frontiers | Frontiers in Lab on a Chip Technologies

TYPE Editorial
PUBLISHED 27 May 2025
DOI 10.3389/frlct.2025.1623274

Check for updates

OPEN ACCESS

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RECEIVED 05 May 2025
ACCEPTED 19 May 2025
PUBLISHED 27 May 2025

CITATION
Damiati S, Catarino SO and Xuan X (2025) Editorial: Insights in micro- and nano-fluidics. *Front. Lab Chip Technol.* 4:1623274.
doi: 10.3389/frlct.2025.1623274

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Editorial: Insights in micro- and nano-fluidics

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KEYWORDS

microfluidics, nanofluidics, dimensions, environmental monitoring, low-cost materials

Editorial on the Research Topic
Editorial: Insights in micro- and nano-fluidics

There is an increasing demand to explore various aspects of microfluidics, nanofluidics, and lab-on-a-chip technologies, as these fields hold significant promise for advancing future scientific and industrial applications. One key advantage of microfluidic and nanofluidic systems is their cost-effectiveness and environmental sustainability, primarily due to the reduction in reagent consumption and waste generation. These miniaturized systems also offer benefits such as faster analysis times, improved sensitivity, and the potential for high-throughput screening.

Microfluidics is a powerful technology that processes and manipulates small amounts of fluids, typically in the range of microliters to picoliters (10^{-6} to 10^{-12} L). The channel dimensions usually range from tens to hundreds of micrometers, allowing for precise control of fluid behavior in microscale and nanoscale systems. Microfluidic devices are revolutionizing various fields, including medical diagnostics and therapeutics, drug development, chemical analysis, and environmental monitoring, with enhanced potential for point-of-care. At microscale dimensions, fluids exhibit unique properties that differ significantly from those observed at the macroscale. This is evidenced by the very low Reynolds numbers, which result from low flow rates and lead to the dominance of laminar flow in microfluidic devices. In such systems, fluids flow in parallel layers with minimal mixing, allowing for precise control over chemical reactions and fluid interfaces. Additional parameters—such as capillary forces, surface tension, and viscosity—play a much more significant role at the microscale, while others, such as gravitational effects, become negligible. The advancement of microfluidics has further paved the way for the development of nanofluidics, where channel dimensions range from 1 to 100 nm. These nanoscale systems enable the study of phenomena influenced by the molecular nature of fluids, including surface charge effects and electrostatic interactions.

Innovative materials and fabrication techniques, such as soft lithography, 3D printing, and the use of hybrid materials, have made it possible to construct increasingly complex and functional micro- and nanofluidic devices. Furthermore, integrating microfluidics and nanofluidics with emerging fields such as artificial intelligence and machine learning has the potential to create new platforms for rapid, economical exploration across diverse applications, including biomedicine, pharmaceutics, and biomimetic research. This integration could reduce the complexity involved in designing and operating custom microfluidic devices, enabling fully automated platforms accessible to non-experts while providing innovative methods for data interpretation. Furthermore, the incorporation of sensors and actuators into microfluidic chips enables real-time monitoring and automation of complex reactions within a single platform. To provide deeper insight into developments in the fields of micro- and nanofluidics, this Research Topic collected a selection of articles that highlight recent advancements and trends.

Mesquita et al. from the University of Rhode Island discussed recent advances in low-cost microfluidics for rapid and efficient environmental monitoring and assessment. In their work, the authors reviewed commonly used low-cost materials such as paper-based analytical devices (μPADs), thread-based analytical devices (μTADs), cloth, and polymers, which have been utilized to develop tools for environmental monitoring. In addition to low-cost materials, the study also covered various fabrication techniques including wax printing, 3D printing, micromilling, laser micromachining, hand cutting, and xurography. The microfluidic devices developed using these methods have been employed to detect contamination in water, air, and soil, as well as to assess their quality. The authors argued that portable, low-cost microfluidic systems offer significant potential for *in situ* measurements, addressing a major limitation of traditional, high-cost analytical techniques that typically require well-equipped laboratories.

Shi et al. from the Hong Kong University of Science and Technology reviewed recent progress in nanofluidic systems with tunable surface charges for ion transport. Their work highlighted theoretical models, experimental methodologies, and performance comparisons related to surface fabrication, surface charge characterization, and three major application areas: nanofluidic ionic diodes, osmotic power generators, and ion transport enhancement. The authors emphasized that further investigation is required to address existing challenges and improve the performance of nanofluidic systems with tunable surface charge properties for future applications.

Ohshima from Tokyo University of Science developed a theoretical model of transient electrophoresis of colloidal particles in a salt-free medium, offering valuable insights for the design of effective electrophoresis-based measurements in micro- and nanofluidic lab-on-a-chip systems. The study identified a critical threshold for particle surface charge that distinguishes two behaviors: at low surface charge, transient electrophoretic mobility resembles that of a sphere in a dilute electrolyte, whereas at high surface charge, counterion condensation near the particle surface causes the transient mobility to become independent of the surface charge. Additionally, an equation was derived to predict the ratio of transient to steady electrophoretic mobility, providing a means to evaluate how the system evolves toward its steady state.

Aryal and Henry from Colorado State University presented a comprehensive review on the design and sensing applications of microfluidic μPADs. Their work detailed various fabrication methods used in both research and commercialization, including photolithography, plasma treatment, inkjet printing, wax printing/patterning, laser treatment, cutting and shaping, wet etching, and stacking and origami techniques. The review also discussed several detection methods for μPADs—such as colorimetry, fluorescence, electrochemical techniques, and chemiluminescence—across a wide range of applications in point-of-care diagnostics, health monitoring, environmental detection, and food safety.

In summary, the Research Topic of articles in this Research Topic highlights the diverse and expanding applications of microfluidics and nanofluidics. These studies contribute to advancing fundamental science within a dynamic and interdisciplinary field that continues to evolve. Furthermore, this technology is enabling transformative innovations across healthcare, environmental science, and materials engineering. As the availability of low-cost materials and fabrication techniques improves, and integration with digital technologies increases the impact of micro- and nanofluidic systems is expected to grow significantly in the coming decades.

Author contributions

SD: Writing – original draft, Conceptualization. SC: Writing – review and editing. XX: Writing – review and editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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