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From Interfacial Charge to Measured Voltage: A Critical Review of Liquid-Solid Triboelectric Nanogenerator Mechanisms and Models

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ABSTRACT

Liquid-solid triboelectric nanogenerators (LS-TENGs) have attracted considerable attention for energy harvesting and self-powered liquid sensing. Their operation relies on contact electrification at the liquid-solid interface coupled with electrostatic induction driven by changing interfacial charge distributions. However, unifying charge generation, ionic redistribution, electrostatic screening, and external circuit response within a single predictive framework remains challenging. This review critically examines electron transfer, specific ion adsorption, and electrical double-layer (EDL) formation as complementary mechanisms governing liquid-solid electrification, highlighting how interfacial chemistry, ionic concentration, wettability, and dielectric properties regulate charge retention. Using Debye screening, interfacial capacitance, and charge-relaxation timescales, we clarify how ionic strength and conductivity influence electrostatic coupling and why conductivity cannot serve as a universal predictor of electrical output. We further evaluate theoretical frameworks spanning Maxwell's displacement current, capacitive equivalent circuits, Thévenin and Norton terminal representations, quasi-electrostatic field solvers, and coupled ionic-electrostatic models, contrasting their governing assumptions, physical interpretations, and experimental validation requirements. A central argument is that surface charge density, transferred charge, open-circuit voltage, and instrument-recorded voltage are physically distinct quantities that must not be treated interchangeably due to circuit loading, parasitic capacitance, and bandwidth constraints. Finally, we outline key challenges in mechanism isolation, transient droplet dynamics, and parameter identifiability, introducing a discrete-time phenomenological model for cycle-by-cycle surface charge evolution alongside a structured conceptual framework linking interfacial physics to observable sensing signals for reliable liquid identification and environmental monitoring.

1. INTRODUCTION

Triboelectric nanogenerators (TENGs) have emerged as a class of electromechanical energy-conversion devices capable of transforming mechanical interactions into electrical signals through contact electrification and electrostatic induction. Their applications have expanded from mechanical energy harvesting to self-powered sensing, environmental monitoring, wearable electronics and intelligent systems. In liquid–solid triboelectric nanogenerators (LS-TENGs),

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the interaction between a moving liquid and a solid dielectric provides the physical mechanism for generating and redistributing interfacial charges (Kaswan *et al.*, 2024; Wang *et al.*, 2025).

The operation of an LS-TENG generally involves three interconnected processes. First, contact between the liquid and the dielectric establishes an interfacial charge distribution. Second, ions and other charged species in the liquid respond to the resulting electrical potential, modifying the electrostatic environment near the interface. Third, liquid motion, including spreading, sliding and separation, changes the spatial distribution of charges and the electrical coupling to the electrodes, generating a measurable electrical response (Xu *et al.*, 2020; Lin *et al.*, 2022).

Despite considerable progress in LS-TENG research, the physical origin of liquid-solid contact electrification remains an important subject of investigation. Classical explanations emphasise ion adsorption and electrical double-layer formation; however, more recent experimental and theoretical studies identify electron transfer as a significant contributor to interfacial charging. These mechanisms are not necessarily mutually exclusive because electron transfer, surface ionisation, specific ionic adsorption and electrostatic screening may occur together, with their relative contributions depending on the properties of the interacting liquid and solid (Lin *et al.*, 2020; Panda *et al.*, 2022; Munirathinam *et al.*, 2025).

Understanding these mechanisms is particularly important for liquid-sensing applications. Changes in liquid conductivity, ionic strength, pH, surface tension, viscosity and molecular composition can modify the electrical response of a triboelectric system. However, a voltage difference between two liquids does not independently identify the mechanism influencing that difference. For example, increasing ionic concentration may modify contact charge generation, enhance electrostatic screening or change the electrical impedance of the liquid-electrode interface. These effects may contribute simultaneously to the electrical response of the triboelectric system (Yoo *et al.*, 2023; Li *et al.*, 2024; Wang *et al.*, 2025).

Mathematical modelling offers a means of relating these processes to measurable device performance. Established approaches include parallel-plate capacitance models, lumped equivalent circuits, Maxwell displacement-current formulations, quasi-electrostatic field models and more recently, coupled ionic-electrostatic descriptions (Dharmasena *et al.*, 2018; Shao *et al.*, 2020; Sriphan *et al.*, 2024; Wang, Zhao, *et al.*, 2026).

Nevertheless, each modelling framework describes different aspects of LS-TENG behaviour. Microscopic models address charge transfer at the interface (Wang & Wang, 2019), electrochemical models describe ionic redistribution (Lin *et al.*, 2020), field-based models determine electrostatic induction (Shao *et al.*, 2020), and circuit models relate the resulting electrical response to an external measuring system (Niu & Wang, 2015). Consequently, predictions obtained from different models are not automatically comparable unless their state variables, boundary conditions and measurement assumptions are consistent (Wang, Zhao, *et al.*, 2026).

A further difficulty arises from the distinction between electrical quantities. Surface charge density, transferred charge, short-circuit current and open-circuit voltage are related but physically different (Niu & Wang, 2015). Moreover, the output recorded by an amplifier or microcontroller may differ substantially from the intrinsic voltage generated at the liquid-solid interface (Fachechi *et al.*, 2023; Mulvihill *et al.*, 2025). Measurement bandwidth, input impedance, parasitic capacitance and sampling frequency can therefore influence the interpretation and validation of theoretical models (Fachechi *et al.*, 2023; Jiang *et al.*, 2025; Mulvihill *et al.*, 2025).

Recent developments demonstrate the

need for an integrated assessment of charge-transfer mechanisms and electrical modelling approaches rather than examining them independently (Wang, Zhao, *et al.*, 2026; Wu *et al.*, 2026). Although individual studies have advanced the understanding of interfacial charging and device operation, the applicability of their assumptions across different dielectric materials, electrode configurations, liquids and measurement conditions remains an important challenge (Mulvihill *et al.*, 2025; Wang, Liang, *et al.*, 2026; Wu *et al.*, 2026).

The central objective of this review is to critically evaluate how the physical mechanisms of liquid-solid charge transfer are incorporated into mathematical models and how these models connect interfacial phenomena to measurable electrical output. Specifically, the review examines the structure and role of the EDL, electron and ion transfer mechanisms, theoretical approaches to electrostatic induction, lumped and distributed electrical models, and the limitations associated with predictive sensing. The distinctive emphasis is on the relationship between physical mechanism, mathematical representation, experimentally accessible quantity and model validation.

2. FUNDAMENTAL PRINCIPLES OF LIQUID-SOLID CONTACT ELECTRIFICATION

2.1 Contact electrification and electrostatic induction

Contact electrification describes the redistribution or transfer of electrical charge when two materials interact at an interface (Wang & Wang, 2019). In LS-TENGs, this occurs when a liquid contact a solid material such as fluorinated ethylene propylene (FEP), polytetrafluoroethylene (PTFE), polydimethylsiloxane (PDMS) or another dielectric (Lin *et al.*, 2013; Nie *et al.*, 2020; Wu *et al.*, 2026).

Depending on the interfacial chemistry, contact may involve electron transfer, ion adsorption, surface ionization or other material-specific charge-transfer processes (Lin *et al.*, 2020; Nie *et al.*, 2020; Zhan *et al.*, 2020). Following separation, some interfacial charge may remain on the solid while charge associated with the liquid is transported away or redistributed (Lin *et al.*, 2020; Wang, Zhao, *et al.*, 2026; Wu *et al.*, 2026). The charge generated by contact electrification establishes the electrostatic conditions from which the electrical output develops (Niu & Wang, 2015; Shao *et al.*, 2020). However, charge generation and electrostatic induction are conceptually distinct (Dharmasena *et al.*, 2018; Wang & Wang, 2019).

Electrostatic induction occurs when the position or distribution of interfacial charges changes relative to conducting electrodes. As a droplet spreads, recoils or moves across the dielectric, the electric field and electrode potentials may vary. If the electrodes are connected through a suitable circuit, charge redistribution can produce an external current (Kim *et al.*, 2021; Shao *et al.*, 2020).

This distinction is central to mathematical modelling because a model of charge generation does not, by itself, determine the voltage or current delivered to an external circuit.

2.2 Importance of liquid and solid properties

The electrical response of LS-TENGs depends on properties of both interacting phases. For the solid dielectric, important factors include surface chemistry, electron affinity, relative permittivity, thickness, surface roughness, hydrophobicity and charge-trapping behaviour. For the liquid, relevant properties include ionic concentration, conductivity, pH, molecular structure, dielectric permittivity, viscosity, surface tension and wetting characteristics.

The liquid triboelectric series developed by Yoo *et al.* (2023) demonstrates the importance of molecular composition in

liquid–solid charge-transfer behaviour. The study examined the relative charging characteristics of different liquids and showed that chemical functionality can substantially influence triboelectric response. For example, polyols containing multiple hydroxyl groups may display stronger charging characteristics than certain other liquids under the measurement conditions examined. Nevertheless, the ranking obtained from a triboelectric series should not automatically be interpreted as the ranking of voltage amplitudes in an arbitrary LS-TENG architecture.

Differences in electrode geometry, contact area, loading conditions and electrical measurement configuration can alter the relationship between interfacial charge and the recorded response. This implies that experimentally measured liquid triboelectric characteristics provide valuable reference information, but their use as numerical inputs to device-specific models requires careful consideration.

3. CHARGE TRANSFER MECHANISMS AT LIQUID–SOLID INTERFACES

3.1 Electron transfer

The electron-transfer mechanism proposes that contact between a liquid and a solid permits redistribution of electronic charge across the interface (Lin *et al.*, 2020; Wang & Wang, 2019). Within electron-cloud-overlap descriptions, sufficiently close approach of the interacting materials allows their electronic states to interact, potentially enabling electron transfer (Lin *et al.*, 2020; Wang & Wang, 2019; Xu *et al.*, 2018). The transferred charge may subsequently become localized or trapped in surface states of the dielectric (Xu *et al.*, 2018; Zhang *et al.*, 2021).

The electron-transfer interpretation has received support from experimental and atomistic studies. Lin *et al.* (2020) investigated liquid–solid contact electrification using approaches designed to distinguish electronic and ionic contributions, while Panda *et al.* (2022) employed density functional theory and electronic-structure analysis to investigate charge redistribution at liquid–solid interfaces.

These investigations support the importance of electron transfer in selected systems and challenge explanations that attribute all interfacial charging exclusively to ion adsorption (Lin *et al.*, 2020; Nie *et al.*, 2020). Nevertheless, electron transfer should not be treated as universally dominant across every material combination (Lacks & Shinbrot, 2019; Lin *et al.*, 2020). The relative contribution may depend on dielectric surface chemistry, pH, available electronic states, adsorbed water and contact conditions (Lin *et al.*, 2020; Panda *et al.*, 2022; Zhang *et al.*, 2024).

The electron-transfer model is particularly relevant to fluoropolymer-based LS-TENGs because materials such as PTFE and FEP can retain negative charge following contact with selected liquids (Nie *et al.*, 2020; Wu *et al.*, 2026; Zhan *et al.*, 2020). However, observing a negative surface charge after separation does not independently establish the proportion produced by direct electron transfer (Lin *et al.*, 2020; Nie *et al.*, 2020).

A rigorous assessment requires experimental techniques capable of separating electronic charging from ion adsorption, residual liquid effects and subsequent electrochemical redistribution.

3.2 Ion transfer and adsorption

The ion-transfer mechanism attributes part of interfacial electrification to the movement or adsorption of charged ionic species between the liquid and solid (Dassanayaka *et al.*, 2026; McCarty & Whitesides, 2008). Depending on the surface chemistry, species such as hydroxide, hydronium and dissolved electrolyte ions may interact with functional groups or adsorption sites at the dielectric surface (Lin *et al.*, 2020; Suh *et al.*, 2024; Zhan *et al.*, 2020).

Specific adsorption can create or modify

interfacial charge independently of direct electron transfer (Lin *et al.*, 2020; Nie *et al.*, 2020). Furthermore, changes in pH and ionic composition can alter surface ionization equilibria, particularly for materials containing ionizable surface groups (Lin *et al.*, 2020; Sosa *et al.*, 2023; Zhan *et al.*, 2020).

3.3 Coexistence of electronic and ionic mechanisms

A coupled interpretation recognizes that initial charge generation and subsequent ionic redistribution may occur over different physical timescales (Lin *et al.*, 2020; Wang & Wang, 2021). Contact may first establish a surface charge through electronic transfer or surface ionization (Lin *et al.*, 2020; Zhan *et al.*, 2020). Mobile ions then respond to the resulting electrical potential, reorganizing near the interface and modifying the local electrostatic field (Lin *et al.*, 2020; Wang, Zhao, *et al.*, 2026; Zhan *et al.*, 2020).
Within this interpretation, electron transfer and EDL formation are complementary processes rather than competing explanations of the same observable (Lin *et al.*, 2022; Wang & Wang, 2021). The coexistence of these mechanisms has been discussed in experimental and theoretical investigations of liquid-solid contact electrification (Li *et al.*, 2025; Lin *et al.*, 2022; Panda *et al.*, 2022).

3.4 Critical comparison of charge-transfer mechanisms

In Table 1, we compare the transfer mechanism for the process.

Table 1: Charge-Transfer Mechanisms

Mechanism	**Principal process**	**Relevant evidence or observable**	**Main limitation**	**Key references**
Electron transfer	Electronic charge crosses the liquid–solid interface	Surface potential, charge retention, electronic-structure analysis	Difficult to isolate from ionic effects	Lin *et al.* (2020); Wang & Wang (2019); Xu *et al.* (2018)
Ion transfer or adsorption	Ionic species adsorb or interact with surface sites	pH, ion specificity, desorption and chemical analysis	Confusion with reversible EDL screening	Lin *et al.* (2020); McCarty & Whitesides (2008); Nie *et al.* (2020)
EDL formation	Mobile ions redistribute near a charged interface	Interfacial capacitance, potential and ionic-strength dependence	Does not identify original charge carrier	Li *et al.* (2025); Wang & Wang (2021); Zhan *et al.* (2020)
Coupled electron-ion	Charging and ionic redistribution	Combined electronic, electrochemi	Greater parameter-identifi-	Lin *et al.* (2020, 2022); Panda *et al.* (2022); Wang,

	act to-gethe r	cal and elec-trical meas-ure-ments	ca-tion diffi-culty	Zhao, *et al.* (2026)

The critical implication is that no single output-voltage measurement can generally establish the microscopic charge-transfer mechanism without further constraints.

4. ELECTRICAL DOUBLE-LAYER FORMATION AND DYNAMICS

4.1 Debye screening length

The Debye length describes the characteristic distance over which electrostatic potential is screened by mobile ions in the dilute-electrolyte approximation. For a suitable electrolyte under the Debye-Hückel approximation:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 \varepsilon_r k_B T}{2 N_A e^2 I}} \quad (1)$$

$\varepsilon_0 \varepsilon_r$ are the relative and vacuum permittivity; k_B Boltzmann's constant T absolute temperature; N_A is Avogadro's number; e is the electron charge. I is ionic strength in mol/m³.

The expression implies $\lambda_D \propto \mathrm{I}^{-1/2}$ when temperature and permittivity are constant. Increasing ionic strength therefore generally reduces Debye length.

In LS-TENGs this provides a physical basis for analysing how electrolyte concentration affects electrostatic screening. However, Debye length alone does not establish the amount of charge transferred to the dielectric or determine voltage at an external electrode. For concentrated electrolytes, specific adsorption or strong ion correlations, the assumptions of the simplified Debye-Hückel relationship may no longer apply.

4.2 Interfacial capacitance

In a first-order GCS representation, the compact and diffuse-layer capacitances are series elements: (Bard & Faulkner, 2001; Stern, 1924):

$$\frac{1}{C_{EDL}} = \frac{1}{C_H} + \frac{1}{C_D} \quad (2)$$

Here C_H and C_D represent compact and diffuse layer capacitances. For a linearised planar diffuse layer, capacitance per unit area may be expressed as (Bard & Faulkner, 2001; Israelachvili, 2011):

$$C_D = \frac{\varepsilon_0 \varepsilon_r}{\lambda_D} \quad (3)$$

The solid-dielectric capacitance can be approximated by (Niu & Wang, 2015; Sriphan *et al.*, 2024)

$$C_F(t) = \frac{\varepsilon_0 \varepsilon_F A_F(t)}{d_F} \quad (4)$$

Here $A_F(t)$ is the effective wetted area and d_F is the dielectric thickness.

4.3 Dynamic regulation of the EDL by contact electrification

The EDL is not necessarily static during droplet impact. When a droplet approaches, contacts, spreads and separates from a charged dielectric, the interfacial area and charge distribution change (Sriphan *et al.*, 2024; Xu *et al.*, 2020). Contact electrification can alter local surface potential while ionic migration and diffusion modify the electrostatic environment (Wang, Zhao, *et al.*, 2026; Zhan *et al.*, 2020).

A characteristic bulk charge-relaxation timescale for a homogeneous conductive liquid is (Melcher & Taylor, 1969; Saville, 1997):

$$\tau = \frac{\varepsilon_0 \varepsilon_r}{\kappa} \quad (5)$$

Here κ is conductivity, τ is the charge relaxation time

Electrical relaxation becomes faster as conductivity increases, assuming constant permittivity (Melcher & Taylor, 1969). However, bulk dielectric relaxation is not equivalent to complete kinetics of EDL formation, adsorption or charge transfer; τ

should not automatically be treated as the full time required for electrochemical equilibrium (Bazant *et al.*, 2004; Li *et al.*, 2024). More advanced models may incorporate ionic transport, electrode geometry and time-dependent boundary conditions (Bazant *et al.*, 2004; Wang, Zhao, *et al.*, 2026).

5. THEORETICAL AND MATHEMATICAL MODELS OF LS-TENGS

5.1 Maxwell's displacement-current framework

The theoretical foundation of triboelectric energy conversion is related to time-varying electric fields and electric displacement. In classical electromagnetism:

$$J_D = {}^{\partial D}/_{\partial t} \quad (6)$$

For a material described by $D = \varepsilon_0 E + P$ displacement-current density becomes:

$$J_D = \varepsilon_0 \, {}^{\partial E}/_{\partial t} + {}^{\partial \mathrm{P}}/_{\partial t} \quad (7)$$

Here E is electric field and P is polarization.

5.2 Capacitive equivalent-circuit models

A common approximation represents the TENG through a time-varying capacitance and an effective electrical source (Niu & Wang, 2015; Shao *et al.*, 2020). For systems with an independent triboelectric source contribution, one useful charge relationship is (Niu & Wang, 2015; You *et al.*, 2021):

$$Q_{electrode}(t) = C(t)V(t) + Q_{source}(t) \quad (8)$$

Differentiation gives (Shao *et al.*, 2020; You *et al.*, 2021):

$$i(t) = C(T) \, {}^{dV}/_{dt} + V(t) \, {}^{dC}/_{dt} + {}^{dQ_{source}}/_{dt} \quad (9)$$

This shows current may arise from changes in voltage, capacitance and source-charge coupling (Sriphan *et al.*, 2024; You *et al.*, 2021). For a droplet interacting with a uniform dielectric (Sriphan *et al.*, 2024; Xu *et al.*, 2020):

$$C_F(t) = c_F A_F(t) \quad (10)$$

Where; $c_F = {}^{\varepsilon_0 \varepsilon_F}/_{d_F}$

Fixed parasitic capacitances may be included when their connection to the electrical nodes is justified and double counting is avoided (Mulvihill *et al.*, 2025; Shao *et al.*, 2020). Equivalent circuits are practical because they integrate with amplifier and load models, but simplified forms may neglect fringing fields, nonuniform charge, finite electrode effects and liquid conduction (Dharmasena *et al.*, 2018; Shao *et al.*, 2020; Wang, Zhao, *et al.*, 2026).

5.3 Thévenin and Norton equivalent representations

The Thévenin approach represents a linear network at a specified operating state with an equivalent voltage source and source impedance (Alexander & Sadiku, 2021; Niu & Wang, 2015). Norton uses an equivalent current source in parallel with the source impedance (Alexander & Sadiku, 2021; Shao *et al.*, 2020). At a given frequency or fixed operating point, their representations are related by (Alexander & Sadiku, 2021; Shao *et al.*, 2020):

$$V_{Th} = I_N Z_{eq}. \quad (11)$$

5.4 Quasi-electrostatic field models

Quasi-electrostatic models resolve spatial charge and electrode induction where mechanical motion is sufficiently slow to neglect electromagnetic propagation over device dimensions (Chen *et al.*, 2023; Shao *et al.*, 2020). For spatially varying permittivity and prescribed free charge density, electric potential satisfies

(Griffiths, 2017; Shao *et al.*, 2020);

$$\nabla[\varepsilon(r)\nabla\phi(r,t)] = -\rho_f(r,t) \quad (11)$$

∇ is the spatial gradient/divergence differential operator in m^{-1};

$\varepsilon(r) = \varepsilon_0\varepsilon_r(r)$ is the spatially varying absolute electrical permittivity of the medium at position $r(F \cdot m^{-1})$

$\phi(r,t)$ is the scalar electrostatic potential as a function of spatial position r and time t and

$\rho_f(r,t)$ is the prescribed volumetric free charge density at position r and time t

Solutions can account for finite electrode sizes, dielectric interfaces and non-uniform charge (Chen *et al.*, 2023; Shao *et al.*, 2020). This is useful for ridges, patterned electrodes and discontinuous electrical contacts where a uniform field approximation may be inadequate (Dharmasena *et al.*, 2018; Shao *et al.*, 2020). The source discusses quasi-electrostatic three-dimensional approaches in relation to Shao *et al.* (2020) and Chen *et al.* (2023). More detailed fields demand reliable geometry, boundary conditions and charge distributions and impose greater computational costs (Chen *et al.*, 2023; Wang, Zhao, *et al.*, 2026).

5.5 Coupled ionic-electrostatic models

Recent coupled modelling frameworks seek to integrate liquid-solid charge generation, electrical double-layer (EDL) screening, droplet hydrodynamics, and external circuit loading within a unified formulation (Sriphan *et al.*, 2024; Wang, Zhao, *et al.*, 2026). For instance, Wang, Zhao, *et al.* (2026) link interfacial contact electrification and concentration-dependent EDL screening with droplet contact-area dynamics and electrode geometry to predict transient electrical outputs. More generally, the measured output voltage of an LS-TENG can be expressed functionally as:

$$V_{out}(t) = F[\sigma(t), \mathrm{K}, \mathrm{I}, \mathrm{A(t)}, \varepsilon, \mathrm{geometry}, Z_L] \quad (12)$$

where σ is the interfacial surface charge density, K is the liquid electrical conductivity, I is the ionic strength, A(t) is the time-varying wetted contact area, ε represents the material permittivities, and Z_L denotes the external load or measuring-system impedance. These coupled models provide a clear physical link from liquid properties to induced electrical output. However, adding more sub-models increases the number of parameters, making individual mechanisms harder to identify from limited experimental measurements (Mulvihill *et al.*, 2025; Wang, Liang, *et al.*, 2026).

5.6 Comparison of modelling frameworks

In Table 2, we compare the modelling frameworks for the process.

Table 2: Comparison of modelling frameworks

Framework	Physical basis	Typical prediction	Major limitation	Key References
Maxwell displacement current	Time-dependent displacement and polarisation	Field-driven electrical response	Needs charge and boundary conditions	Shao *et al.* (2020); Wang (2017, 2020)
Parallel-plate capacitance	Dielectric geometry	Voltage, charge and current	Neglects complex field	Dharmasena *et al.* (2018);

	and capacitance	under simplified assumptions	geometry	Niu & Wang (2015)
Thévenin/Norton	Terminal electrical characteristics	Loaded terminal response	Does not identify microscopic mechanism	Niu & Wang (2015); Shao *et al.* (2020)
Quasi-electrostatic	Poisson equation, spatial charge	Electrode potentials and fields	Requires detailed inputs	Chen *et al.* (2023); Shao *et al.* (2020)
EDL electrostatic	Ionic screening and interfacial capacitance	Ionic-strength dependence	Electrolyte and boundary assumptions	Bard & Faulkner (2001); Li *et al.* (2025); Stern (1924)
Coupled Multiphysics	Interface, hydrodynamics, circuit	Dynamic output	Complexity and identifiability	Mulvihill *et al.* (2025); Sriphan *et al.* (2024); Wang, Zhao, *et al.* (2026)

6. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

6.3 Incorporating surface-charge history

Successive droplets progressively alter the surface charge state of the dielectric (Stetten *et al.*, 2019). Experimental slide-electrification studies show that interfacial charge evolves exponentially toward a steady-state saturation regime governed by surface chemistry and droplet repetition frequency (Stetten *et al.*, 2019). To represent this cycle-by-cycle evolution in a discrete-time framework, we propose a simple phenomenological history model:

$$\sigma_{n+1} = (1-\alpha)\sigma_n + \alpha\sigma_{target} \quad (18)$$

where σ_n is the surface charge density after the $n-th$ droplet, σ_{target} is the asymptotic saturation charge density, and $\alpha(0 < \alpha \leq 1)$, is an effective per-droplet adjustment coefficient. This formulation is illustrative and requires empirical calibration for specific liquid-solid systemsrather than being treated as a universal law or a direct microscopic transfer rate.

6.4 Parameter identifiability

Distinct combinations of charge density, capacitance, area and circuit gain may produce nearly identical voltage responses. Therefore, good fits do not prove microscopic mechanisms. Future models should separate independently measured, literature constrained and fitted parameters and include uncertainty and held-out validation.

6.5 Environmental sensing

Liquid conductivity does not uniquely determine composition. Differences in pH, ionic identity, viscosity and wetting may confound sensor response. Reliable sensors require controlled tests of specificity, cross-sensitivity, repeatability, ageing, and operating conditions rather than voltage classification alone.

7. CONCLUSION

This review critically examined the interfacial charge-transfer mechanisms, electrochemical double-layer dynamics, mathematical modelling frameworks, and measurement considerations governing liquid-solid triboelectric nanogenerators (LS-TENGs). Electron transfer, specific ion adsorption, and electrical double-layer (EDL) formation describe complementary aspects of liquid-solid contact electrification rather than mutually exclusive phenomena. Because their relative contributions depend strongly on solid surface chemistry, liquid composition, and contact conditions and as repeated droplet contacts progressively modify the dielectric surface state, individual carrier mechanisms cannot be uniquely inferred from macroscopic voltage or current measurements alone.

Within the interfacial region, the EDL regulates electrostatic screening and effective interfacial capacitance, however, variations in ionic concentration or conductivity simultaneously alter primary charge generation, diffuse-layer screening, bulk resistance, and wetting dynamics. Consequently, bulk conductivity cannot serve as a universal predictor of electrical output across diverse devices and liquids. Similarly, established modelling approaches, from Maxwell displacement-current formulations, lumped equivalent circuits, Thévenin/Norton terminal representations, quasi-electrostatic field solvers, and coupled ionic-electrostatic descriptions, can capture distinct physical scales and rely on fundamentally different state variables, geometric simplifications, and boundary assumptions.

The intrinsic electrostatic response of an LS-TENG must be rigorously separated from the signal recorded by the external measurement chain. Input impedance, parasitic capacitance, amplifier bandwidth, and sampling frequency can substantially attenuate or distort transient waveforms; accordingly, matching a recorded terminal voltage trace does not independently validate underlying surface charge densities, carrier identities, or unmeasured fast dynamics. To bridge interfacial physics with practical device simulation, this review organizes primary charging, EDL screening, droplet hydrodynamics, electrode induction, and instrument loading into a unified conceptual dependency while introducing a discrete-time phenomenological history formulation to capture cycle-by-cycle surface charge evolution across successive droplets. Together, these contributions provide a physically interpretable foundation for future LS-TENG model calibration, standardization, and low-cost liquid sensing and environmental monitoring.

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