Electrochimica Acta 567 (2026) 148831

Contents lists available at ScienceDirect

Electrochimica Acta

journal homepage: www.journals.elsevier.com/electrochimica-acta

Review

Chemical pumping and wireless electrochemical platforms for next-generation reactors

Sara Grecchi , Serena Arnaboldi *

Department of Chemistry, Università degli Studi di Milano, Via Golgi 19 20133, Milan Italy

ARTICLE INFO

Keywords:
Bipolar electrochemistry
Chemical pumping
Wireless electrochemical reactors
Microfluidics
Asymmetric Electrosynthesis
Electroassisted Chiral Resolution

ABSTRACT

The precise control of fluid dynamics and mass transport is essential across analytical chemistry, catalysis, and process engineering. While traditional macroscale systems rely on external mechanical pumps, the push toward miniaturized, autonomous platforms like Lab-on-a-Chip (LoC) devices necessitates a critical shift toward non-mechanical fluidic mechanisms. This review provides a selective and critical analysis of non-mechanical pumping systems, ranging from purely chemical propulsion (e.g., self-driven micro-motors) to systems actuated by external physical stimuli (e.g., thermal or acoustic fields). However, while these methods offer remote control, they frequently suffer from fuel dependency and, critically, the operational decoupling of actuation from reaction kinetics. Electrochemical principles, particularly Bipolar Electrochemistry (BE), provide a superior solution through Faradaic-coupled fluidic actuation, where localized chemical changes (e.g., gas evolution, pH gradients) generate self-regulating flow. The central focus of this work is the emergence of truly autonomous, wireless, and self-pumping electrochemical reactors (WERs). We establish the physical foundations for efficiency in these systems using dimensionless parameters like the Wagner number (W_a) and provide a mechanistic link between mass transport and selectivity via the Chiral Induced Spin Selectivity (CISS) effect. This rigorous assessment approach enables 'unplugged' asymmetric electrosynthesis and high-resolution chiral separation, positioning autonomous arrays as an operational framework for smart chemical manufacturing.

1. Introduction

The precise control of fluid flow and mass transport remains a central challenge in chemical engineering, catalysis, and analytical chemistry [1–3]. In conventional process engineering, flow regulation is typically achieved through external mechanical pumps and feedback control systems [4]. Although robust and scalable, such approaches become increasingly complex upon miniaturization, requiring intricate fluidic connections, external power supplies, and additional control hardware. More fundamentally, in mechanically pumped systems, actuation and reaction kinetics are generally decoupled: the flow rate is imposed externally and does not intrinsically respond to the chemical state of the reactor. This separation limits the development of platforms in which transport and reaction rates are dynamically co-regulated.

These considerations have motivated sustained efforts toward non-mechanical flow generation strategies that rely on intrinsic physical or chemical forces rather than moving parts [5–9]. Approaches explored to date include thermally driven flows (thermo-capillary and thermo-osmotic effects) [10–12], acoustically induced streaming [13, 14], and chemically powered propulsion, where local concentration or interfacial gradients generated by reactions induce motion of droplets, particles, or surrounding fluids [15]. Such systems demonstrate that fluid transport can emerge from localized energy conversion processes; however, the degree of controllability, scalability, and integration varies substantially across implementations.

Within this broader landscape, electrochemical methods offer distinctive advantages because they directly couple charge transfer to chemical transformation and interfacial phenomena [16–19]. Established examples include (alternating current, AC) electro-osmosis [20], as well as electrochemical hydrogen pumps for gas management and separation [21]. More generally, electrochemistry plays a central role in sustainable synthesis [22–27], energy conversion and storage [28,29], and chemical sensing [30,31], owing to its ability to precisely regulate redox potential, stoichiometry, and selectivity. Nevertheless, most conventional electrochemical systems rely on wired electrode configurations, macroscopic reactors, and often external pumping to regulate mass transport. These architectures, although powerful, impose constraints in terms of system complexity, scaling, and integration.

* Corresponding author.
E-mail address: serena.arnaboldi@unimi.it (S. Arnaboldi).

https://doi.org/10.1016/j.electacta.2026.148831
Received 23 January 2026; Received in revised form 2 April 2026; Accepted 7 April 2026
Available online 8 April 2026

A key research direction therefore concerns redefining how mass transport is generated and controlled in electrochemical environments. Rather than relying exclusively on externally imposed convection, increasing attention has been devoted to chemically or electrochemically induced fluid motion, sometimes referred to as chemical pumping or chemically driven transport. In this context, bipolar electrochemistry (BE) has emerged as a versatile strategy for contactless electrochemical activation [32–37]. In BE, electrically floating conductive objects, bipolar electrodes (BPEs), are polarized by an electric field applied across the electrolyte [36,37]. It is important to clarify that terms such as "autonomy" are used here in an operational sense. Wireless bipolar systems remain dependent on externally applied electric fields and defined boundary conditions. Their adaptive behavior arises from feedback between local electrochemical reactions and the surrounding environment, rather than from complete energetic self-sufficiency. Not all field-induced systems exhibit self-regulation, and careful mechanistic analysis is required to distinguish genuine coupling effects from externally imposed forcing. In fact, the applied field induces a potential difference along the BPE ($\Delta V = \varepsilon \cdot L$), driving simultaneous oxidation and reduction at opposite poles [33,38]. Reaction rates are governed by local interfacial overpotential, electrolyte conductivity, electrode geometry, and charge-transfer kinetics, providing indirect but quantifiable control parameters distinct from conventional three-electrode configurations. Beyond enabling redox transformations without wired contacts, BE can generate local physicochemical gradients, such as pH shifts, gas evolution, or asymmetric ion fluxes, that induce fluid motion near the electrode surface. In this configuration, fluid displacement emerges directly from Faradaic processes rather than from externally imposed pressure gradients, establishing a partial coupling between reaction and transport within a single electrochemical framework. The magnitude and stability of such flows depend strongly on boundary conditions, including field strength, cell geometry, and electrolyte composition.

Recent studies have extended these principles to wireless electrochemical microreactors and self-actuated platforms [23–27,38–41], including systems for asymmetric electrosynthesis and electroassisted chiral resolution. In these cases, field-induced polarization not only drives the redox transformation but can also modulate local mass transport. Compared to conventionally stirred reactors, such architectures may enable improved spatial confinement and interfacial control. However, performance improvements must be evaluated quantitatively, with appropriate normalization of flow rate, energy input, and overall efficiency. Bibliometric analyses (Fig. 1) indicate a growing research interest in BE and chemically driven microactuation; however, publication trends alone do not necessarily reflect technological maturity or comparative performance. While BE represents the most established electrochemical wireless strategy, other emerging contactless or field-driven approaches, including triboelectric and ultrasonication-assisted charge generation at solid–liquid interfaces, have also demonstrated the ability to produce asymmetric charge distributions and induce redox transformations without conventional wired electrodes. Although mechanistically distinct, these systems similarly rely on interfacial polarization and gradient formation, broadening the conceptual framework for next-generation reactor design.

This review therefore provides a selective and critical analysis of non-mechanical pumping strategies, with particular emphasis on electrochemically induced fluid motion and wireless bipolar platforms, examining the specific conditions under which coupling between Faradaic reactions and mass transport yields measurable functional advantages. By clearly distinguishing established mechanisms from forward-looking interpretations, we aim to delineate both the opportunities and the current limitations of wireless electrochemical reactors for advanced chemical synthesis and analysis [42–45].

2. Foundations of non-mechanical fluid control

The evolution of modern analytical chemistry and process engineering is intrinsically linked to the ability to precisely control fluid dynamics and mass transport. While traditional macroscale systems successfully employ conventional mechanical pumps (e.g., syringe, peristaltic) to generate bulk fluid movement, the transition to miniaturize and integrate chemical analysis platforms, notably Lab-on-a-Chip (LoC) and micro-reactors, has exposed the fundamental limitations of these methods [46]. Mechanical pumps are often bulky, consume significant power, and introduce undesirable effects such as dead volumes, fluidic pulsation, and shear forces that can damage delicate components (e.g., cells or biological molecules). The necessity of achieving seamless integration, enhanced portability, and superior control at the microscale has catalyzed significant research into non-mechanical fluid control systems, which harness inherent physical or chemical forces to induce fluid motion [47,48].

2.1. *Chemical propulsion and self-driven micro-swimmers*

One major category involves generating fluid motion via self-

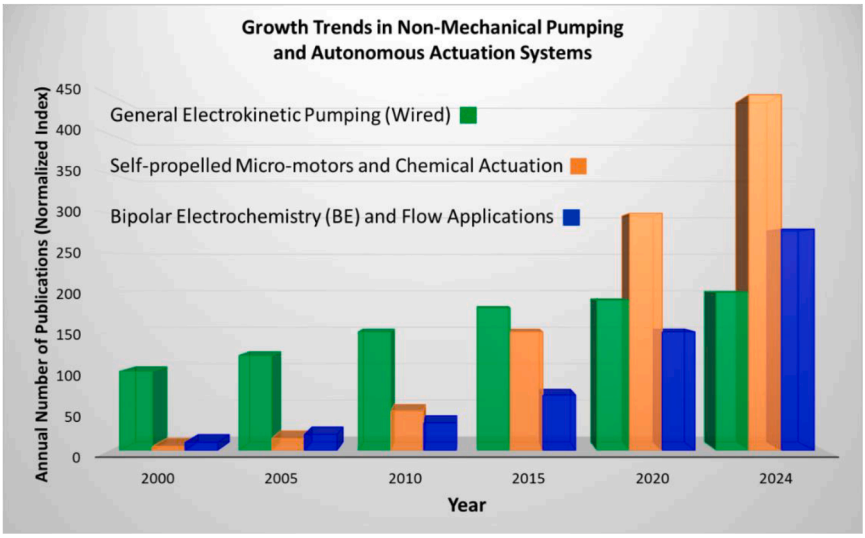

Fig. 1. Publication trends illustrating the convergence of established electrokinetics, rapidly expanding chemical self-propulsion, and BE for flow control. The exponential growth in BE and micro-motor research highlights the shift toward autonomous and contactless fluidic actuation, which is the core focus of this review (Source: Scopus).

propulsion driven solely by chemical reactions occurring in situ. These systems are fundamentally autonomous, converting chemical potential energy directly into kinetic energy for movement or fluid mixing. The drive toward designing Micro/Nanorobots for environmental, industrial, and biomedical tasks has made this field a cornerstone of modern actuation research [49,50]. In these systems, a localized chemical reaction establishes an asymmetric gradient (chemical or thermal) across the surface of the microdevice (often called a micro-swimmer or micro-motor, Fig. 2). This asymmetry generates a net force through two primary mechanisms:

1. Diffusiophoresis/Chemotaxis, where the asymmetric release or consumption of chemicals results in a local concentration gradient. The resulting diffusion of these species past the particle surface creates an electrokinetic flow, driving the particle forward [48,51].
2. Marangoni Effect, which is applicable at fluid interfaces, where the chemical reaction creates a localized gradient in surface tension. The fluid flows from regions of lower surface tension to regions of higher surface tension, resulting in directional movement of droplets or particles floating at the interface [52].

A key manifestation of chemical propulsion is the development of catalytic micro-motors. These microscopic devices, often Janus particles (bifunctional particles with two distinct surfaces), utilize the catalytic decomposition of a fuel (e.g., hydrogen peroxide) on one part of the particle surface (e.g., coated with platinum) [49,53]. This asymmetric reaction creates a local concentration gradient that translates into self-generated motion, which can reach speeds of several body lengths per second, consequently inducing highly localized fluid mixing or directional propulsion. These methods are particularly effective for tasks such as targeted drug delivery, environmental remediation, and enhanced mixing at the microscale where conventional stirring is ineffective [46,49].

From the perspective of electrical decoupling, chemically propelled micro-swimmers exhibit low wireless relevance, as actuation is entirely driven by intrinsic chemical energy conversion rather than by externally applied electric fields. Although these systems are autonomous in terms of fuel consumption, no electrochemical field-induced coupling is involved. This distinction becomes important when comparing such self-propelled systems with bipolar electrochemical platforms, where fluid motion and redox transformations are intrinsically linked through externally imposed electric fields.

2.2. *Physico-Chemical pumping: operational principles and challenges*

Beyond purely chemical reactions, fluid flow can be robustly induced by exploiting external physical stimuli such as thermal, acoustic, or magnetic fields [54–56]. Thermally driven systems generate controlled gradients that produce motion through mechanisms including thermo-capillary effects in multiphase environments, thermo-osmosis along channel walls, or buoyancy-driven thermo-hydrodynamic convection [57]. Similarly, acoustically driven platforms employ high-frequency Surface Acoustic Wave (SAW) transducers to generate directional streaming and efficient mixing in microchannels [58–61]. Magnetic actuation further extends this toolbox, particularly in micro- and nanorobotic systems where external magnetic fields enable remote propulsion and steering of mobile structures. Collectively, these approaches enable contactless manipulation of fluid and particle motion, providing high levels of temporal and spatial control (Fig. 3). The technological roadmap for micro/nanorobots increasingly emphasizes this transition from simple self-propulsion toward externally guided systems in which the physical stimulus not only supplies energy but also dictates the directionality of motion [62]. However, such strategies inevitably rely on external hardware, heaters, acoustic transducers, or electromagnetic generators, thereby increasing the complexity and energy demand of the overall system [63,64].

Despite their effectiveness for remote manipulation, these methods generally remain operationally decoupled from the underlying reaction kinetics. For example, thermal and acoustic actuation can generate flow rates in the range of 1–10 μL/min, but often require relatively high power densities (10–100 mW/cm^2), which may lead to parasitic heating effects [54,61]. By comparison, electrochemical actuation can achieve comparable flow rates (0.1–5 μL/min) with significantly lower power consumption (<1 mW), while maintaining a direct Faradaic coupling

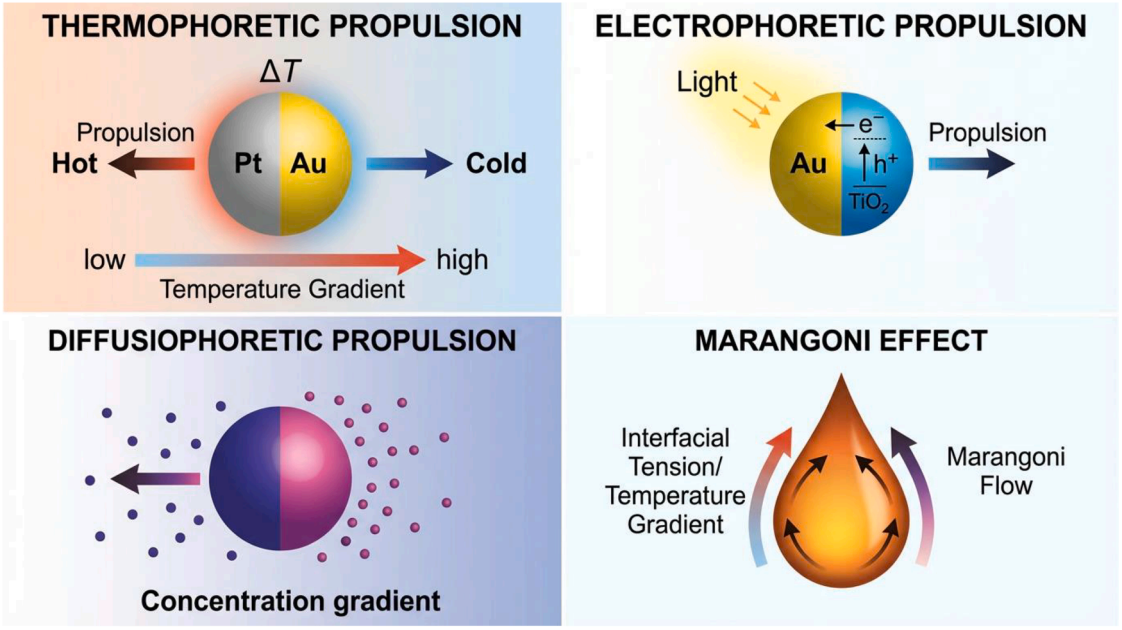

Fig. 2. Overview of different propulsion mechanisms for microscale motors. The graphic displays four primary methods of movement: thermophoretic propulsion, where a temperature gradient drives a Pt/Au particle toward colder regions; electrophoretic propulsion, which utilizes light to generate electron-hole pairs in materials like TiO_2 to create motion; diffusiophoretic propulsion, where a concentration gradient of particles or solutes induces displacement; and the Marangoni effect, where gradients in interfacial tension or temperature trigger internal and external flows that propel a liquid droplet.

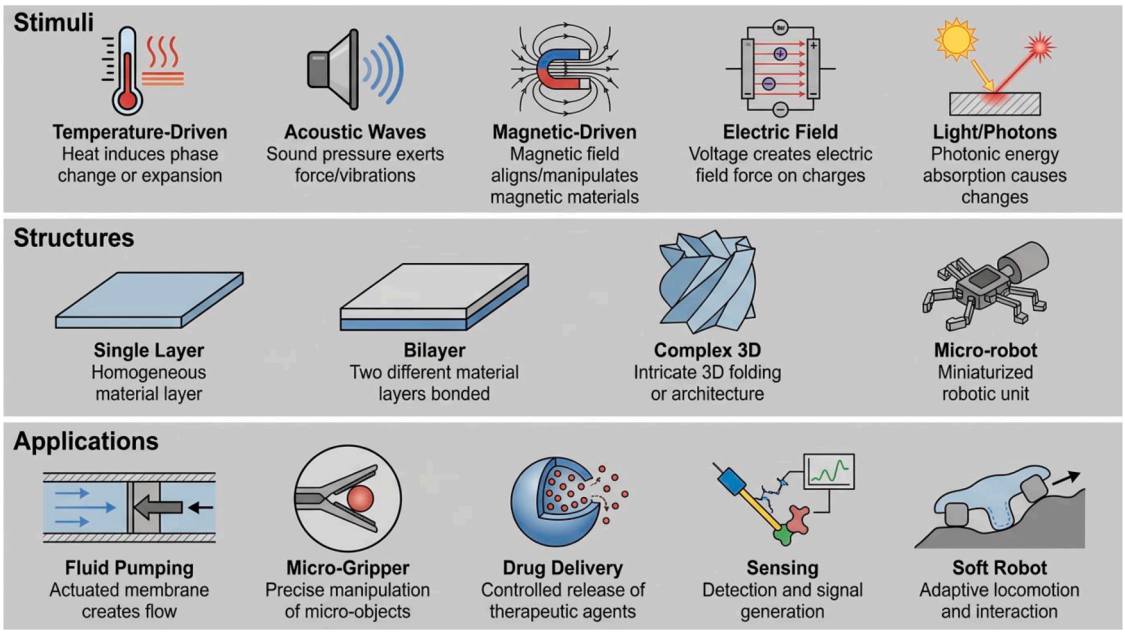

Fig. 3. Classification of microscale actuation systems based on stimuli, structural design, and practical applications. The schematic categorizes the field into three primary levels, starting with the external stimuli used to trigger motion or deformation, such as thermal changes, acoustic waves, magnetic and electric fields, or light energy. These inputs act upon various structural configurations, ranging from simple single-layer and bilayer materials to complex 3D architectures and fully integrated micro-robotic units. The diagram also highlights diverse real-world applications, demonstrating how these systems enable advanced functions like fluid pumping, micro-manipulation with grippers, targeted drug delivery, environmental sensing, and the adaptive locomotion of soft robots.

with the chemical transformation [17,20].

This distinction highlights a fundamental limitation of non-electrochemical actuation strategies: fluid motion acts as an externally imposed perturbation that must be synchronized with the reaction progress. In contrast, BE treats flow as an intrinsic consequence of the electrochemical process itself. This conceptual difference distinguishes BE from recent approaches such as the “Wi-eChem” system [65], where fluid mixing is achieved through mechanically driven stirring that remains independent of the reaction dynamics. In miniaturized electrochemical platforms, the overall performance is governed by the Wagner number (W_a), which defines the balance between interfacial charge transfer and solution resistance [66,67]. Proper tuning of W_a allows the applied electric field to be efficiently converted into Faradaic work, enabling a self-regulating regime in which the reaction rate directly determines the local mass-transport environment.

Table 1 provides a comparative overview of these strategies, highlighting the transition toward the functional autonomy achieved by next-generation wireless platforms. The criteria for categorization in Table 1 are based on the degree of functional coupling between the energy source and the fluidic work. We define 'Autonomy' not as a measure of general superiority, but as the spatial proximity of the actuation site to the chemical reaction site. This classification underscores the trade-off between absolute power, which is maximal in mechanical systems, and energy localization, which reaches its peak in electrochemical wireless platforms.

3. Bipolar electrochemistry: fundamental principles

To properly contextualize Faradaic-coupled fluidic actuation, the physical framework of Bipolar Electrochemistry (BE) must first be strictly defined. In BE, electrically floating conductive objects, termed bipolar electrodes (BPEs), are polarized by an electric field applied across the electrolyte. Importantly, "wireless" in this context does not imply the absence of external energy input; instead, it denotes the absolute absence of a direct ohmic connection between the power supply and the electroactive object [33–38].

When an external electric field (ε) is applied, it induces a potential gradient in the solution. The conductive BPE acts as an equipotential body that reaches an equilibrium floating potential, establishing an interfacial potential difference along the length of the BPE ($\Delta V = \varepsilon L$)

Table 1
Comparative overview of fluid actuation strategies in miniaturized reactors, highlighting the transition from externally driven mechanical systems to wireless electrochemical platforms based on energy transduction and operational autonomy.

Actuation Strategy	Primary Energy Source	Fluidic Driver	Autonomy Level	Key Limitation	System Complexity and Scalability
Mechanical	External Electricity	Peristaltic/Syringe Pumps	Low	Bulky, high dead volume	Low complexity / High scalability
Electrokinetic	Direct DC/AC Field	Electrical Double Layer (EDL)	Moderate	Requires wired contact	High complexity / Medium scalability
Chemically Driven	In situ Fuel (H_2O_2)	Concentration Gradients	High	Fuel dependency/Toxicity	Medium complexity / Low scalability
Bipolar (BE)	Induced Electric Field	Bubble/Ion Gradients	High	Requires field control, high sensitivity to media conductivity; rigid electrode geometry requirements; limited to low-throughput applications	High complexity / Very Low scalability
Wireless (WER)	Inductive/Light Power	Integrated PPy Actuators	Absolute	Throughput constraints	High complexity / Very Low scalability

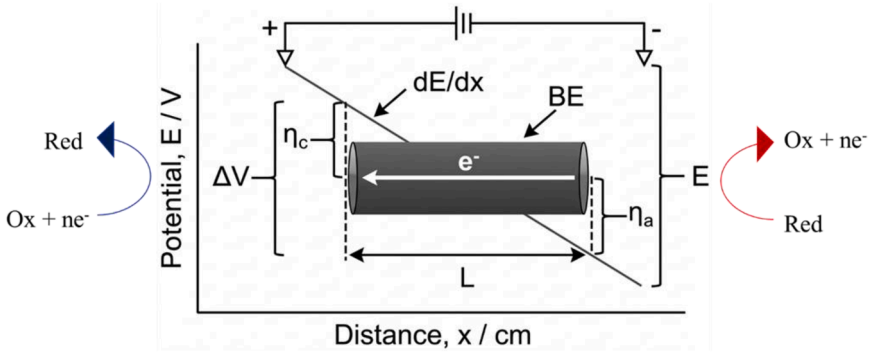

Fig. 4. Interfacial potential distribution and reaction mechanism in a bipolar electrochemical cell. An external power supply generates a linear potential gradient (dE/dx) across the electrolyte. A bipolar electrode (BE) of length L is immersed in the solution, where the potential difference across its length (ΔV) acts as the driving force for wireless electrochemical reactions. Due to this gradient, the left extremity of the BE acts as the cathodic side (η_c), facilitating the reduction of "Ox" to "Red," while the right extremity acts as the anodic side (η_a) where the oxidation of "Red" to "Ox" occurs. To maintain charge neutrality, electrons (e^-) flow internally through the conductive body of the BE from the anodic side to the cathodic side.

(Fig. 4). This potential gradient forces the BPE to act as a unified anode and cathode, driving simultaneous oxidation and reduction at opposite extremities. Reaction rates are strictly governed by the local interfacial overpotential, electrolyte conductivity, electrode geometry, and charge-transfer kinetics, providing indirect but highly predictable control parameters distinct from conventional three-electrode configurations [33–38].

3.1. Dimensional analysis and the wagner number

The spatial resolution and efficiency of BE platforms are intrinsically governed by the Wagner number (W_a) [66]. This dimensionless parameter mathematically defines the balance between the kinetic charge-transfer resistance at the interface and the ohmic resistance of the surrounding electrolyte. W_a is defined as in Eq. (1):

$$W_a = \frac{\kappa\left(\frac{\delta\eta}{\delta j}\right)}{L} \quad (1)$$

Where κ represents the electrolyte conductivity, L is the characteristic length of the bipolar electrode, and $\delta\eta/\delta j$ is the specific activation resistance (derived from the Tafel slope).

The magnitude of W_a dictates the current distribution across the wireless reactor. When $W_a << 1$, the system is dominated by ohmic resistance, creating a primary current distribution where faradaic reactions are intensely focused strictly at the extreme poles of the BPE. This intensely localized reaction is highly advantageous for generating the asymmetric fluidic thrust required for chemical pumping. Conversely, a high W_a results in a secondary current distribution, yielding uniform polarization across the BPE, which reduces pumping efficiency but ensures homogenous surface functionalization.

3.2. Coupling kinetics with mass transport: Da and Pe numbers

While W_a dictates the current distribution, the continuous operation of Faradaic-coupled pumping relies on a delicate balance between reaction kinetics and mass transport. This balance is defined by the Damköhler number (Da), which represents the ratio of the electrochemical reaction rate to the mass diffusion rate [67]. When $Da >> 1$, the reaction is entirely mass-transport limited because it occurs at a much faster pace than diffusion, leading to severe reactant depletion at the poles. To sustain autonomous operation, the system must self-generate a convective flow that overcomes this limitation. This establishes a high Péclet number (Pe), where convective transport dominates over diffusive transport, ensuring that fresh reactants are continuously supplied to the catalytic interfaces [68].

4. Faradaic-Coupled fluidic actuation

Unlike purely chemical or physico-chemical methods, electrochemical actuation provides a level of electrical controllability over fluid manipulation. When the BPE is polarized as defined in Section 3, the highly localized Faradaic reactions at the poles create asymmetric chemical environments, converting electrical energy into localized mechanical work (fluid motion).

4.1. Rigorous kinetic framework: the butler-volmer constraint

The distribution of the local current density (*j*) along the length of the BPE determines the intensity of the fluidic thrust. The Faradaic current density is governed by the modified Butler-Volmer equation (Eq. (2)), which is a general electrochemical relationship and is not exclusive to bipolar systems; in BE it applies locally at the induced poles:

$$j(x) = j_0 \left\{ \exp\left[\frac{\alpha_a F}{RT}\,\eta(x)\right] - \exp\left[\frac{\alpha_c F}{RT}\,\eta(x)\right] \right\} \quad (2)$$

Where j_0 is the exchange current density, $\eta(x)$ is the local overpotential at position x, α_a and α_c are the anodic and cathodic transfer coefficients, and *F*, *R*, and *T* are the Faraday constant, universal gas constant, and absolute temperature.

Crucially, in accordance with rigorous quantum mechanical principles explicitly formalized in the second and third editions of Bard and Faulkner's *Electrochemical Methods*, the probability of the simultaneous transfer of more than one electron in an elementary kinetic step is energetically highly improbable and considered negligibly small. Therefore, the stoichiometric number of electrons (n) in the exponential activation terms has been strictly set to 1, accurately representing a single-electron transfer rate-determining step. Assuming a multielectron transfer ($n > 1$) artificially compresses the Tafel slopes and yields non-physical symmetry factors. Understanding precise Tafel kinetics is vital, as it determines the threshold overpotential required to overcome activation barriers and initiate pumping [69].

4.2. Pumping mechanisms beyond H_2 and O_2

The most visible mechanism for BPE propulsion is the production of gaseous products (e.g., H_2 or O_2) at the poles. The unequal release of gas generates a strong recoil force, propelling the BPE or inducing vigorous localized fluid motion [70].

However, relying solely on sacrificial water splitting limits the scope of advanced synthesis, as multiphase gas evolution creates chaotic turbulence and limits spatial control. To achieve sophisticated, non-pulsating fluid control, modern wireless reactors utilize alternative,

single-phase redox chemistries. Replacing violent gas evolution with the continuous oxidation and reduction of highly soluble redox mediators, such as the ferri/ferrocyanide couple ($[Fe(CN)_6]^{3-}$ / $[Fe(CN)_6]^{4-}$) [71], ensures that the BPE operates smoothly under single-phase hydrodynamic conditions (Fig. 5). Furthermore, the integration of Bipolar Membranes (BPMs) allows for fluidic actuation driven by sustained pH gradients, initiating intense electrokinetic and diffusiophoretic transport without any gas generation [72,73].

To further contextualize the advantages of this Faradaic coupling, Table 2 compares normalized performance metrics across different actuation paradigms.

5. The emerging paradigm: wireless and self-pumping electrochemical reactors

The most advanced frontier involves systems that integrate remote energy delivery (e.g., inductive or AC fields) with internal, self-generated fluid dynamics. By eliminating the necessity for direct electrical connection and integrating the fluid drive into the reaction process itself, these Wireless Electrochemical Reactors (WERs) represent a promising step toward decentralized chemical manufacturing (Table 3).

5.1. Chiral induced spin selectivity (CISS)

To explore possible mechanisms underlying chiral effects in wireless electrochemical platforms, it is crucial to consider the Chiral Induced Spin Selectivity (CISS) effect. CISS refers to the experimentally observed ability of chiral materials to preferentially transmit electrons of a given spin orientation [74–76].

At chiral electrochemical interfaces, spin-polarized electron transport has been shown to influence reaction kinetics and overpotentials. For example, the competition between H_2O_2 production and triplet oxygen evolution is heavily influenced by the spin-polarization of the surface [76]. The combination of wireless operation and chemical pumping creates unique electrochemical environments that leverage these interfacial phenomena to control stereoselectivity autonomously. A significant breakthrough involves the use of fully autonomous micro-reactors for unplugged asymmetric electrosynthesis, where alternating current (AC) protocols drive near-quantitative yield and exceptional enantioselectivity. However, establishing a definitive causal link between self-pumping and selectivity is strictly constrained by the Péclet number (Pe). If the pumping velocity is too high, the residence time of reactants within the spin-active interfacial layer drops, ultimately disrupting the CISS-governed kinetic window.

5.2. Self-Powered actuation via triboelectric nanogenerators

While wireless bipolar systems eliminate direct ohmic contacts, they still fundamentally rely on an external power supply to generate the driving electric field. To achieve absolute energetic autonomy, recent advancements have integrated Triboelectric Nanogenerators (TENGs) to create fully Self-Powered Electrochemical Systems (SPES). TENGs convert ambient mechanical energy, such as fluid flow, acoustic vibrations, or human motion, directly into high-voltage electrical pulses through the coupling of contact electrification and electrostatic induction [77].

In the context of microfluidics and wireless reactors, fluid-based TENGs operating at the liquid-solid interface have introduced the paradigm of contact-electro-chemistry (CE-Chemistry) [78]. Here, the dynamic interaction of the fluid itself generates the localized electric

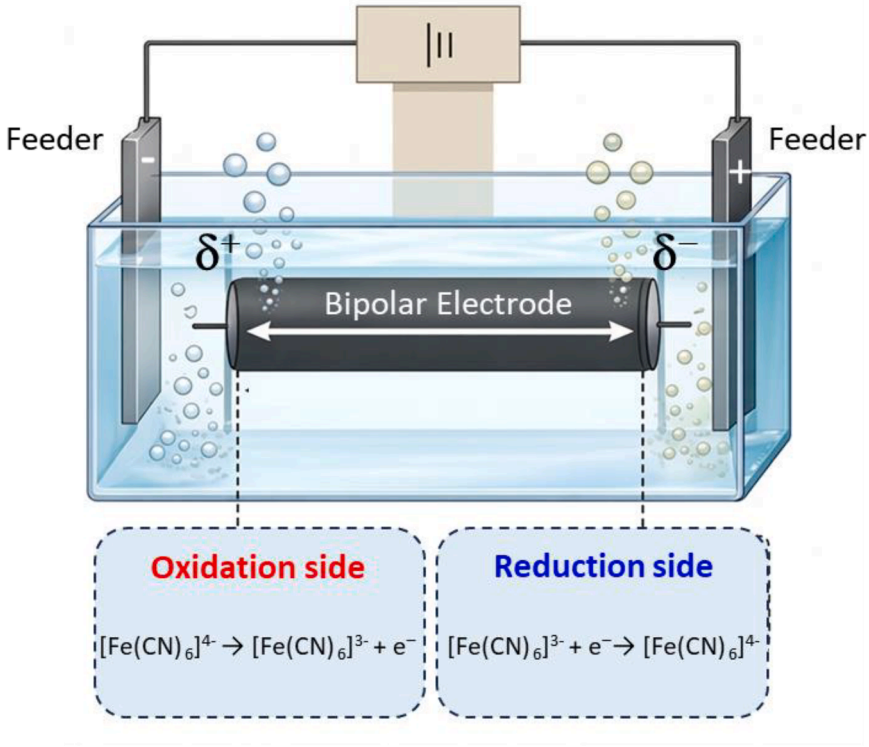

Fig. 5. The figure shows a bipolar electrode (BE) immersed in an electrolyte solution between two external feeder electrodes. Under the influence of the applied electric field, the BE becomes polarized, developing a δ^+ and a δ^-. On the oxidation side (left), facing the negative feeder electrode, the ferrocyanide species $[Fe(CN)_6]^{4-}$ is oxidized to ferricyanide $[Fe(CN)_6]^{3-}$, releasing electrons. These electrons flow internally through the conductive body of the electrode toward the reduction side (right), where they facilitate the reduction of $[Fe(CN)_6]^{3-}$ back to $[Fe(CN)_6]^{4-}$. This process demonstrates the ability of bipolar electrochemistry to drive coupled chemical reactions at the electrode extremities without direct electrical wiring.

Table 2
Normalized performance metrics (orders of magnitude) for prominent fluid actuation strategies. The comparison highlights the physical trade-offs between throughput, energy efficiency, and the degree of operational autonomy across different platforms.

Actuation Strategy	Flow Rate (μL/min)	Specific Energy (mW·min/μL)	Max Pressure (Pa)	Control Mode	Massive Throughput (Flow Rate)
Mechanical Pumping	1.0 - 1000	High (at microscale)	$> 10^5$	Direct / Wired	High (>10 mL/min).
DC Electro-osmosis	0.1 - 5.0	Moderate	$10^2 – 10^4$	Direct / DC Field	Low (<100 μL/min)
AC Electrohydrodynamics	0.5 - 15.0	Low	10 - 100	Indirect / Inductive	Low (<100 μL/min)
Chemical Propulsion	0.01 - 1.0	N/A (Fuel-driven)	< 10	Autonomous / Low Control	Low (<100 μL/min)
Wireless Bipolar (BE)	0.2 - 5.0	Very Low	50 - 500$	Wireless (Functional)	Very Low (<10 μL/min)

Table 3
Critical comparison of contemporary wireless electrochemical reactors based on their energy transduction pathways and the degree of integration between mass transport and chemical transformation.

Platform	Power Source	Actuation Mechanism	Integrated Pumping	Primary Application
PPy-Tube WER	Inductive (AC)	Faradaic-Coupled Flow	YES	Asymmetric Synthesis & Chiral Resolution
Wi-eChem	Inductive (RF)	Magnetic Stirring	No (Mechanical)	Robotic Parallel Synthesis
SPECS (Surface Physics and Electro-Chemical Systems)	Visible Light	Photo-induced Potential	No	High-Throughput Screening (HTE)

fields required to drive faradaic reactions, effectively using the fluid's kinetic energy to power its own electrochemical transformations. Furthermore, the localized charges generated by TENGs can induce fluidic motion via electrowetting-on-dielectric (EWOD) effects or by generating capillary waves that actuate microbots without any external pumping hardware.

Crucially, the high-voltage pulsed output characteristic of TENGs is highly compatible with bipolar electrochemistry. Recent studies have demonstrated that these pulsed fields can efficiently power multiple bipolar electrochemical reactors simultaneously, driving processes ranging from conducting polymer synthesis to complex asymmetric transformations. This synergy between triboelectric energy harvesting and Faradaic-coupled flow represents the ultimate frontier in autonomous chemical pumping, paving the way for self-sustaining micro-reactors that require neither wiring nor batteries [79].

6. Quantitative visualization of wireless reactors

The true impact of this emerging paradigm is realized when applied to complex chemical transformations where autonomous and precise fluid control is critical for selectivity, such as chiral synthesis and resolution [23–25,80,81]. The combination of wireless operation and chemical pumping creates unique electrochemical environments that leverage interfacial phenomena to control stereoselectivity. A significant breakthrough involves the use of fully autonomous micro-reactors for unplugged asymmetric electrosynthesis (Fig. 6) [23,24].

The reactor consists of a hollow, conductive polymer tube where an external PPy shell acts as an electromechanical pump, and the inner layer, functionalized with a chiral catalyst, serves as the enantioselective site. The system utilizes an internal electrochemical mechanism to generate both the necessary redox potential (via wireless AC induction) and the intrinsic flow, achieving near-quantitative yield (99%) and exceptional enantioselectivity (>99% ee) for benchmark reductions without any wired connections. This configuration significantly reduces the need for direct wiring and external fluidic infrastructure [23].

The ability to control the flow at the reaction interface allows for fine-tuning of the kinetics, which is paramount in chiral chemistry. By employing chiral ionic liquids in a wireless electrochemical microreactor, it has been shown that the interplay between the wireless potential (specifically, the frequency and potential of the DC signal) and the self-generated flow can be precisely tuned to control the stereoselectivity of the product [24]. This highlights the powerful potential of controlling mass transport at the chiral interface autonomously, demonstrating that flow itself can be an electrochemical control parameter for selectivity. The self-pumping principle has also been extended beyond synthesis to complex separation tasks (Fig. 7) [80,81]. Designs utilizing Wireless Hollow Miniaturized Objects (WHMOs) integrate electromechanical principles with wireless separation techniques [80,81]. These conductive tubular devices, functionalized internally with a chiral selector, utilize the wireless-induced electrochemical reaction to generate internal pressure (pumping) and external motion. The objects act as miniaturized, flow-generating chromatophores, enabling the electromechanical wireless separation of chiral analytes, effectively merging the concepts of fluid control, electrochemistry, and separation science in a single, autonomous unit.

6.1. *Helically shaped micro-pumps for enhanced efficiency*

The morphology of the BPE or the wireless actuator plays a crucial role in maximizing the pumping efficiency. Helically shaped geometries have been demonstrated to provide a significant advantage in channeling forces into directed fluid flow. Recent studies have explored the use of hollow PPy helical structures for efficient molecular pumping [82]. It has been demonstrated that the helical geometry, analogous to an Archimedes' screw, not only optimizes the conversion of the induced field into fluidic pressure but also predictably modulates the distribution of the induced polarization along the structure. Resistive mapping of these devices confirmed that the geometric asymmetry is intrinsically linked to the electrochemical asymmetry necessary to generate the propulsive or pumping thrust. The findings highlight how the morphology dictates the local redox distribution, supporting the interpretation of the asymmetric pressure-driven transport mechanisms governing the wireless pumping performance. The benefits of these autonomous WER systems are compelling: unprecedented portability, minimal footprint, elimination of complex plumbing, and high potential for parallelization (as multiple reactors can be operated by a single external coil). However, major limitations remain that define the current research frontier, in fact current devices often exhibit low volumetric throughput compared to bulk industrial reactors (scaling up the self-pumping mechanism without losing efficiency remains a significant challenge). Moreover, the complexity of the self-regulating mechanisms, where flow and reaction are intrinsically interdependent, makes design, modeling, and optimization challenging (small changes in geometry or electrolyte viscosity can drastically alter the self-pumping performance). Finally, the efficiency of wireless power transfer (e.g., maximizing the induced AC potential relative to the energy input) and its stability across different media and distances are critical areas that require further fundamental investigation before widespread industrial adoption is feasible.

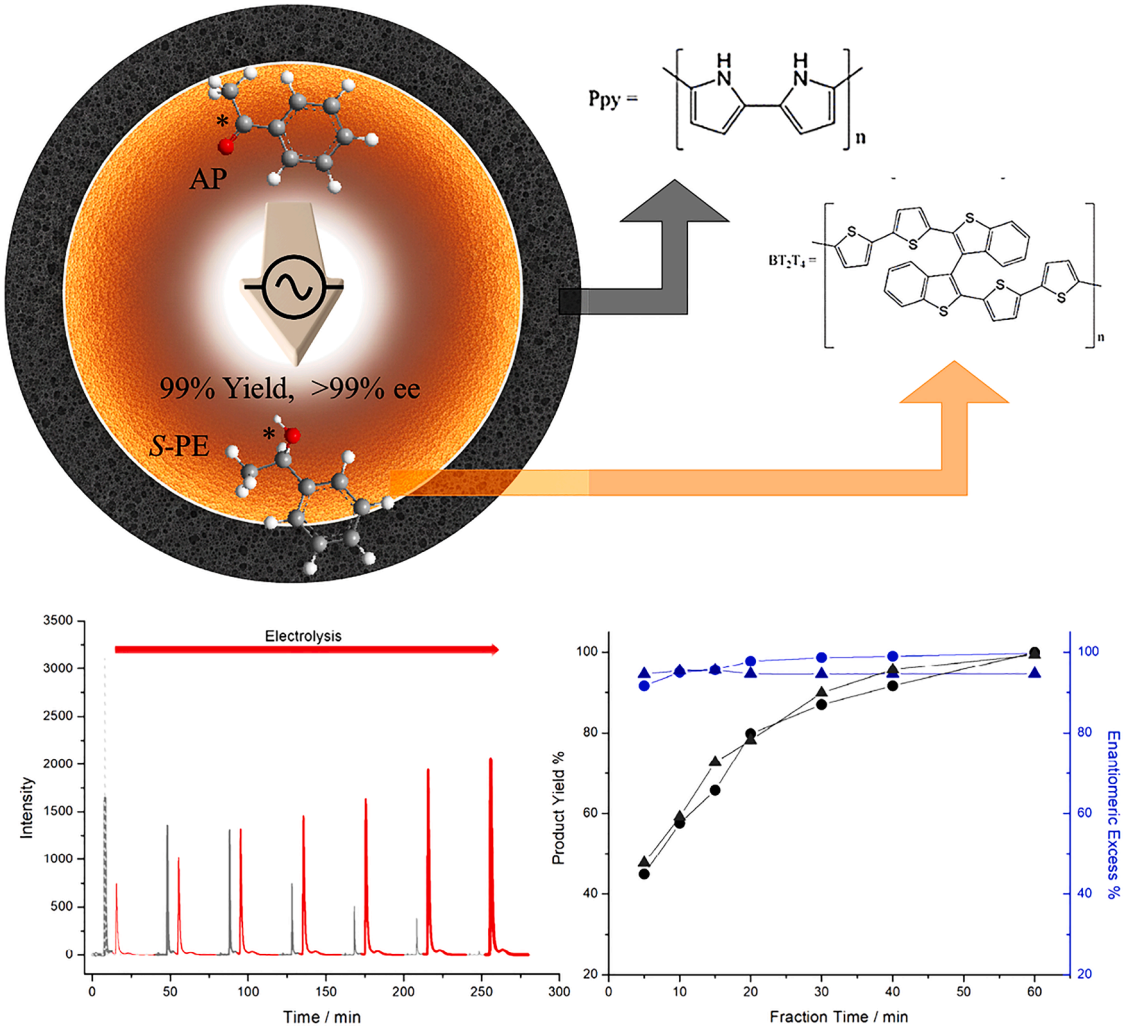

Fig. 6. Schematic representation of a wireless, autonomous bipolar miniaturized soft tube. The hollow polypyrrole (PPy, in black) structure acts as an electrochemical pump under an external AC field, while the internal chiral coating (in orange) promotes the asymmetric reduction of acetophenone to (*S*)-phenylethanol with high enantioselectivity and near-quantitative yield [23].

7. Strategic frontiers and future directions

The development of chemical pumping systems challenges traditional reactor conventions, with two key frontiers for industrial translation. First, massive parallelization ("numbering-up") can scale single micro-reactors to pharmaceutical production levels while maintaining high surface-to-volume ratios, though electric field inhomogeneity ('edge effects') must be addressed through optimized reactor geometries. Second, the intrinsic coupling of flow and reaction demands advanced computational oversight. Future autonomous reactors will likely use AI to manage wireless protocols (AC frequency, potential, pulse duration) in real-time, optimizing residence times to maximize yield and enantiomeric excess from sensor feedback.

Progress also depends on innovations in energy harvesting, smart materials, and alternative stimuli. New metamaterials and circuits can enhance wireless energy efficiency, enabling portable, low-power operation. Conductive polymer actuators like polypyrrole require replacement with chemically responsive materials capable of modulating flow based on local conditions, approaching true chemical intelligence. Meanwhile, integrating unconventional stimuli (magnetic, acoustic) with wireless electrochemistry could achieve highly directional, localized synthesis. Together, these strategies aim to create efficient, adaptive, and digitally controlled autonomous chemical reactor arrays.

8. Conclusions

This review has examined how different strategies for non-mechanical fluid manipulation have evolved from externally driven pumping approaches toward reaction-coupled electrochemical actuation. The evolution of chemical pumping systems, from the initial rejection of bulky mechanical pumps to the development of sophisticated Bipolar and Wireless Electrochemical Reactors, represents a fundamental conceptual shift in reactor engineering. By demonstrating full operational autonomy and integrating fluid control into the chemical process, particularly in high-stakes areas like enantioselective synthesis and chiral resolution, this technology is not merely an academic curiosity. It is positioning electrochemistry as a versatile platform for the development of decentralized and potentially autonomous chemical manufacturing strategies.

CRediT authorship contribution statement

Sara Grecchi: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Serena Arnaboldi:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

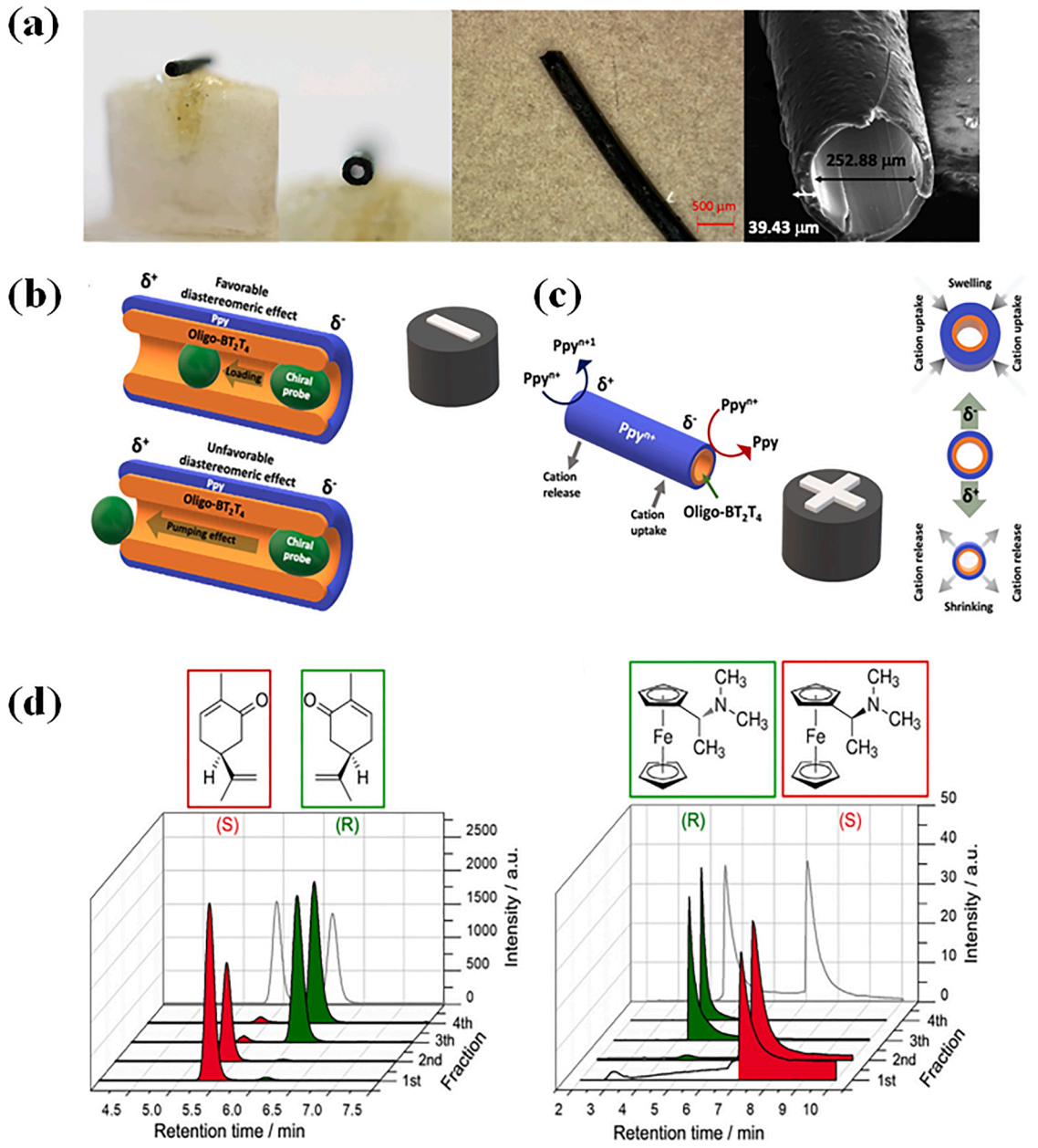

Fig. 7. (a) Optical and microscopic images of the miniaturized tubular devices, showing the morphology and structural integrity of the wireless hollow objects. (b) Schematic illustration of the wireless energy delivery mechanism via BE, highlighting the elimination of physical connections. (c) Working principle of the self-pumping action: the generation of asymmetric chemical gradients at the poles of the tubular device induces an internal fluid flow that sustains mass transport. (d) Enantioselective loading and separation process: the chiral selector (e.g., oligomer-based coating) interacts differently with (*R*)- and (*S*)-enantiomers, enabling the preferential transport or separation of chiral analytes within the wireless platform. (Adapted with permission from Ref., [80]).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been funded by the H2020 European Research Council (ERC) under the HORIZON-ERC-2021 work program (grant agreement no. 101040798, ERC Starting grant CHEIR).

Data availability

Data will be made available on request.

References

[1] J.S. Kuo, D.T. Chiu, Controlling mass transport in microfluidic devices, Annu. Rev. Anal. Chem. 4 (2011) 275–296, https://doi.org/10.1146/annurev-anchem-061010-113926.

[2] R. Klaewkla, M. Arend, W.F. Hoelderich, A Review of Mass Transfer Controlling the Reaction Rate in Heterogeneous Catalytic Systems (Vol. 5), INTECH Open Access Publisher, Rijeka, 2011.

[3] M.T. Kreutzer, F. Kapteijn, J.A. Moulijn, J.J. Heiszwolf, Multiphase monolith reactors: chemical reaction engineering of segmented flow in microchannels, Chem. Eng. Sci. 60 (2005) 5895–5916, https://doi.org/10.1016/j.ces.2005.03.022.

[4] D.E. Seborg, T.F. Edgar, D.A. Mellichamp, F.J. Doyle, Process Dynamics and Control, John Wiley & Sons, 2016.
[5] S. Bohm, H.B. Phi, L. Dittrich, E. Runge, Chip-integrated non-mechanical microfluidic pump driven by electrowetting on dielectrics, LoC 24 (2024) 2893–2905, https://doi.org/10.1039/D4LC00178H.
[6] A.P. Iakovlev, A.S. Erofeev, P.V. Gorelkin, Novel pumping methods for microfluidic devices: a comprehensive review, Biosensors 12 (2022) 956, https://doi.org/10.3390/bios12110956.
[7] E. Noviana, T. Ozer, C.S. Carrell, J.S. Link, C. McMahon, J. Ilhoon, C.S. Henry, Simple microfluidic paper-based analytical devices, Chem. Rev. 121 (2021) 11835–11885, https://doi.org/10.1021/acs.chemrev.0c01335.
[8] C.M. Whitesides, The origins and the future of microfluidics, Nature 442 (2006) 368–373, https://doi.org/10.1038/nature05058.
[9] N.-T. Nguyen, X. Huang, T.K. Chuan, MEMS-micropumps: a review, J. Fluids Eng. 124 (2002) 384–392, https://doi.org/10.1115/1.1459075. Jun.
[10] Z. Chen, J. Wang, S. Qiana, H.H. Bau, Thermally-actuated, phase change flow control for microfluidic systems, Lab Chip. 5 (2005) 1277–1285, https://doi.org/10.1039/B508275G.
[11] A. Khater, M. Mohammadi, A. Mohamad, A.S. Nezhad, Dynamics of temperature-actuated droplets within microfluidics, Sci Rep. 9 (2019) 3832, https://doi.org/10.1038/s41598-019-40069-9.
[12] C. Zhang, D. Xing, Y. Li, Micropumps, microvalves, and micromixers within PCR microfluidic chips: advances and trends, Biotechnol. Adv. 5 (2007) 483–514, https://doi.org/10.1016/j.biotechadv.2007.05.003.
[13] A. Wixforth, Acoustically driven planar microfluidics, Superlattices Microstruct. 33 (2003) 389–396, https://doi.org/10.1016/j.spmi.2004.02.015.
[14] T.A. Franke, A. Wixforth, Microfluidics for miniaturized laboratories on a chip, ChemPhysChem 15 (2008) 2140–2156, https://doi.org/10.1002/cphc.200800349.
[15] P.S. Glockner, G.F. Naterer, Recent advances in nano-electromechanical and microfluidic power generation, Int. J. Energy Res. 31 (2007) 603–618, https://doi.org/10.1002/er.1282.
[16] C.R. Neagu, J.C.E. Gardeniers, M. Elwenspoek, J.J. Kelly, An electrochemical microactuator: principle and first results, J. Microelectromech. Syst. 5 (1996) 2–9, https://doi.org/10.1109/84.485209.
[17] J. Causley, S. Stitzel, S. Brady, D. Diamond, G. Wallace, Electrochemically-induced fluid movement using polypyrrole, Synth. Met. 1 (2005) 60–64, https://doi.org/10.1016/j.synthmet.2005.04.001.
[18] W.B. Zimmerman, Electrochemical microfluidics, Chem. Engin. Sci. 7 (2011) 1412–1425, https://doi.org/10.1016/j.ces.2010.03.057.
[19] W. Ehrfeld, Electrochemistry and microsystems, Electrochim. Acta 20 (2003) 2857–2868, https://doi.org/10.1016/S0013-4686(03)00350-5.
[20] H. Sugioka, H. Nakamura, The weaving of the carbon fiber using induced-charge electro-osmosis with DC–AC alternating switching, Colloids Surf. A, Coll. Surf. A 655 (2022) 130190, https://doi.org/10.1016/j.colsurfa.2022.130190.
[21] R. Bagacki, M. Reinhardt, R. Schlatmann, S. Calnan, R. van de Krol, M.P. Browne, Electrochemical hydrogen pumps: a researcher's guide and review, Chem Comm. 61 (2025) 10210–10227, https://doi.org/10.1039/D5CC01815C.
[22] S. Rani, N. Sbei, S. Rahali, S. Aslam, T. Hardwick, N. Ahmed, Electrochemical synthesis: a green & powerful approach to modern organic synthesis and future directions, Chin. Chem. Lett. 36 (2025) 111216, https://doi.org/10.1016/j.cclet.2025.111216.
[23] S. Grecchi, G. Salinas, M. Niamlaem, A. Kuhn, S. Arnaboldi, Unplugging asymmetric synthesis with a wireless, self-pumping electrochemical reactor, JACS (2025), https://doi.org/10.1021/jacs.5c16187.
[24] S. Grecchi, A. Mezzetta, L. Guazzelli, S. Arnaboldi, Tunable stereoselectivity in a wireless electrochemical microreactor using natural chiral ionic liquids, Green Chem. 27 (2025) 14769–14775, https://doi.org/10.1039/D5GC04756K.
[25] S. Arnaboldi, S. Grecchi, G. Salinas, A. Kuhn, Bipolar Organic Electrochemistry. Organic Electrochemistry: Fundamentals, Modern Concepts, and Methods, 1st Edition, Elsevier, 2025.
[26] G. Salinas, S. Arnaboldi, P. Garrigue, G. Bonetti, R. Cirilli, T. Benincori, A. Kuhn, Magnetic field-enhanced redox chemistry on-the-fly for enantioselective synthesis, Faraday Discuss. 247 (2023) 34–44, https://doi.org/10.1039/d3fd00041a.
[27] S. Arnaboldi, G. Salinas, G. Bonetti, P. Garrigue, R. Cirilli, T. Benincori, A. Kuhn, Autonomous chiral microswimmers with self-mixing capabilities for highly efficient enantioselective synthesis, Angew. Chem., Int. Ed. 61 (2022) e202209098, https://doi.org/10.1002/anie.202209098.
[28] I.T. Bello, L.A. Jolaoso, R.A. Ahmed, A. Bello, Electrochemical energy conversion and Storage Systems: a perspective on the challenges and opportunities for sustainable energy in Africa, Energ. Rev. 4 (2025) 100109, https://doi.org/10.1016/j.enrev.2024.100109.
[29] B. Zhu, L. Fan, N. Mushtaq, R. Raza, M. Sajid, Y. Wu, W. Lin, J.-S. Kim, P.D. Lund, S. Yun, Semiconductor electrochemistry for clean energy conversion and storage, Electrochem. Energ. Rev. 4 (2021) 757–792, https://doi.org/10.1007/s41918-021-00112-8.
[30] E. Bakker, M. Telting-Diaz, Electrochemical sensors, Anal. Chem. 74 (2002) 2781–2800, https://doi.org/10.1021/ac0202278.
[31] J. Baranwal, B. Barse, G. Gatto, G. Broncova, A. Kumar, Electrochemical sensors and their applications: a review, Chemosensors 10 (2022) 363, https://doi.org/10.3390/chemosensors10090363.
[32] S.E. Fosdick, K.N. Knust, K. Scida, R.M. Crooks, Bipolar electrochemistry, Angew. Chem., Int. Ed. 52 (2013) 10438, https://doi.org/10.1002/anie.201300947.
[33] N. Karimian, P. Hashemi, A. Afkhami, H. Bagheri, The principles of bipolar electrochemistry and its electroanalysis applications, Curr. Opin. Electrochem. 17 (2019) 30–37, https://doi.org/10.1016/j.coelec.2019.04.015.
[34] L. Koefoed, S.U. Pedersen, K. Daasbjerg, Bipolar electrochemistry: a wireless approach for electrode reactions, Curr. Opin. Electrochem. 2 (2017) 13–17, https://doi.org/10.1016/j.coelec.2017.02.001.
[35] K.L. Rahn, R.K. Anand, Recent advancements in bipolar electrochemical methods of analysis, Anal. Chem. 93 (2021) 103–123, https://doi.org/10.1021/acs.analchem.0c04524.
[36] Y.-L. Wang, J.-T. Cao, Y.-M. Liu, Bipolar electrochemistry —A powerful tool for micro/nano-electrochemistry, ChemistryOpen 11 (2022) e202200163, https://doi.org/10.1002/open.202200163.
[37] G. Loget, D. Zigah, L. Bouffier, N. Sojic, A. Kuhn, Bipolar electrochemistry: from materials science to motion and beyond, Acc. Chem. Res. 46 (2013) 2513–2523, https://doi.org/10.1021/ar400039k.
[38] S. Arnaboldi, Wireless electrochemical actuation of soft materials towards chiral stimuli, Chem Comm. 59 (2023) 2072–2080, https://doi.org/10.1039/D2CC06630K.
[39] S. Arnaboldi, G. Salinas, S. Bichon, S. Gounel, N. Mano, A. Kuhn, Bi-enzymatic chemo-mechanical feedback loop for continuous self-sustained actuation of conducting polymers, Nat. Comm. 14 (2023) 6390, https://doi.org/10.1038/s41467-023-42153-1.
[40] S. Arnaboldi, G. Salinas, A. Karajić, P. Garrigue, T. Benincori, G. Bonetti, R. Cirilli, S. Bichon, S. Gounel, N. Mano, A. Kuhn, Direct dynamic read-out of molecular chirality with autonomous enzyme-driven swimmers, Nat. Chem. 13 (2021) 1241–1247, https://doi.org/10.1038/s41557-021-00798-9.
[41] S.B. Beil, D. Pollok, S.R. Waldvogel, Reproducibility in electroorganic synthesis—myths and misunderstandings, Angew. Chem. Int. Ed. 60 (2021) 14750–14759, https://doi.org/10.1002/anie.202014544.
[42] S. Mohle, M. Zirbes, E. Rodrigo, T. Gieshoff, A. Wibe, S.R. Waldvogel, Modern electrochemical aspects for the synthesis of value-added organic products, Angew. Chem. Int. Ed. 57 (2018) 6018–6041, https://doi.org/10.1002/anie.201712732.
[43] R.D. Little, A perspective on organic electrochemistry, J. Org. Chem. 85 (2020) 13375–13390, https://doi.org/10.1021/acs.joc.0c01408.
[44] G. Hilt, Basic strategies and types of applications in organic electrochemistry, ChemElectroChem 7 (2020) 395–405, https://doi.org/10.1002/celc.201901799.
[45] H.A. Stone, A.D. Stroock, A. Ajdari, Engineering flows in small devices: microfluidics toward a lab-on-a-chip, Annu. Rev. Fluid Mech. 36 (2004) 381–411, https://doi.org/10.1146/annurev.fluid.36.050802.122124.
[46] G. Fuhr, T. Schnellet, B. Wagnert, Travelling wave-driven microfabricated electrohydrodynamic pumps for liquids, J. Micromech. Microeng. 4 (1994) 217–226.
[47] W.F. Paxton, K.C. Kistler, C.C. Olmeda, A. Sen, S.K. St. Angelo, Y. Cao, T. E. Mallouk, P.E. Lammert, V.H. Crespi, Catalytic nanomotors: autonomous movement of Striped nanorods, J. Am. Chem. Soc. 126 (2004) 13424–13431, https://doi.org/10.1021/ja047697z.
[48] S. Sánchez, L. Soler, J. Katuri, Chemically powered micro- and nanomotors, Angew. Chem. Int. Ed. 54 (2015) 1414–1444, https://doi.org/10.1002/anie.201406096.
[49] J. Wang, K.M. Manesh, Motion control at the nanoscale, Small 6 (2010) 345, https://doi.org/10.1002/smll.200901746.
[50] S.J. Ebbens, J.R. Howse, In pursuit of propulsion at the nanoscale, Soft Matter. 6 (2010) 726–738, https://doi.org/10.1039/B918598D.
[51] A. Karbalaei, R. Kumar, H.J. Cho, Thermocapillarity in microfluidics—a review, Micromachines 7 (2016) 13, https://doi.org/10.3390/mi7010013.
[52] B. Jurado-Sánchez, A. Escarpa, Milli, micro and nanomotors: novel analytical tools for real-world applications, Trends Anal. Chem. 84 (2016) 48–59. https://www.sciencedirect.com/science/article/pii/S0165993616300127.
[53] D.J. Laser, J.G. Santiago, A review of micropumps, J. Micromech. Microeng. 14 (2004) R35, https://doi.org/10.1088/0960-1317/14/6/R01.
[54] G. Whitesides, The origins and the future of microfluidics, Nature 442 (2006) 368–373, https://doi.org/10.1038/nature05058.
[55] C.N. Baroud, F. Gallaire, R. Dangla, Dynamics of microfluidic droplets, Lab Chip. 10 (2010) 2032–2041, https://doi.org/10.1039/C001191F.
[56] T.M. Squires, S.R. Quake, Microfluidics: fluid physics at the nanoliter scale, Rev. Mod. Phys. 77 (2005) 977, https://doi.org/10.1103/RevModPhys.77.977.
[57] T.L. Edwards, B.K. Gale, A.B. Frazier, A microfabricated thermal field-flow fractionation system, Anal. Chem. 74 (2002) 1211–1216, https://doi.org/10.1021/ac010653d.
[58] W. Connacher, N. Zhang, A. Huang, J. Mei, S. Zhang, T. Gopesh, J. Friend, Micro/nano acoustofluidics: materials, phenomena, design, devices, and applications, Lab. Chip. 18 (2018) 1952–1996, https://doi.org/10.1039/C8LC00112J.
[59] P. Zhang, H. Bachman, A. Ozcelik, T.J. Huang, Acoustic microfluidics, Annu. Rev. Anal. Chem. 13 (2020) 17–43, https://doi.org/10.1146/annurev-anchem-090919-102205.
[60] J. Friend, L.Y. Yeo, Microscale acoustofluidics: microfluidics driven via acoustics and ultrasonics, Rev. Mod. Phys. 83 (2011) 647, https://doi.org/10.1103/RevModPhys.83.647.
[61] X. Ju, C. Chen, C.M. Oral, S. Sevim, R. Golestanian, M. Sun, N. Bouzari, X. Lin, M. Urso, J.S. Nam, Y. Cho, X. Peng, F.C. Landers, S. Yang, A. Adibi, N. Taz, R. Wittkowski, D. Ahmed, W. Wang, V. Magdanz, M. Medina-Sánchez, M. Guix, N. Bari, B. Behkam, R. Kapral, Y. Huang, J. Tang, B. Wang, K. Morozov, A. Leshansky, S.A. Abbasi, H. Choi, S. Ghosh, B.Borges Fernandes, G. Battaglia, P. Fischer, A. Ghosh, B.Jurado Sánchez, A. Escarpa, Q. Martinet, J. Palacci, E. Lauga, J. Moran, M.A. Ramos-Docampo, B. Städler, R.S.Herrera Restrepo, G. Yossifon, J.D. Nicholas, J. Ignés-Mullol, J. Puigmartí-Luis, Y. Liu, L.D. Zarzar, C. W.Shields IV, L. Li, S. Li, X. Ma, D.H. Gracias, O. Velev, S. Sánchez, M.J. Esplandiu, J. Simmchen, A. Lobosco, S. Misra, Z. Wu, J. Li, A. Kuhn, A. Nourhani, T. Maric, Z. Xiong, A. Aghakhani, Y. Mei, Y. Tu, F. Peng, E. Diller, M.S. Sakar, A. Sen, J. Law,

Y. Sun, A. Pena-Francesch, K. Villa, H. Li, D.E. Fan, K. Liang, T.J. Huang, X.Z. Chen, S. Tang, X. Zhang, J. Cui, H. Wang, W. Gao, V.K. Bandari, O.G. Schmidt, X. Wu, J. Guan, M. Sitti, B.J. Nelson, S. Pané, L. Zhang, H. Shahsavan, Q. He, I.D. Kim, J. Wang, M. Pumera, Technology roadmap of micro/nanorobots, ACS Nano. 19 (2025) 24174–24334, https://doi.org/10.1021/acsnano.5c03911.

[62] M. Pumera, Nano/microscale motors: biomedical opportunities and challenges, ACS Nano. 6 (2012) 5691–5697, https://doi.org/10.1021/nn3028997.

[63] D.J. Laser, J.G. Santiago, A review of micropumps, J. Micromech. Microeng. 14 (2004) R35, https://doi.org/10.1088/0960-1317/14/6/R01.

[64] J. Chen, Y. Mo, Wireless electrochemistry (Wi-eChem) based on wireless power transfer technology, ACS Cent. Sci. 9 (2023) 1750–1761, https://doi.org/10.1021/acscentsci.3c00856.

[65] I. Rodríguez-Torres, E.R. Henquín, General simplified model to calculate current distribution in electrochemical reactors with N bipolar electrodes, J. Electrochem. Soc. 166 (2019), https://doi.org/10.1149/2.1291906jes. E201.

[66] T.M. Braun, D.T. Schwartz, Localized electrodeposition and patterning using bipolar electrochemistry, J. Electrochem. Soc. 162 (2015) D180, https://doi.org/10.1149/2.1031504jes.

[67] Z. Deng, C. Renault, Unravelling the last milliseconds of an individual graphene nanoplatelet before impact with a Pt surface by bipolar electrochemistry, Chem. Sci. 12 (2021) 12494–12500, https://doi.org/10.1039/D1SC03646G.

[68] A.J. Bard, L.R. Faulkner, Electrochemical Methods: Fundamentals and Applications, 2nd ed., John Wiley & Sons, 2001.

[69] R. Guidelli, R.G. Compton, J.M. Feliu, E. Gileadi, J. Lipkowski, W. Schmickler, S. Trasatti, Defining the transfer coefficient in electrochemistry: an assessment (IUPAC technical report), Pure Appl. Chem. 86 (2014) 245–258, https://doi.org/10.1515/pac-2014-5026.

[70] S. Goodwin, D.A. Walsh, Closed bipolar electrodes for spatial separation of H_2 and O_2 evolution during water electrolysis and the development of high-voltage fuel cells, ACS Appl. Mater. Interface. 9 (2017) 23654–23661, https://doi.org/10.1021/acsami.7b04226.

[71] N.L. Walker, J.E. Dick, On the mechanism of the bipolar reference electrode, Analyst 148 (2023) 2149–2158, https://doi.org/10.1039/d3an00107e.

[72] J.C. Bui, K.R.M. Corpus, A.T. Bell, A.Z. Weber, On the nature of field-enhanced water dissociation in bipolar membranes, J. Phys. Chem. C 125 (2021) 24974–24987, https://doi.org/10.1021/acs.jpcc.1c08276.

[73] T. Kulkarni, B. Yang, X. Zhang, R. Kumar, C.G. Arges, ACS spotlight: bipolar membranes for electrochemical energy conversion, chemical manufacturing, and separations, ACS Appl. Energ. Mater. 7 (2024) 11361–11389, https://doi.org/10.1021/acsaem.3c03260.

[74] R. Naaman, D.H. Waldeck, Chiral-induced spin selectivity effect, J. Phys. Chem. Lett. 3 (2012) 2178–2187, https://doi.org/10.1021/jz300793y.

[75] B.P. Bloom, Y. Paltiel, R. Naaman, D.H. Waldeck, Chiral induced spin selectivity, Chem. Rev. 124 (2024) 1950–1991, https://doi.org/10.1021/acs.chemrev.3c00661.

[76] B.P. Bloom, Y. Lu, T. Metzger, S. Yochelis, Y. Paltiel, C. Fontanesi, S. Mishra, F. Tassinari, R. Naaman, D.H. Waldeck, Asymmetric reactions induced by electron spin polarization, Phys. Chem. Chem. Phys. 22 (2020) 21570–22158, https://doi.org/10.1039/D0CP03129A.

[77] C. Luo, L. Zhou, R. Xu, y. Hou, CNT array-based aluminum bipolar electrode iontronic memristors, Iontronics 2 (2026) 6, https://doi.org/10.20517/iontronics.2026.06.

[78] S. Li, Z.L. Wang, D. Wei, Chemical reactions at electrified interfaces, Acc. Chem. Res. 59 (2026) 285–297, https://doi.org/10.1021/acs.accounts.5c00735.

[79] C. Xu, S. Li, Y. Zhang, Z. Wang, Z.L. Wang, D. Wei, Contact-electro-chemistry induced by flow electrification in dielectric tubes, Nano Energ. 134 (2025) 110526, https://doi.org/10.1016/j.nanoen.2024.110526.

[80] S. Grecchi, G. Salinas, R. Cirilli, T. Benincori, S. Ghirardi, A. Kuhn, S. Arnaboldi, Miniaturized enantioselective tubular devices for the electromechanical wireless separation of chiral analytes, Chem 10 (2023) 660–674, https://doi.org/10.1016/j.chempr.2023.11.001.

[81] S. Grecchi, F. Malacarne, R. Cirilli, M. Dell'Edera, S. Ghirardi, T. Benincori, S. Arnaboldi, Wireless Hollow Miniaturized Objects for Electroassisted Chiral Resolution, Anal. Chem. 96 (2024) 4901–4908, https://doi.org/10.1021/acs.analchem.3c05544.

[82] S. Grecchi, M. Niamlaem, S. Arnaboldi, Helically shaped hollow polypyrrole for efficient molecular pumping, Electrochim. Acta 548 (2026) 147910, https://doi.org/10.1016/j.electacta.2025.147910.