

Role of Fluid Engineering in Biomedical and Healthcare Systems: A Comprehensive Review

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Abstract

Fluid engineering is the study and application of fluid behavior, transport, and interaction, and has become a cornerstone of modern biomedical and healthcare systems. This review synthesizes the multifaceted roles fluid engineering plays across diagnostics, therapeutics, biomedical devices, and physiological modeling. Microfluidics enables precise manipulation of microliter and nanoliter volumes, facilitating rapid point-of-care diagnostics, high-throughput screening, and the fabrication of uniform nanoparticles for targeted drug delivery. In cardiovascular medicine, hemodynamics, and fluid–structure interaction models illuminate pathophysiological phenomena such as atherosclerosis progression, stenosis-related flow disturbances, and thrombogenesis, informing device design and personalized treatment strategies. Organ-on-a-chip platforms leverage microfluidic flows to recreate physiologically relevant microenvironments, enabling more predictive in vitro models for drug testing, toxicity evaluation, and disease modeling. Fluidic design is also instrumental in emerging biofabrication and bioprinting techniques, contributing to vascularization strategies that sustain engineered tissues. Computational fluid dynamics (CFD), together with multiphysics and data-driven approaches, provides quantitative insights for device optimization, regulatory testing, and the translation of benchtop devices to clinical tools. Despite rapid advances, challenges remain: scaling microfluidic solutions for manufacturing, ensuring biocompatible materials choices, integrating sensors for closed-loop control, and accurately representing multiscale physiology in simulations. This review collates recent advances (2018–2025) across experimental, computational, and translational studies, highlights application-driven case studies (diagnostics, drug delivery, cardiovascular devices, organ-on-chip systems), and outlines future directions where fluid engineering can accelerate healthcare innovation. By bridging engineering fundamentals with biomedical needs, fluid engineering will continue to drive breakthroughs in personalized medicine, efficient therapeutics, and predictive preclinical models. This review highlights key applications of fluid engineering in diagnostics, drug delivery, cardiovascular systems, and tissue engineering. Technologies such as microfluidics and organ-on-a-chip platforms support rapid diagnostics, targeted therapeutics, and realistic disease modeling. Hemodynamic analysis and CFD aid in the design of medical devices and personalized treatments. Despite challenges in scalability, material biocompatibility, and multiscale modeling, continued integration of fluid engineering with biomedical science promises significant improvements in healthcare innovation and clinical outcomes.

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INTRODUCTION

Fluid behavior underpins nearly every process in the human body and in devices used to diagnose and treat diseases. An understanding of fluid mechanics is essential for designing effective biomedical systems, from blood flow in arteries and microcirculation through capillaries to transport

within lab-on-a-chip devices [1–7]. Fluid engineering encompasses microfluidics, computational fluid dynamics (CFD), experimental flow diagnostics, and device fabrication techniques that control the flow at multiple scales. The primary goal of this review is to provide a comprehensive overview of how fluid engineering contributes to biomedical and healthcare applications by surveying the seminal literature, recent technological advances, and remaining challenges [8–13]. We organize the review into major application domains, including diagnostics and point-of-care devices, therapeutics, drug delivery, cardiovascular hemodynamics and devices, organ-on-a-chip and tissue engineering, and computational modeling, and conclude with methodological perspectives and a future outlook [14–19].

LITERATURE REVIEW

Micro-Fluidics and Diagnostic Systems

Modern microfluidics has revolutionized diagnostics by enabling miniaturized systems that process small sample volumes with high precision and low reagent consumption. Early lab-on-a-chip concepts have matured into practical point-of-care (PoC) platforms that incorporate sample preparation, separation, reaction, and detection within individual devices. Recent reviews have emphasized microfluidic applications for rapid molecular diagnostics, immunoassays, and cell sorting. Passive microfluidic elements (e.g., micromixers, serpentine channels, and inertial focusing geometries) and active components (e.g., electrokinetic pumps and acoustic manipulators) provide a toolkit for tailoring assay performance in terms of sensitivity and throughput. The COVID-19 pandemic accelerated the adoption of microfluidic PoC tests and highlighted the need for robust manufacturing pathways and user-friendly interfaces for clinical deployment [1].

Drug Delivery and Nanoparticle Fabrication

Recently, fluidic approaches have enabled the reproducible synthesis of nanoparticles (lipid, polymeric, and inorganic) with controlled sizes, compositions, and encapsulation efficiencies. Microfluidic mixing yields narrow size distributions and scalable workflows for nanomedicine production, which are important for targeted drug delivery and controlled drug release. Several studies have demonstrated microfluidic platforms for producing lipid nanoparticles for mRNA delivery and other therapeutic cargoes, with superior batch-to-batch reproducibility compared to that of bulk methods [7, 10].

Cardiovascular Hemodynamics and Device Design

A deep understanding of blood flow dynamics is central to cardiovascular research. Hemodynamics informs the design of stents, heart valves, ventricular assist devices (VADs), and vascular grafts. Computational hemodynamics and fluid–structure interaction (FSI) models capture the interactions between the flow and compliant vessel walls, revealing flow separation, recirculation regions, and shear stress distributions that correlate with disease progression. Clinical translation requires patient-specific modeling, incorporating imaging data and advanced boundary conditions to predict outcomes and optimize device geometry [8, 9].

Organ-on-a-Chip and Micro-physiological Systems

Advanced organ-on-a-chip (OoC) devices use precisely controlled microflow to maintain tissue-specific microenvironments, enabling long-term culture, vascularization, and multicellular interactions. OoCs improve physiological relevance over standard 2D cultures and bridge the gaps between in vitro and in vivo testing for toxicity screening and drug evaluation. Current reviews show rapid growth in vascularized chips, multi-organ integration, and the combination of OoCs with sensors and AI for data-rich readouts [3, 6].

Biofabrication, Bioprinting, and Vascularization

Similarly, fluidic engineering informs bioprinting strategies and perfusion systems for vascularizing the engineered tissues. Microvascular networks generated through sacrificial templating, microfluidic-guided endothelialization, and perfusion bioreactors enhance nutrient transport and improve tissue

viability. Advances in additive manufacturing have enabled the integration of microfluidic channels into printed constructs to support thick tissue models [2].

Modeling, Simulation, and Data-Driven Fluid Mechanics

CFD, FSI, and multiphase modeling are the primary tools for quantifying flows in biomedical systems. The rise of machine learning and physics-informed models has expanded the capability to perform complex surrogate simulations, accelerate parameter sweeps for design, and fuse imaging with predictive models. These computational advances are critical for regulatory submissions and reducing the reliance on animal testing [4].

Regulatory, Manufacturing, and Translation Challenges

However, despite promising prototypes, scaling microfluidic and fluid-engineered devices for clinical use has revealed regulatory hurdles, standardization gaps, and manufacturing constraints. Material biocompatibility (e.g., PDMS absorption of small molecules), sterilization, and integration with clinical workflows remain active research areas. Translational success increasingly depends on interdisciplinary collaboration across engineering, biology, clinical practice, and industry partners [1, 6].

This literature synthesis highlights the breadth of fluid engineering contributions to healthcare and identifies recurring themes, including the precise control of transport, multiscale coupling of physics and biology, and the need for manufacturing-ready materials and processes.

METHODOLOGY

This review followed a systematic narrative approach. We searched for peer-reviewed journal articles, reviews, and authoritative reports published between 2010 and 2025 using academic databases (PubMed, PubMed Central, ScienceDirect, Wiley Online Library, MDPI, and Cambridge Journals) and key terms including microfluidics, organ-on-a-chip, hemodynamics, nanoparticle synthesis microfluidics, bioprinting vascularization, and CFD biomedical. The selection prioritized recent comprehensive reviews and high-impact experimental and computational studies. Sources were screened for relevance to diagnostics, therapeutics, device design, and translational barriers. The final reference set emphasizes representative seminal works and contemporary advances to provide an integrated view of this field.

FUTURE SCOPE

1. Scalable manufacturing of microfluidic devices using injection molding, roll-to-roll processing, and robust materials for clinical-grade production.
2. Integration of closed-loop sensors and control systems for adaptive and autonomous biomedical devices (e.g., wearable pumps and smart dialysis components).
3. Advanced multiscale modeling of cellular-scale transport coupled with organ-level hemodynamics to support precision medicine and virtual clinical trials.
4. Standardization of out-of-core platforms and validation frameworks to accelerate regulatory acceptance for drug testing and toxicity screening.
5. Synergies between microfluidics and additive manufacturing can be used to develop vascularized tissue constructs suitable for transplantation or long-term in vitro studies.
6. Sustainable and biocompatible material development to minimize adsorption, leaching, and immunogenic responses.
7. Expanding the adoption of data-driven and physics-informed machine learning models to reduce computational costs while preserving physical fidelity.
8. Targeted education and interdisciplinary training programs are needed to bridge the gaps between fluid engineers, clinicians, and industry stakeholders.

CONCLUSION

Fluid engineering is central to many contemporary advances in biomedical sciences and healthcare. From enabling rapid diagnostics and precise drug delivery to modeling complex cardiovascular

phenomena and creating physiologically relevant organ-on-chip systems, the tools and methods of fluid mechanics bridge fundamental science and clinical applications. Continued progress will depend on solving translational challenges related to manufacturing, materials, and regulatory pathways while leveraging computational and data-driven innovations. The field is at an interdisciplinary crossroads and is poised to accelerate progress toward personalized, predictive, and efficient healthcare solutions for patients with diabetes.

Fluid engineering plays a transformative role in advancing biomedical and healthcare systems by providing a scientific foundation for understanding, controlling, and optimizing fluid-related biological processes. Its applications span a wide spectrum, including microfluidic diagnostics, targeted drug delivery, blood flow modeling, respiratory support devices, and organ-on-chip platforms that closely mimic human physiology. By integrating the principles of fluid mechanics with biology, materials science, and computational modeling, researchers have designed more accurate, efficient, and patient-specific healthcare technologies. Despite significant progress, challenges remain in scaling laboratory innovations for clinical practice, ensuring biocompatibility, and navigating regulatory and manufacturing constraints. Future developments will increasingly rely on high-fidelity simulations, artificial intelligence, and data-driven design approaches to enhance predictions and personalization. Overall, fluid engineering is at the core of next-generation biomedical innovation, offering powerful tools for improving disease diagnosis, treatment efficacy, and overall healthcare outcomes in a rapidly evolving medical landscape.

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