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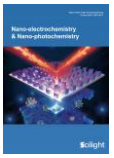

Editorial

A New Era at a New Scale for Nanoscale Electrochemistry and Photochemistry

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Scientific advancements have often been steered by the capacity to investigate matter at increasingly smaller scales. Traditional studies of electrochemistry and photochemistry at the ensemble level involve large numbers of molecules contributing to an aggregate signal. However, probing these processes at the nanoscale through single-entity measurements reveals dynamics that are submerged in ensemble measurements, thereby allowing the observation of intrinsic heterogeneity and providing mechanistic insights. For instance, single-nanoparticle electrochemistry has unveiled heterogeneity in electron transfer events for individual particles and dynamic disorder over extended timescales. The nanoscale realm highlights stochastic fluctuations and rare events invisible at the bulk level, offering fresh perspectives on catalytic mechanisms and energy transduction pathways that supply our comprehension of the natural world. At this scale, heterogeneity in nanoparticle performance arises not only from size effects but also from interfacial phenomena and fluctuations. To give an example, nanoparticles in low Reynolds number fluids experience stochastic Brownian forces and viscous resistance, akin to swimming in a violent rainstorm, rendering the directed transport of functional nanoparticles highly inefficient and challenging. This paradigm shift introduces new principles that reshape long-held assumptions about the flow of matter and energy at the smallest scales, emphasizing the aim to observe and control over the rare events rather than averaging them away.

The rapid advancement of nanofabrication technologies, including those used in scanning electrochemical microscopy, has enabled the detection of currents at the femtoampere scale. Consequently, there is a need for the development of novel sensing technologies and microscopic analysis techniques that can match the sensitivity of nanoprobes. These methods must provide high spatial resolution, low background interference, and a wide response range, enabling them to dynamically measure signals in real-time and in situ, study long-term behaviors stably, or with high temporal resolution, capture transient nanoscale interactions. Apart from solid nanomaterials, even micro- and nanodroplets [1] have demonstrated acceleration of chemical reactions at multiphase interfaces, expanding our knowledge of fundamental electrochemistry. Research in this field has revealed the intrinsic variability of catalytic activity, charge transfer, photon-matter interactions, and even single-site catalytic events [2], thus enabling site-specific studies that guide the selection of more effective catalysts. Such knowledge addresses longstanding scientific questions and raises new ones about the applicability of conventional rules in the quantum realm. Nanoscale electrochemistry and photochemistry thus open a new era: one in which reactions can be probed, manipulated, and designed at their most elementary level. This paradigm shift offers high resolution in fundamental science and further reveals opportunities in energy, sensing, and catalysis.

Light in nanoscale chemical systems serves a dual role, acting not only as an illuminator for the sensing interface but also as an energy source that propels photo-induced charge transfer and catalytic processes. When electrons and photons interact with nanosized material, the system unveils confined phenomena and discrete energy landscapes [3]. State-of-the-art imaging and spectroscopic techniques, combined with artificial intelligence for accelerated data analysis and in-operando characterization, are narrowing the gap between idealized model systems and practical devices. These developments extend beyond technical progress; they redefine the scope of questions that chemists can address. Phenomena once elusive, such as the quantum efficiency of a single semiconductor nanoparticle or the stochastic dynamics of a redox enzyme on a nanoelectrode, have now become

quantifiable. Beyond its detective role, light also provides energetic input in a manner comparable to electron injection. Photoelectrocatalysis, exemplified by CO_2 reduction and water splitting, represents a typical platform where these two processes converge. Special nanoconfinements, such as plasmonic nanostructures and similar spatial constraints, facilitate light harvesting beyond classical efficiency limits, leading to highly active surfaces and strong optical absorption that produce hot electrons and enable unconventional reaction pathways [4,5]. These include bond dissociations, excited-state transfers, and multi-electron processes. Ultrafast spectroscopy has uncovered the transient dynamics of photogenerated carriers, while strong light-matter coupling has been observed to accelerate the reactions, reshape energy barriers, challenge efficiency constraints, and enable previously unattainable selectivity. With the novel energy conversion mechanisms, hybrid electrochemical-photochemical platforms hold the potential to drive next-generation carbon-neutral technologies and promote sustainable energy conversion strategies central to green chemistry.

Control over nanoscale electrochemical and photochemical reactions is expected to yield diverse applications. Nevertheless, several challenges persist. In nano electrochemistry, achieving precise control over reactivity, ensuring long-term stability, and scaling laboratory advances to industrially relevant systems remain challenging tasks. In nano photochemistry, improving light absorption efficiency, extending carrier lifetimes, and bridging the gap between proof-of-concept studies and practical deployment are critical bottlenecks. Artificial intelligence is increasingly playing a transformative role in this blueprint [6]. Data processing assisted by machine learning accelerates the analysis of mechanisms, renews theoretical frameworks, and refreshes the computational modeling approaches. AI-driven materials discovery promotes the design of nanomaterials with precise control over reactivity and selectivity. By examining single particles or even individual molecules, researchers unravel the complexity of heterogeneous systems and achieve unprecedented precision in material design. High-throughput nano electrochemistry and nanoarray platforms have already accelerated single-particle and single-molecule research, while the convergence of comprehensive data with biocompatible devices promises to shape the future of diagnostics and health care. Nano-bio interfaces, formed by the interaction between nanoprobes and biological systems, involve dynamic physical and chemical interactions between probes and biological components. Compared to interfaces with cell populations and macroscopic detectors, nanoscale interfaces help provide information about cellular heterogeneity and molecular diversity. Besides measurement, nanoprobes can also exert influence on physiological activities and regulate cell fate through specific stimulations. The impact of nanoprobes on cellular signaling is influenced by their morphologies, sizes, and surface chemical states, making interface design pivotal for biological analysis. Nanoscale electrochemical sensors and biosensors, together with light-responsive nanoplatforms, for instance, photodynamic therapy, are paving the way toward advanced diagnostics, precision therapies, and pre-treatments that bring nanoscience into healthcare practice [7].

With the launch of *Nano-electrochemistry & Nano-photochemistry*, we invite the community to share original works that advance fundamental understanding and inspire practical solutions, and shape the future of this highly interdisciplinary field integrating chemistry, physics, biology, materials science, nanotechnology, and engineering. We are committed to propelling forward this exciting new era of science, where light and charge converge at the nanoscale to reveal further secrets of our world and provide powerful technologies that shape our future.

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Conflicts of Interest

The author declares no conflict of interest.

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