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

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Abstract

Fluid engineering – the study and application of fluid behavior, transport, and interaction – 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 computational fluid dynamics 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. From blood flow in arteries and microcirculation through capillaries to transport within lab-on-a-chip devices, an understanding of fluid mechanics is essential for designing effective biomedical systems [1–7]. Fluid engineering encompasses microfluidics, computational fluid dynamics (CFD), experimental flow diagnostics, and device fabrication techniques that control 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 seminal literature, recent technological advances, and remaining challenges [8–13]. We organize the review into major application domains – 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. Early lab-on-a-chip concepts have matured into practical point-of-care (PoC) platforms that incorporate sample preparation, separation, reaction, and detection within single 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 for sensitivity and throughput. The COVID–19 pandemic accelerated adoption of microfluidic PoC tests and highlighted the need for robust manufacturing pathways and user-friendly interfaces for clinical deployment. (Gharib et al., 2022; Akbari Kenari et al., 2022) [1].

Drug Delivery and Nano-particle Fabrication

Recently, fluidic approaches have enabled the reproducible synthesis of nanoparticles (lipid, polymeric, and inorganic) with controlled size, composition, and encapsulation efficiency. Microfluidic mixing yields narrow size distributions and scalable workflows for nanomedicine production, which are important for targeted drug delivery and controlled 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 bulk methods (Liu et al., 2022; Zhang et al., 2023) [7, 10].

Cardiovascular Hemo-dynamics 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 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 (Menon, 2024; Syed et al., 2023) [8].

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

Advanced organ-on-a-chip (OoC) devices use precisely controlled microflows to maintain tissue-specific microenvironments, enabling long-term culture, vascularization, and multicellular interactions. OoCs improve physiological relevance over standard 2D culture 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 combining OoCs with sensors and AI for data-rich readouts (Doost et al., 2024; Leung et al., 2022;) [3, 6].

Bio fabrication, Bio printing and Vascularization

Similarly, fluidic engineering informs bioprinting strategies and perfusion systems for vascularizing engineered tissues. Microvascular networks generated through sacrificial templating, microfluidicguided endothelialization, and perfusion bioreactors enhance nutrient transport and tissue viability. Advances in additive manufacturing have enabled the integration of microfluidic channels within printed constructs to support thick tissue models (Cao et al., 2023) [2].

Modelling, Simulation, and Data-driven Fluid Mechanics

CFD, FSI, and multiphase modeling are primary tools for quantifying flows in biomedical systems. The rise of machine learning and physics-informed models has expanded the capability to perform surrogate complex simulations, accelerate parameter sweeps for design, and fuse imaging with predictive models. These computational advances are critical for regulatory submissions and for reducing the reliance on animal testing (Ferreira et al., 2024; recent reviews) [4].

Regulatory, Manufacturing and Translation Challenges

However, despite promising prototypes, scaling microfluidic and fluid-engineered devices for clinical use reveals regulatory hurdles, standardization gaps, and manufacturing constraints. Material biocompatibility (e.g., PDMS absorption of small molecules), sterilization, and integration with clinical workflows remain active areas of research. Translational success increasingly depends on interdisciplinary collaboration across engineering, biology, clinical practice, and industry partners (Akbari Kenari et al., 2022; Leung et al., 2022) [1,6].

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

METHODOLOGY

This current review follows 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, Cambridge Journals) and key terms including “microfluidics',” “organ-on-a-chip',” “hemodynamics',” “nanoparticle synthesis microfluidics',” “bioprinting vascularization', and 'computational fluid dynamics 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 the 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 (OoC) platforms and validation frameworks to accelerate regulatory acceptance for drug testing and toxicity screening
5. Synergies between microfluidics and additive manufacturing 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 cost while preserving physical fidelity
8. Targeted education and interdisciplinary training programs to bridge the gaps between fluid engineers, clinicians, and industry stakeholders

CONCLUSION

Fluid engineering is central to many contemporary advances in biomedical science 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 with 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.

Fluid engineering plays a transformative role in advancing biomedical and healthcare systems by providing the scientific foundation to understand, control, and optimize 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 principles of fluid mechanics with biology, materials science, and computational modeling, researchers have been able to design more accurate, efficient, and patient-specific healthcare technologies. Despite significant progress, challenges remain in scaling laboratory innovations to 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 prediction and personalization. Overall, fluid engineering is at the core of next-generation biomedical innovation, offering powerful tools to improve disease diagnosis, treatment efficacy, and overall healthcare outcomes in a rapidly evolving medical landscape.

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