybrid energy harvesting systems that couple water-based energy conversion with other energy sources, enabling stable and efficient power generation under diverse environmental conditions, with solar panels merging with the droplet electricity generators (DEGs), receiving solar energy during sunlight and water energy during rainfall. Compared with other hybrid solar water energy harvester simply stacking the solar panel and the DEG with separate electrodes, which will lead to transmittance, conversion efficiency, low instantaneous peak power output and manufacturing problems, Liao et al. proposed a hybrid solar–water energy generator with a common-electrode architecture (HEG-CEA)[397] (Figure 19g). In this design, the solar cell itself serves simultaneously as the electrode for the DEG, with both solar panel and DEG sharing the same electrode, taking advantage of its high electrical conductivity and avoiding the optical losses typically associated with stacked configurations. By directly covering the solar cell with an FEP film and introducing a micro top-electrode, the HEG-CEA achieves synergistic conversion of both solar and droplet energy without sacrificing light transmittance. Experimental results show that, compared with conventional systems without a shared electrode, the HEG-CEA with the absence of the barrier of additional conductive layer, improves solar energy conversion efficiency by ~10% and enhances droplet energy conversion efficiency by more than two orders of magnitude. Other optimization of the device includes the control of FEP thickness, which the open circuit voltage and short circuit are quasi-proportional to the thickness, reaching the optimum at thickness 70μm. The salt concentration of the water droplet, the droplet volume and release height are other parameter that affect the output performance of the device. In experimental results, even enables a single droplet to directly power a 20 W light bulb at the end. Furthermore, in real outdoor environments, the system can simultaneously harvest sunlight and high-velocity droplet impact energy to charge capacitors and power wireless temperature–humidity sensors, demonstrating reliable all-weather energy supply capability.

Other than the shared electrode design of the solar water energy harvesting hybrid system. Guo et al. proposed a design that integrates the water droplet TENG and the photovoltaics (PV) using a copper electrode, ethylene tetrafluoroethylene (ETFE) layer and bottom silicon cell [398]. The design is to improve the light absorption by using surface modification techniques, the ETFE layer, which is an anti-reflection layer to increase the light transmission to the PV cell and a hydrophobic material for the TENG. With the textured ETFE layer with pyramid pattern on the silicone PV cell, which increases the optical distance and light absorption.

All in all, I would like to give a major revision chance for this manuscript.

Our response: We thank you again for your valuable comments.

Reviewer #3

This manuscript provides a comprehensive, well-organized, and timely review of small-scale water energy harvesting technologies. It successfully bridges fundamental transduction mechanisms, state-of-the-art materials and device architectures, and diverse applications—from self-powered sensors to wearable systems. The review is thorough, logically structured, and richly supported with recent references and illustrative figures.

> **Our response**: We appreciate the reviewer's positive feedback. These constructive comments and valuable suggestions will help us enhance the quality of the manuscript. We have carefully addressed each of the reviewer's concerns below.

1.Sections 3.1–3.3 thoroughly describe examples but could benefit from more comparative critique. For instance, in Table 1, some power density ranges span several orders of magnitude. Adding a brief commentary on what factors lead to such variability (e.g., material choices, testing conditions, scaling effects) would provide deeper insight.

> **Our response**: We thank the reviewer for raising this important point regarding the lack of standardized performance metrics. In response, we have revised Table 1 to explicitly include the "operating/test conditions" and "main performance contributors" used to evaluate each energy-harvesting transduction mechanism. Furthermore, The pros and cons. that were originally in Table 1 are separately summarized in Table 2, as the editorial policy in Communication Materials allows the single-page table only.
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> **Table 1**. Comparison of energy transduction mechanisms for small-scale water energy harvesting.
>
> **Table 2**. Advantages and disadvantages of energy transduction mechanisms for small-scale water energy harvesting.

Table 1. Comparison of energy transduction mechanisms for small-scale water energy harvesting.

Mechanisms	Water forms	Operating/test conditions	Main performance contributors	Device size† (cm^2)	Energy density* ($\mu W/cm^2$)	Ref.
Phase-change–induced capillary flow	Gas, Liquid	➢ Humidity control - arid to humid air ➢ Direct water stream ➢ - soak one side of the device in water	➢ Wettability ➢ Continuous water uptake dynamics	0.25 - 30	0.0063-101	17-21
Ion concentration gradient	Gas	➢ Humidity control ➢ - arid to humid air	➢ Wettability ➢ Ion flux dynamics in active layer	0.01 - 25	0.0184-110	14, 21-24
Thermoelectric harvesting	Gas, Liquid, Solid (Snow/Ice)	➢ Temperature gradient - solar-driven steam ➢ - aboveground/subgrade	➢ Thermal coupling ➢ Optical/thermal properties	~10-200	~10-500	25-28
Thermo-osmotic and thermoelectro-kinetic conversion	Gas, Liquid	➢ Temperature gradient - water steam ➢ - hot/chilly water sinks	➢ Ionic Seebeck coefficient ➢ Soret-driven ionic migration	~0.09-1	~0.00008 -5	29-32
Electromagnetic transduction	Gas, Liquid	➢ Flow velocity - vapor or water flow	➢ Rate of magnetic flux change ➢ Flow induced rotation speed	30-700	0.09 - 4	33-38
Piezoelectric transduction	Liquid, Solid	➢ Mechanical oscillation - vortex in fluid - falling water droplets	➢ Strain amplitude ➢ Piezoelectric coupling	~0.13-0.5	0.0001-0.005	39-44
Triboelectric transduction	Gas, Liquid,Solid (Snow/Ice)	➢ Directional water flow - rotation of wheel - passing tap water ➢ Water wave - reciprocation of tube - rolling sphere ball	➢ Contact-separation dynamics ➢ Contact area	~0.03-200	~0.00005-1060	45-56
Droplet-driven mechanisms	Liquid	➢ Collision of droplet - impact & sliding droplet on device ➢ Motion of droplet - oscillating droplet in device on wave	➢ Wetting dynamics ➢ Droplet sliding dynamics	1-20	0.01863-~2.6×10^5	50-53, 57-65

† Unit for electromagnetic transduction is cm^3.
* Unit for electromagnetic transduction is $\mu W/(L\cdot min^{-1})$. Power (μW) measured under flow rate ($L\cdot min^{-1}$) conditions.

Table 2. Advantages and disadvantages of energy transduction mechanisms for small-scale water energy harvesting.

Mechanisms	Water forms	Advantages	Disadvantages	Ref.
Phase-change–induced capillary flow	Gas, Liquid	➢ Continuous energy input from the ambient ➢ Low cost ➢ Versatile material selection	➢ Environmental sensitivity ➢ Limited durability and power density ➢ Limited efficiency in non-optimized channels	17-21
Ion concentration gradient	Gas	➢ Continuous energy input from ambient ➢ Simple design and flexible ➢ Scalable through series or parallel connection.	➢ Environmental sensitivity ➢ Low Efficiency ➢ Depletion of ion concentration gradient over time	14, 21-24
Thermoelectric harvesting	Gas, Liquid, Solid	➢ High Reliability ➢ Low Maintenance	➢ Low Conversion Efficiency ➢ Cost	25-28
Thermo-osmotic and thermoelectro-kinetic conversion	Gas, Liquid	➢ Range of Material ➢ Flexibility ➢ High adhesive ➢ Self-Healing ➢ Small and Lightweight	➢ Stability and Durability ➢ Limited Power Output	29-32
Electromagnetic transduction	Gas, Liquid	➢ Easily retrofit and Modularization ➢ Long lifetime ➢ Wide power range	➢ Flow threshold behavior ➢ Noise/cavitation ➢ Environmental durability issues	33-38
Piezoelectric transduction	Liquid, Solid	➢ Low sensitivity to environment ➢ Compactness and Structural Simplicity ➢ Material Versatility	➢ Low power output ➢ Electrical Impedance Matching problem	39-44
Triboelectric transduction	Gas, Liquid,Solid(Snow/Ice)	➢ Material Versatility ➢ Long term stability ➢ Wide range of application scenarios ➢ Fast response time ➢ Low cost	➢ Electrical Impedance Matching problem ➢ High Internal Impedance ➢ Environmental Sensitivity ➢ Instant output power	45-56
Droplet-driven mechanisms	Liquid	➢ Material Versatility ➢ Long term stability ➢ Fast response time ➢ Low cost	➢ Limited Frequency Response ➢ Difficulty of maintaining the same output every drop ➢ Instant output power	50-53, 57-65

2.Section 4 covers many applications but could be more structured. Subdividing "4.4 Other Applications" into thematic areas (e.g., environmental remediation, corrosion protection, hybrid systems) might improve flow and readability.

Our response: We thank the reviewer's comment. We've amended the section 4.4 by subdividing it into several thematic subsections based on application categories as follows:

4.4 Other applications

In addition to the typical applications discussed above, such as energy harvesting, self-powered sensing, and self-powered wearable device, high-performance small-scale water energy transducers have also demonstrated significant value in some other scenarios[308,393-396], expanding their functional boundaries in real-world environments.

4.4.1 Corrosion protection

Sun et al. addressed the challenge of metal corrosion in humid and marine environments by integrating liquid–solid TENGs with cathodic protection (CP) technology, proposing a self-powered cathodic protection system based on an array of liquid–solid TENG units[308] (Figure 19e). In their design, PTFE ultrafiltration membranes were used as the liquid–solid triboelectric layer, and multiple water-sealed TENG cells were encapsulated and connected in parallel to form an energy-harvesting array capable of continuously extracting mechanical energy from wave-induced vibrations. The array delivered a short-circuit current of up to 2.68 mA and an output voltage of 105 V in a 3.5 wt% NaCl solution, and successfully provided an impressed cathodic bias for A3 carbon steel. As a result, the open-circuit potential of the steel shifted negatively by approximately 330 mV, markedly suppressing its corrosion tendency compared with unprotected samples.

4.4.2 Remote wireless communication

Remote wireless communication represents an important emerging application of small-scale water energy harvesting, particularly in scenarios where wired power supply or frequent battery replacement is impractical. Shen et al. utilized a MEG based on ionized hydrogels to achieve stable operation in an underwater environment and continuously power a wireless transmitter, thus enabling real-time underwater signal transmission[224] (Figure 19f). When integrated into an underwater device, the device can continuously output a voltage of approximately 1.0 V and successfully power the wireless communication module, thereby achieving real-time underwater signal transmission without any auxiliary power source. Their research results demonstrate that small hydroelectric harvesters are not merely passive energy converters; rather, they can act as active communication nodes, driving wireless electronic devices, transmitting environmental information, and supporting autonomous operation in complex environments, especially where batteries are unreliable or difficult to obtain.

4.4.3 Solar-water energy harvesting hybrid system

To further expand the application scenarios of small-scale water-energy harvesters, researchers have begun to explore hybrid energy harvesting systems that couple water-based energy conversion with other energy sources, enabling stable and efficient power generation under diverse environmental conditions, with solar panels merging with the droplet electricity generators (DEGs), receiving solar energy during sunlight and water energy during rainfall. Compared with other hybrid solar water energy harvester simply stacking the solar panel and the DEG with separate electrodes, which will lead to transmittance, conversion efficiency, low instantaneous peak power output and manufacturing problems, Liao et al. proposed a hybrid solar–water energy generator with a common-electrode architecture (HEG-CEA)[397] (Figure 19g). In this design, the solar cell itself serves simultaneously as the electrode for the DEG, with both solar panel and DEG sharing the same electrode, taking advantage of its high electrical conductivity and avoiding the optical losses typically associated with stacked configurations. By directly covering the solar cell with an FEP film and introducing a micro top-electrode, the

HEG-CEA achieves synergistic conversion of both solar and droplet energy without sacrificing light transmittance. Experimental results show that, compared with conventional systems without a shared electrode, the HEG-CEA with the absence of the barrier of additional conductive layer, improves solar energy conversion efficiency by ~10% and enhances droplet energy conversion efficiency by more than two orders of magnitude. Other optimization of the device includes the control of FEP thickness, which the open circuit voltage and short circuit are quasi-proportional to the thickness, reaching the optimum at thickness 70μm. The salt concentration of the water droplet, the droplet volume and release height are other parameter that affect the output performance of the device. In experimental results, even enables a single droplet to directly power a 20 W light bulb at the end. Furthermore, in real outdoor environments, the system can simultaneously harvest sunlight and high-velocity droplet impact energy to charge capacitors and power wireless temperature–humidity sensors, demonstrating reliable all-weather energy supply capability.

Other than the shared electrode design of the solar water energy harvesting hybrid system. Guo et al. proposed a design that integrates the water droplet TENG and the photovoltaics (PV) using a copper electrode, ethylene tetrafluoroethylene (ETFE) layer and bottom silicon cell[398]. The design is to improve the light absorption by using surface modification techniques, the ETFE layer, which is an anti-reflection layer to increase the light transmission to the PV cell and a hydrophobic material for the TENG. With the textured ETFE layer with pyramid pattern on the silicone PV cell, which increases the optical distance and light absorption.

3. The reference list is extensive and up-to-date. A quick check for very recent breakthroughs in this area such as : (Advanced Materials. 18 (2025), 2505613. https://doi.org/10.1002/adma.202505613; J. Adv. Manuf. Sci. Technol. 4 (2024), 2024005. https://doi.org/10.51393/j.jamst.2024005; ACS Appl. Mater. Interfaces 16 (2024), 32249. https://doi.org/10.1021/acsami.4c04251; Nano Energy 129 (2024), 110056. https://doi.org/10.1016/j.nanoen.2024.110056; Adv. Mater. Technol. 2400554. https://doi.org/10.1002/admt.202400554; Applied materials today 41 (2024), 102492. https://doi.org/10.1016/j.apmt.2024.102492)should be commented.

Our response: We thank the reviewer for recommending these recent and relevant references. We have carefully reviewed the suggested works and have cited them in the revised manuscript as follows.

1. Introduction

Beyond the traditional water energy harvesting, the rapid expansion of the Internet of Things (IoT), with device counts projected in the tens of billions[9,R1], is shifting demand patterns toward numerous, spatially distributed, low-power loads. This evolution has renewed interest in localized electrical generation paradigms—such as microgrids, distributed generators, and energy-harvesting systems—that are intended to supplement, rather than supplant, centralized generation.

2.2.1.3 Triboelectric transduction

Since 2012, when Wang's group first reported energy harvesting through the interaction of two solid materials, extensive research has been conducted in the field of triboelectric nanogenerator (TENG) with laboratory experiments achieving power densities in the μW–mW range[157]. The triboelectric effect describes the process by which charges are generated and separated at the interface of two dissimilar materials upon contact and subsequent separation (Figure 3c and 3d). Subsequent separation or relative motion induces a flow of current through an external circuit[49,158-160,R2,R3]. In hydromechanical applications, TENGs can be actuated by flapping motion[159,163] or sliding surfaces driven by fluid forces. Unlike the traditional electromagnetic induction effect, the triboelectric effect mainly uses interface physical processes to achieve energy conversion[157], and therefore shows unique advantages in the collection of decentralized and microscale water flow[164,165] and water wave energy[166,167].

4.2.1 Self-powered physical sensors

Sensors, as a core component of Internet of Things (IoT) systems, are key devices for collecting physical parameters such as ambient temperature[200,351,352], humidity[353,354], and motion[355, 356.R4-R6]. In the field of self-powered physical sensors, small-scale water energy harvesting technology not only serves as an energy supplier[242,360] but also achieves a "signal-for-sensing" functional mode through the inherent coupling relationship between its output signal and the information to be measured in the environment[291,361].

R1. Yang, J. et al. Triboelectric nanogenerators with machine learning for internet of things. *Adv. Mater. Technol.* **10**, 2400554 (2025).

R2. Zhu, X. et al. A review of charge excitation triboelectric nanogenerator performance enhancement and related applications. *Appl. Mater. Today* **41**, 102492 (2024).

R3. Hao, Y. et al. Self-powered terahertz modulators based on metamaterials, liquid crystals, and triboelectric nanogenerators. *ACS Appl. Mater. Interfaces* **16**, 32249-32258 (2024).

R4. Hao, Y. et al. Evaluation and rehabilitation system for ulnar‐Innervated muscles facilitated by rare earth oxide‐enhanced triboelectric sensor. *Adv. Mater.*, 2505613 (2025).

R5. Yang, J. et al. Mica/nylon composite nanofiber film based wearable triboelectric sensor for object recognition. *Nano Energy* **129**, 110056 (2024).

R6. Hao, Y. et al. Flexible and sensitive sensor based on triboelectric nanogenerator and electrospinning. *J. Adv. Manuf. Sci. Technol* **4**, 10.51393 (2024).