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Unlocking Interfacial Charge at Dielectric Solid–Liquid Interfaces via Triboelectric Nanogenerator Probe

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1 | Introduction

Electrical double layers (EDLs) are fundamental to solid–liquid interfacial phenomena, orchestrating charge compensation, ionic ordering, and solvent reorganization. Through these coupled processes, EDLs regulate a wide spectrum of behaviors from electrochemical reactivity and colloidal stability to energy transduction and information signaling [1–5]. Despite their central importance across chemistry, materials science, and physics, experimental insight into EDLs has been largely shaped by a narrow subset of interfaces, those involving electrically conductive solids [6–9]. Classical EDL models, originating from the Helmholtz [10], Gouy–Chapman [11, 12], and Gouy–Chapman–Stern [13] descriptions, were developed to rationalize charge separation at electrode–electrolyte boundaries. Although these frameworks have been progressively refined to account for ion size, specific adsorption, hydration, and ion–ion correlations, both their formulation and experimental validation rely predominantly on interfaces where electrical potentials can be externally imposed and directly measured [14–16]. Consequently, the concept of the EDL has often become, implicitly, synonymous with electrochemically addressable interfaces.

This electrochemical electrode-centric perspective obscures a far broader and more pervasive class of interfaces: dielectric solids in contact with liquids. Electrically insulating materials, including polymers, oxides, and biological surfaces, dominate both natural and engineered environments, where interfacial charge organization is expected on fundamental grounds. Probing EDLs at dielectric solid–liquid interfaces is fundamentally important as their interfacial charge organization governs ionic transport and interfacial electric fields. Yet direct experimental access to the structure and dynamics of EDLs at dielectric-liquid interfaces remains strikingly limited [17–19]. Dielectric surfaces, unlike conductive electrodes, lack mobile charge carriers and cannot sustain applied potentials, making conventional electrochemical probes largely ineffective. The key challenge lies in the absence of experimental strategies to access their interfacial EDLs [20, 21]. Existing methods typically rely on applied bias or conductive substrates to convert ionic rearrangements into measurable signals, leaving fundamental questions unresolved: how do EDLs form and evolve at nonconductive interfaces, and how are they governed by ionic strength, ion identity, and interfacial asymmetry beyond the dilute limit? Addressing these issues requires moving beyond electrode-centric paradigms to probe interfacial charge without direct electrical control.

2 | Current Methods for Accessing EDLs

Over recent decades, a diverse experimental toolbox has emerged to probe EDLs at solid-liquid interfaces as shown in Figure 1. Electrochemical techniques, such as electrochemical impedance spectroscopy [22] (EIS, Figure 1A), scanning electrochemical microscopy [23] (SECM, Figure 1B), and electrochemical quartz crystal microbalance [24] (EQCM, Figure 1C), enable detailed characterization of interfacial capacitance, charge-transfer kinetics, mass transport, and local heterogeneity, whereas spectroscopic approaches, notably surface-enhanced Raman spectroscopy [25] (SERS, Figure 1D), provide molecular-level insight into ion adsorption, solvation structure, and interfacial chemistry. Together, these methods form the foundation of our understanding of EDL structure and dynamics at electrochemically addressable interfaces. Their effectiveness, however,

depends critically on conductive or semiconductive substrates: by leveraging applied potentials, currents, or electrode-coupled transduction, they sensitively track potential-dependent ionic rearrangements and interfacial reactions. Extending this paradigm to dielectric materials exposes intrinsic limitations: insulating solids cannot sustain controlled interfacial potentials, and even adapted measurements often rely on auxiliary electrodes or indirect perturbations that obscure the intrinsic EDL of dielectric-liquid interfaces.

To circumvent these constraints, alternative approaches have been explored. X-ray-based techniques offer atomic-scale sensitivity to interfacial structure and composition [26] (Figure 1E), scanning probe methods, such as Kelvin probe force microscopy [27] (KPFM), provide spatially resolved surface potential information (Figure 1F), and vibrational spectroscopies, such as Fourier transform infrared spectroscopy [28] (FTIR), yield insight into interfacial water structure and ion-specific interactions (Figure 1G). Although these approaches have provided valuable snapshots of dielectric-liquid interfaces, they entail inherent trade-offs. X-ray techniques require large-scale facilities and offer limited temporal resolution; scanning probe methods are sensitive to environmental fluctuations and challenging to implement in liquids; and vibrational spectroscopies infer electrostatics indirectly, often without quantitative access to interfacial charge distributions. These limitations are magnified at high ionic strength, where screening lengths collapse and signals are attenuated. These methods expose a fundamental asymmetry: conductive-interface EDLs are directly accessible, whereas dielectric-liquid EDLs remain largely elusive. A simple, robust, and bias-free strategy is still lacking to transduce interfacial charge organization at nonconductive surfaces into measurable signals under realistic conditions.

3 | Probing Dielectric Solid–Liquid EDLs Through Triboelectric Nanogenerator

A triboelectric nanogenerator (TENG) probe, leveraging the coupled mechanisms of contact electrification and electrostatic induction, provides a powerful strategy for interrogating interfacial charge transfer [29–33]. By exploiting intrinsic contact electrification between dielectric solids and liquids, interfacial charge

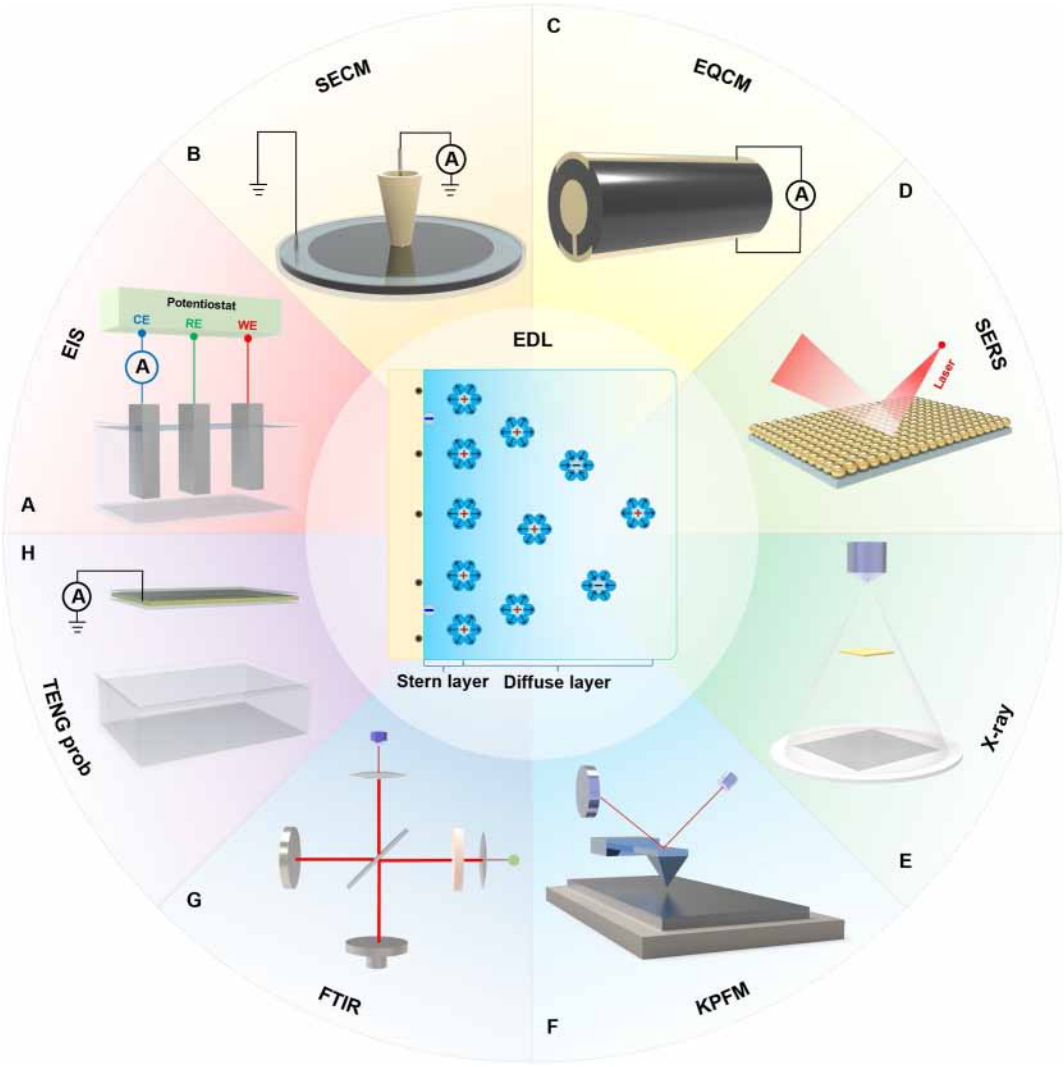

FIGURE 1 | Methods for probing EDLs at solid–liquid interfaces. (A) EIS. (B) SECM. (C) EQCM. (D) SERS. (E) X-ray. (F) KPFM. (G) FTIR. (H) TENG probe.

organization can be directly converted into measurable electrical signals without electrodes or applied bias. EDL formation at dielectric solid–liquid interfaces results from coupled electron transfer, ionic redistribution, and electrostatic screening, processes that are challenging to disentangle experimentally in the absence of electrical control. TENG probe overcomes this limitation, functioning as an interfacial transduction mechanism that provides operando access to EDL dynamics otherwise inaccessible (Figure 1H). Interfacial charge generation during contact electrification encodes the EDL configuration, which is converted into measurable electrical signals via electrostatic induction under mechanical modulation. Unlike existing techniques, it operates without electrodes or external bias, enabling operando access to dynamic EDLs at dielectric interfaces. The power of this approach is particularly evident during solid–liquid phase transitions, where interfacial composition and electrostatic character evolve continuously [34] (Figure 2A). When a dielectric polymer contacts ice undergoing gradual melting, interfacial charge transfer displays a pronounced nonmonotonic evolution. At low temperatures, electron transfer dominates, characteristic of solid–solid contact. As melting begins, the formation of microscopic liquid domains enhances charge transfer, reflecting increased interfacial interactions. This enhancement is transient: once a continuous liquid film forms, the transferred charge decreases sharply and stabilizes at a lower level, signaling the establishment of an EDL at the dielectric solid–liquid interface. In this regime, the triboelectric signal no longer reflects direct electron exchange but encodes EDL formation and maturation through surface charge screening.

Once formed, the EDL enters a steady-state regime, with its structure and screening strength continuously modulated by electrolyte concentration. The TENG probe provides direct access to this dynamic evolution [35] (Figure 2B). At low ionic strength, limited ion availability leads to weak screening and modest charge transfer. As concentration increases, the transferred charge rises, consistent with the development of a more compact interfacial layer. Beyond an intermediate concentration, further increases in ionic strength suppress charge transfer as dense ionic packing enhances electrostatic screening and inhibits additional electron and ion exchange. The triboelectric response thus provides a steady-state readout of EDL compactness at dielectric-liquid interfaces. Beyond concentration effects, interfacial charge transfer is particularly sensitive to qualitative EDL reorganization induced by ionic asymmetry [36] (Figure 2C). For symmetric electrolytes, such as LiCl, increasing concentration monotonically suppresses charge transfer while preserving polarity, indicating progressive screening without altering the charge-compensation mechanism. In contrast, asymmetric electrolytes composed of ions with disparate size, hydration, or mobility exhibit concentration-dependent polarity inversion. At low concentrations, interfacial charging follows conventional trends dominated by electron transfer and counterion accumulation. Above a critical concentration, the net transferred charge reverses sign, signaling a reorganization of interfacial charge distribution rather than simple enhancement of screening. This polarity inversion reflects a nonclassical restructuring of the EDL. At high ionic strength, asymmetries in ion size and mobility drive preferential accumulation of specific species within the Stern

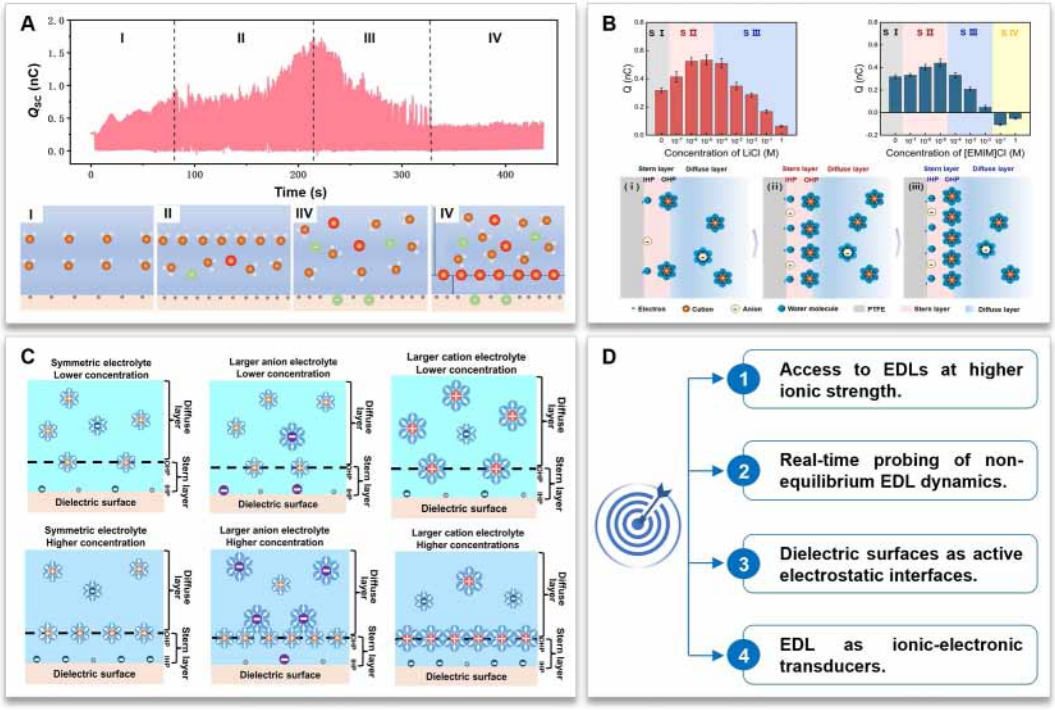

FIGURE 2 | A unified triboelectric framework for probing dielectric-liquid EDLs in dynamic and steady-state environments. (A) TENG probe of EDL formation during solid–liquid phase transition. Reproduced with permission from Ref. [34]. Copyright 2024, Elsevier. (B) TENG probe of steady-state EDL modulation by electrolyte concentration. Reproduced with permission from Ref. [35]. Copyright 2024, Wiley. (C) TENG probe of EDL reorganization induced by ionic asymmetry. Reproduced with permission from Ref. [36]. Copyright 2025, The Authors. (D) Perspectives of the TENG probe of dielectric-liquid EDLs.

layer, producing local charge overcompensation. Correlative measurements and simulations indicate that this transition occurs without collapse of the overall EDL: the inner and outer Helmholtz layers remain spatially defined, whereas the distribution of ionic populations is fundamentally altered. The TENG probe thus provides a direct bias-free measure of EDL symmetry breaking and charge inversion at dielectric solid–liquid interfaces, phenomena challenging to resolve with potential-based methods. By capturing EDL formation during phase transitions, steady-state modulation by electrolyte concentration, and reorganization driven by ionic asymmetry, interfacial charge transfer establishes a unified framework for interrogating dielectric solid–liquid EDLs across nonequilibrium and equilibrium regimes. Beyond its role as a physical phenomenon, contact electrification is reframed here as a powerful interfacial probe, revealing previously hidden electrostatic dynamics.

4 | Perspectives and Challenges

The implications of the TENG probe extend far beyond methodological innovation (Figure 2D). Firstly, direct experimental access to dielectric-liquid EDLs enables systematic exploration of interfacial dynamics under high ionic strength and chemically complex conditions, including seawater [37], concentrated brines [38], ionic liquids [39], and biological fluids [40], regimes where classical EDL models and conventional probes often fail due to strong screening, ion–ion correlations, and steric effects. By directly reporting net interfacial charge redistribution, triboelectric measurements retain sensitivity even when Debye lengths collapse to the nanometer scale. Secondly, beyond equilibrium systems, interfacial charge transfer provides a unique route to interrogating dynamic and nonequilibrium interfaces [41–45]. Processes, such as phase transitions, wetting and dewetting, evaporation, and flow-induced charging, are intrinsically transient and spatially heterogeneous, yet remain difficult to access using steady-state electrochemical techniques. By coupling interfacial dynamics directly to electrical output, TENG probe enables real-time tracking of EDL formation, reorganization, and dissipation under evolving mechanical and hydrodynamic conditions. Thirdly, access to dielectric solid–liquid EDLs reframes electrically insulating materials as active electrostatic interfaces rather than passive boundaries [46–52]. Direct probing enables the rational design of surface chemistries and interfacial architectures, allowing ionic adsorption, screening strength, and charge polarity to be tuned via material selection and electrolyte composition. This capability has broad implications for separation, antifouling, catalysis, and interfacial sensing, where electrostatic interactions play a central role in determining performance. Last but not least, integrating the TENG probe with emerging iontronic and energy-information coupling systems underscores the broader role of EDLs as dynamic transducers bridging ionic and electronic degrees of freedom [53–57]. In this framework, EDLs are no longer merely equilibrium screening layers, but programmable interfacial entities that mediate coupled flows of charge that are carriers of energy and information.

Despite its promise, several challenges must be overcome before the TENG probe of dielectric solid–liquid EDLs can achieve quantitative generality. The most critical challenge is the lack of rigorous relationships linking measured triboelectric output to fundamental EDL parameters. Although qualitative trends, such as screening, concentration-dependent suppression of charge transfer, and polarity inversion, are robust, quantitative interpretation remains difficult because the measured signal integrates multiple coupled processes, including electron transfer, ionic migration, interfacial polarization, and fluidic dynamics. Developing unified theoretical frameworks that explicitly connect triboelectric charge generation to EDL structure and dynamics is therefore essential. A second challenge lies in spatial resolution. Triboelectric measurements typically yield area-averaged readouts, which, though sensitive to net charge reorganization, obscure nanoscale heterogeneity arising from surface roughness, chemical inhomogeneity, and transient contact geometries. Key EDL phenomena, including localized charge inversion and Stern-layer restructuring, occur below the effective resolution of current approaches, necessitating integration with spatially resolved techniques or the development of localized contact architectures. Finally, the intrinsically multiphysical nature of solid–liquid contact electrification complicates reproducibility and cross-system comparison. Mechanical motion, electrostatics, interfacial chemistry, and fluid dynamics are tightly coupled, particularly under nonequilibrium conditions, rendering triboelectric signals sensitive to parameters such as contact force, velocity, and droplet morphology. Establishing standardized protocols and identifying dimensionless descriptors governing interfacial charging will be critical. Addressing these challenges requires close integration of experiment, theory, and simulation and should be viewed not as fundamental limitations but as natural consequences of probing a previously inaccessible interfacial regime.

5 | Conclusions and Outlook

In summary, although EDLs have long been central to interfacial science, their experimental characterization has remained constrained by electrochemical electrode-based paradigms, leaving dielectric solid–liquid interfaces largely unexplored. This perspective highlights interfacial charge transfer as a fundamentally distinct approach, transforming contact electrification from a phenomenological observation into a powerful bias-free probe of interfacial charge organization. By directly transducing interfacial structure into measurable electrical signals, the TENG probe accesses regimes inaccessible to conventional electrochemical methods. Recent studies demonstrate its capacity to capture EDL formation, steady-state modulation, and qualitative reorganization, including charge inversion under high ionic strength and asymmetry. Collectively, these findings establish dielectric solid–liquid EDLs as dynamic adaptive structures that cannot be fully inferred from classical electrode-based measurements. More broadly, TENG probe signals a conceptual shift in interfacial science, from externally imposed electrochemical control to intrinsic, self-consistent interrogation of interfacial charge organization, and promises to extend the reach of interfacial studies well beyond the confines of electrodes, deepening our understanding of charge organization and dynamics at solid–liquid interfaces.

Author Contributions

Xiang Li: writing – original draft, writing – review and editing, funding acquisition. **Gehan Amaratunga:** project administration, supervision. **Zhong Lin Wang:** project administration, supervision, validation. **Di Wei:** funding acquisition, project administration, supervision, validation, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data can be requested from the corresponding author.

References

1. Y. Zhou, M. Su, X. Yu, et al., "Real-Time Mass Spectrometric Characterization of the Solid–Electrolyte Interphase of a Lithium-ion Battery," *Nature Nanotechnology* 15, no. 3 (2020): 224–230, https://doi.org/10.1038/s41565-019-0618-4.

2. L. Yang, F. Yang, X. Liu, et al., "A Moisture-Enabled Fully Printable Power Source Inspired by Electric Eels," *Proceedings of the National Academy of Sciences of the United States of America* 118, no. 16 (2021): e2023164118, https://doi.org/10.1073/pnas.2023164118.

3. X. Li, Z. L. Wang, and D. Wei, "Iontronic Logic Control Driven by Dynamic Electrical Double Layer Regulation," *Iontronics* 1, no. 1 (2025): 2, https://doi.org/10.20517/iontronics.2025.02.

4. Y. Long, B. Zhao, M. Liu, W. Hu, and X. Pu, "Smart Hydrogel Tactile Sensors and Systems: A Comprehensive Review," *SmartSys* 1, no. 4 (2026): e70015, https://doi.org/10.1002/sys3.70015.

5. H. Qian, D. Wei, and Z. Wang, "Bionic Iontronics Based on Nano-Confined Structures," *Nano Research* 16, no. 9 (2023): 11718–11730, https://doi.org/10.1007/s12274-023-5705-z.

6. Q. Wu, M. T. McDowell, and Y. Qi, "Effect of the Electric Double Layer (EDL) in Multicomponent Electrolyte Reduction and Solid Electrolyte Interphase (SEI) Formation in Lithium Batteries," *Journal of the American Chemical Society* 145, no. 4 (2023): 2473–2484, https://doi.org/10.1021/jacs.2c11807.

7. X. Yuan, D. Cheng, B. Liu, et al., "Engineering Battery Corrosion Films by Tuning Electrical Double Layer Composition," *Joule* 8, no. 11 (2024): 3038–3053, https://doi.org/10.1016/j.joule.2024.07.011.

8. X. Wang, A. P. Ivanov, and J. B. Edel, "Biocompatible Biphasic Iontronics Enable Neuron-Like Ionic Signal Transmission," *Research: Ideas for Today's Investors* 7 (2024): 0294, https://doi.org/10.34133/research.0294.

9. Z. Liu, Z. Wang, K. Shi, et al., "Contact-Electro-Catalysis at Dynamic Semiconductor-Water Junctions," *Research: Ideas for Today's Investors* 8 (2025): 0940, https://doi.org/10.34133/research.0940.

10. H. Helmholtz, "Ueber einige gesetze der vertheilung elektrischer ströme in körperlichen leitern mit anwendung auf die thierisch-elektrischen versuche," *Annalen der Physik* 165, no. 6 (1853): 211–233, https://doi.org/10.1002/andp.18531650603.

11. M. Gouy, "Sur la constitution de la charge électrique à la surface d'un électrolyte," *Journal of Theoretical and Applied Physics* 9, no. 1 (1910): 457–468, https://doi.org/10.1051/jphystap:019100090045700.

12. D. L. Chapman, "A Contribution to the Theory of Electrocapillarity," *Philosophical Magazine* 25, no. 148 (1913): 475–481, https://doi.org/10.1080/14786440408634187.

13. D. C. Grahame, "The Electrical Double Layer and the Theory of Electrocapillarity," *Chemical Reviews* 41, no. 3 (1947): 441–501, https://doi.org/10.1021/cr60130a002.

14. X. Xu, X. Xie, A. Pan, H. Duan, G. Fang, and S. Liang, "Constructing Calcium-Rich SEI and H_2O-Poor EDL Enables Stable Zinc-Ion Pouch Cells," *ACS Energy Letters* 10, no. 9 (2025): 4386–4394, https://doi.org/10.1021/acsenergylett.5c02217.

15. K. Su, Z. Bian, Y. Mu, et al., "Pyrrolidine Ionic Liquid Enables Dynamic EDL Regulation for Highly Stable Aqueous Zn Ion Capacitors," *Energy Storage Materials* 81 (2025): 104480, https://doi.org/10.1016/j.ensm.2025.104480.

16. J. Luo, K. Yang, J. Gai, et al., "Anion-Tailored EDL Induced Triple-Layer SEI on High-Capacity Anodes Enabling Fast-Charging and Durable Sodium-Storage," *Angewandte Chemie International Edition* 64, no. 7 (2025): e202419490, https://doi.org/10.1002/anie.202419490.

17. S. Lin, X. Chen, and Z. L. Wang, "Contact Electrification at the Liquid-Solid Interface," *Chemical Reviews* 122, no. 5 (2022): 5209–5232, https://doi.org/10.1021/acs.chemrev.1c00176.

18. S. Lin, L. Xu, C. Xu, et al., "Electron Transfer in Nanoscale Contact Electrification: Effect of Temperature in the Metal-Dielectric Case," *Advanced Materials* 31, no. 17 (2019): 1808197, https://doi.org/10.1002/adma.201808197.

19. Y. Liu, M. Zhu, D. Nan, et al., "Enhanced Durability and Robustness of Triboelectric Nanogenerators With Blade-Enclosed Structure for Breeze Energy Harvesting," *Advanced Sustainable Systems* 7, no. 2 (2022): 2200367, https://doi.org/10.1002/adsu.202200367.

20. X. Li, S. Li, X. Guo, J. Shao, Z. L. Wang, and D. Wei, "Triboiontronics for Efficient Energy and Information Flow," *Matter* 6, no. 11 (2023): 3912–3926, https://doi.org/10.1016/j.matt.2023.08.022.

21. X. Li, R. Li, S. Li, Z. L. Wang, and D. Wei, "Triboiontronics With Temporal Control of Electrical Double Layer formation," *Nature Communications* 15, no. 1 (2024): 6182, https://doi.org/10.1038/s41467-024-50518-3.

22. H. Yuan, H. Shimotani, J. Ye, et al., "Electrostatic and Electrochemical Nature of Liquid-Gated Electric-Double-Layer Transistors Based on Oxide Semiconductors," *Journal of the American Chemical Society* 132, no. 51 (2010): 18402–18407, https://doi.org/10.1021/ja108912x.

23. K. Barman, G. Askarova, R. Somni, G. Hu, and M. V. Mirkin, "Voltage-Driven Molecular Photoelectrocatalysis of Water Oxidation," *Journal of the American Chemical Society* 146, no. 41 (2024): 28500–28507, https://doi.org/10.1021/jacs.4c10896.

24. J. M. Griffin, A. C. Forse, W.-Y. Tsai, P. L. Taberna, P. Simon, and C. P. Grey, "In Situ NMR and Electrochemical Quartz Crystal Microbalance Techniques Reveal the Structure of the Electrical Double Layer in Supercapacitors," *Nature Materials* 14, no. 8 (2015): 812–819, https://doi.org/10.1038/nmat4318.

25. Y. Gu, E.-M. You, J.-D. Lin, et al., "Resolving Nanostructure and Chemistry of Solid-Electrolyte Interphase on Lithium Anodes by Depth-Sensitive Plasmon-Enhanced Raman Spectroscopy," *Nature Communications* 14, no. 1 (2023): 3536, https://doi.org/10.1038/s41467-023-39192-z.

26. M. J. Bedzyk, G. M. Bommarito, M. Caffrey, and T. L. Penner, "Diffuse-Double Layer at a Membrane-Aqueous Interface Measured With X-Ray Standing Waves," *Science* 248, no. 4951 (1990): 52–56, https://doi.org/10.1126/science.2321026.

27. S. Lin, L. Xu, A. C. Wang, and Z. L. Wang, "Quantifying Electron-Transfer in Liquid-Solid Contact Electrification and the Formation of Electric Double-Layer," *Nature Communications* 11, no. 1 (2020): 399, https://doi.org/10.1038/s41467-019-14278-9.

28. B. D. Assresahegn and D. Bélanger, "Multifunctional Carbon for Electrochemical Double-Layer Capacitors," *Advanced Functional Materials* 25, no. 43 (2015): 6775–6785, https://doi.org/10.1002/adfm.201503738.

29. J. Zhang, X. Wang, L. Zhang, S. Lin, S. Ciampi, and Z. L. Wang, "Triboelectric Spectroscopy for in Situ Chemical Analysis of Liquids," *Journal of the American Chemical Society* 146, no. 9 (2024): 6125–6133, https://doi.org/10.1021/jacs.3c13674.

30. J. Zhang, S. Lin, and Z. L. Wang, "Triboelectric Nanogenerator Array as a Probe for in Situ Dynamic Mapping of Interface Charge Transfer at a Liquid-Solid Contacting," *ACS Nano* 17, no. 2 (2023): 1646–1652, https://doi.org/10.1021/acsnano.2c11633.

31. J. Zhang, S. Lin, M. Zheng, and Z. L. Wang, "Triboelectric Nanogenerator as a Probe for Measuring the Charge Transfer Between Liquid and Solid Surfaces," *ACS Nano* 15, no. 9 (2021): 14830–14837, https://doi.org/10.1021/acsnano.1c04903.

32. F. Zhan, A. C. Wang, L. Xu, et al., "Electron Transfer as a Liquid Droplet Contacting a Polymer Surface," *ACS Nano* 14, no. 12 (2020): 17565–17573, https://doi.org/10.1021/acsnano.0c08332.

33. S. Lin, C. Zhang, and J. Liu, "A Review on the Study of Contact Electrification: Mechanism, Control and Application," *Journal of Mechanical Engineering* 61, no. 19 (2025): 112, https://doi.org/10.3901/jme.2025.19.112.

34. Y. Wei, X. Li, Z. Yang, J. Shao, Z. L. Wang, and D. Wei, "Contact Electrification at the Solid-Liquid Transition Interface," *Materials Today* 74 (2024): 2–11, https://doi.org/10.1016/j.mattod.2024.03.013.

35. R. Li, X. Li, Z. Zhang, M. Willatzen, Z. L. Wang, and D. Wei, "Triboelectric Programmed Droplet Manipulation for Plug-And-Play Assembly," *Advanced Functional Materials* 35, no. 10 (2024): 2416457, https://doi.org/10.1002/adfm.202416457.

36. Y. Wei, X. Li, Y. Gu, et al., "Probing Electrical Double Layer via Triboelectric Charge Transfer," *Nature Communications* 17, no. 1 (2025): 402, https://doi.org/10.1038/s41467-025-67094-9.

37. H.-M. Zhang, "Construction of Chlorine-Free Electrical Double Layer for Efficient Seawater Oxidation," *Coordination Chemistry Reviews* 529 (2025): 216463, https://doi.org/10.1016/j.ccr.2025.216463.

38. L. Varela, "Exact mean-field Theory of Ionic Solutions: Non-Debye Screening," *Physics Reports* 382, no. 1–2 (2003): 1–111, https://doi.org/10.1016/s0370-1573(03)00210-2.

39. J. S. Kim, S. C. Lee, J. Hwang, et al., "Enhanced Sensitivity of Iontronic Graphene Tactile Sensors Facilitated by Spreading of Ionic Liquid Pinned on Graphene Grid," *Advanced Functional Materials* 30, no. 14 (2020): 1908993, https://doi.org/10.1002/adfm.201908993.

40. X. Che, H. Yu, T. Wang, et al., "Mechanically Pulsating Liquid Metal Within Biologic Porous Ionogel for Energy Harvest," *Advanced Functional Materials* 35, no. 7 (2024): 2415323, https://doi.org/10.1002/adfm.202415323.

41. S. J. Shin, D. H. Kim, G. Bae, et al., "On the Importance of the Electric Double Layer Structure in Aqueous Electrocatalysis," *Nature Communications* 13, no. 1 (2022): 174, https://doi.org/10.1038/s41467-021-27909-x.

42. Z. Tang, D. Yang, H. Guo, S. Lin, and Z. L. Wang, "Spontaneous Wetting Induced by Contact-Electrification at Liquid-Solid Interface," *Advanced Materials* 36, no. 25 (2024): 2400451, https://doi.org/10.1002/adma.202400451.

43. J. Yin, X. M. Li, J. Yu, Z. Zhang, J. Zhou, and W. Guo, "Generating Electricity by Moving a Droplet of Ionic Liquid Along Graphene," *Nature Nanotechnology* 9, no. 5 (2014): 378–383, https://doi.org/10.1038/Nnano.2014.56.

44. J. Yin, Z. Zhang, X. Li, et al., "Waving Potential in Graphene," *Nature Communications* 5, no. 1 (2014): 3582, https://doi.org/10.1038/ncomms4582.

45. S. Lin, C. Zhang, and T. Shao, "Techniques for Surface Charge Measurements and Exploring Contact Electrification," *Friction* 13, no. 2 (2025): 9440968, https://doi.org/10.26599/frict.2025.9440968.

46. X. Li, Z. L. Wang, and D. Wei, "Scavenging Energy and Information Through Dynamically Regulating the Electrical Double Layer," *Advanced Functional Materials* 34, no. 42 (2024): 2405520, https://doi.org/10.1002/adfm.202405520.

47. J. Chi, C. Liu, L. Che, et al., "Harvesting Water-Evaporation-Induced Electricity Based on Liquid-Solid Triboelectric Nanogenerator," *Advanced Science* 9, no. 17 (2022): 2201586, https://doi.org/10.1002/advs.202201586.

48. Y. Dong, S. Xu, C. Zhang, et al., "Gas-Liquid Two-Phase Flow-Based Triboelectric Nanogenerator With Ultrahigh Output Power," *Science Advances* 8, no. 48 (2022): eadd0464, https://doi.org/10.1126/sciadv.add0464.

49. W. Xu, H. Zheng, Y. Liu, et al., "A Droplet-Based Electricity Generator With High Instantaneous Power Density," *Nature* 578, no. 7795 (2020): 392–396, https://doi.org/10.1038/s41586-020-1985-6.

50. P. Zhuang, L. Chen, Y. Zhang, et al., "Solid-Liquid Interface Lubricating Hydrogels for Tendon-Bone Healing," *Research: Ideas for Today's Investors* 8 (2025): 0924, https://doi.org/10.34133/research.0924.

51. P. Peng, Z. Wang, and D. Wei, "Modulating Multi-ion Dynamics for High-Performance Iontronic Systems," *Iontronics* 2, no. 1 (2026): 5, https://doi.org/10.20517/iontronics.2026.05.

52. S. Lin, X. Ding, G. Li, et al., "Connotation, Research Status and Prospect of Tribovoltaic Effect," *China Surface Engineering* 38, no. 2 (2025): 148–166, https://doi.org/10.11933/j.issn.1007-9289.20241126002.

53. X. Li, Y. Wei, X. Gao, Z. Zhang, Z. L. Wang, and D. Wei, "Harnessing Triboiontronic Maxwell's Demon by Triboelectric-Induced Polarization for Efficient Energy-Information Flow," *Joule* 9, no. 5 (2025): 101888, https://doi.org/10.1016/j.joule.2025.101888.

54. X. Li, T. Cheng, Z. L. Wang, and D. Wei, "Neuromimetic Circuits Enabled by Dynamic Regulation of the Electrical Double Layer," *npj Flexible Electronics* 9, no. 1 (2025): 66, https://doi.org/10.1038/s41528-025-00450-3.

55. X. Zhu, Z. Wu, and Z. Zhao, "Bio-Inspired Heterointerfacial ion-Gating and Iontronic Neuromorphics," *Iontronics* 1, no. 1 (2025): 4, https://doi.org/10.20517/iontronics.2025.04.

56. A. Wang, S. Feng, T. Xiao, et al., "Microenvironment-Engineered Piezoionic Hydrogel Nanogenerators for Enhanced Energy Harvesting and Sensing," *SmartSys* 1, no. 2 (2025): e70004, https://doi.org/10.1002/sys3.70004.

57. X. Dai, Q. Liang, Y. Wu, et al., "Ultrathin and Highly Conformal Self-Powered Sensors by Liquid-Phase Transferring," *Research: Ideas for Today's Investors* 8 (2025): 0785, https://doi.org/10.34133/research.0785.