ISSN 2635-1676, Nanobiotechnology Reports, 2024, Vol. 19, No. 2, pp. 266–268. © Pleiades Publishing, Ltd., 2024.
Russian Text © The Author(s), 2024, published in Rossiiskie Nanotekhnologii, 2024, Vol. 19, No. 3, pp. 386–689.

DEVICES AND PRODUCTS BASED ON NANOMATERIALS AND NANOTECHNOLOGIES

Microfluidic Processes As an Element of Bioinspired Technologies

M. A. Marchenkova[a,b], S. V. Chapek[b], E. A. Mukhanova[b,*], A. V. Soldatov[b], and M. V. Kovalchuk[a,c]

[a]*Shubnikov Institute of Crystallography, National Research Center Kurchatov Institute, Moscow, 119333 Russia*
[b]*Smart Materials Research Institute, Southern Federal University, Rostov-on-Don, 344090 Russia*
[c]*National Research Center Kurchatov Institute, Moscow, 123182 Russia*
**e-mail: kand@sfedu.ru*

Received January 26, 2024; revised January 26, 2024; accepted April 24, 2024

Abstract—Modern microfluidic technologies play an important role in scientific research, medicine, pharmacology, ecology, and biotechnologies and nanotechnologies. The significance of microfluidic processes within bioinspired technologies and their potential for the development of new methods and applications is considered. An important advantage of microfluidic technologies is the ability to work with very small volumes of liquid or gas, which allows one to reduce the consumption of reagents, increase the sensitivity and accuracy of analysis, and shorten the time of analysis, processing, and obtaining of samples. Advances in microfluidic technologies, their advantages and potential applications, as well as prospects for the development of this field are described.

DOI: 10.1134/S2635167624600214

Microfluidics is a promising field of scientific research that studies the behavior of liquids at the microscale and nanoscale. This technology has found wide application in various fields, including medicine, analytics, pharmacology, ecology, the research of biological systems, and nanotechnology. Let us consider the significance of microfluidic processes within the framework of bioinspired technologies and their potential for the development of new methods and applications.

Microfluidics is a field of knowledge at the intersection of physics, chemistry, biology, and engineering, which studies the behavior of liquids and gases at the microscale and nanoscale. Microfluidics uses miniature channels, structures, and devices that can be used to monitor and control ultra small flows of liquids and gases.

Microfluidics emerged in the late 1980s and has become one of the most actively developing research areas since then. It has found application in such industries as nanotechnology and biotechnology, pharmaceutics, medicine, analysis and quality control, energetics, and others.

One of the important features of microfluidics is that it allows one to work with very small volumes of liquid or gas, which reduces the consumption of reagents and increases the sensitivity and accuracy of analysis, and also shortens the time of analysis, processing, and obtaining of samples: for example, when using traditional methods, a new material appears within a few years, while microfluidic technologies shorten this period to months.

The use of microfluidics in medicine, for example, allows one to develop new methods for diagnosing and treating diseases, creating portable medical devices for rapid diagnostics, improving processes of biomanufacturing, etc. Microfluidics is also used in the development of microsystems for detecting harmful substances, analyzing the composition of food products, the quality control of water, and other areas.

Over the past few decades, microfluidics has been closely intertwined with disciplines such as chemistry, biology, and materials science and plays a significant role in the development of bioinspired technologies that recreate, copy, and imitate natural phenomena and structures.

The effective control and analysis of microfluidic processes can be replicated and optimized according to natural principles and the laws of nature. Let us note the promising applications of microfluidic processes in various fields.

Medicine. Microfluidic technologies allow one to develop devices for diagnosing and monitoring diseases, as well as for drug delivery. This opens up opportunities for more precise and personalized medicine [1].

Biotechnology. Microfluidics is used to develop biomimetic devices that can analyze biological samples

Fig. 1. Microfluidic natural systems.

such as blood or tissue and conduct studies in the field of biomedicine and gene therapy [2].

Analytics. In the field of analytics, microfluidic technologies are used to perform precise analyses of biological and chemical samples, which can improve diagnostic and monitoring processes [3].

Pharmacology. Microfluidic devices can be used to study the effects of drugs at the cellular level, as well as to create new ways of drug delivery [4].

Ecology. Microfluidic technologies can help monitor water quality, analyze contaminants, and study the behavior of microorganisms in the environment [5].

Water treatment. Bioinspired technologies in microfluidics can be used to develop more effective methods for purifying water from pollutants and microorganisms [6].

Agronomy. Microfluidic technologies can be used to analyze soil and plants and improve methods of their treatment and care [7].

Nanotechnology. In the field of nanotechnology, microfluidics can be used to create nanoparticles, nanoreactors, and other nanomaterials [8].

Energy production. Microfluidic technologies can be used in the development of new methods for energy conversion, including solar panels and fuel cells [9].

Telecommunications. Microfluidic processes can be applied to create microfluidic devices for signal transmission and processing, which opens up opportunities for the development of more compact and efficient communication technologies [10].

Energetics. Microfluidic systems can be used to develop microturbines or microgenerators. They can help improve energy efficiency and reduce excessive resource consumption [11].

In addition, microfluidic processes have prospects for application in the space-research industry [12]. Because of their ability to work with small volumes of liquid, they can help create microreactors and microbiolabs for analyzing samples in space.

Animals and plants use microchannels to transport nutrients, fluids, cells, and molecules over long distances (Fig. 1). For example, the cardiovascular system with larger arteries, veins and smaller capillaries, as well as the lymphatic system, are used to transport fluid in an adult [13]. The dimensions of the channels in the cardiovascular system range in diameter from 5 μm to 4 mm and can be about 100 000 km long in an adult. The entire vascular system is subjected to mechanical stress. For a long time, researchers have sought to understand not only the nature and properties of blood vessels, but also the complex behavior of blood and its components flowing through the human body. Nowadays, the use of microfluidic devices to mimic natural systems allows one to obtain information about cellular and molecular processes in such complex systems with increasing precision.

The review [14] provides a detailed description of the history and modern versions of lab-on-a-chip technologies, which allow one to accurately reproduce the dimensions, mechanical properties, and biological complexity of vascular systems. The application areas include the detection of pathological changes in red blood cells, leukocytes, and platelets with high sensitivity and the ability to evaluate the effectiveness of drug treatment. Recent efforts have focused on developing microfluidic devices suitable for reproducing complex diseases such as thrombosis. The increasing complexity of microfluidic models will further give them greater clinical relevance and may eventually lead to the use of microfluidic vascular models in clinical applications.

The review [15] considers the progress and challenges currently faced by researchers in developing a new class of portable therapeutic artificial lungs based on microfluidic devices. The precise reproducibility of functions can be implemented due to the sizes of elements and blood-channel designs that closely mimic those found in their natural counterparts. They can have a much smaller surface area and volume than those of current clinical technologies, thereby reducing the device size and foreign-body response; contain branched networks of channels, copying the basic characteristics of those in the human lungs, improving biocompatibility; work effectively with room air, eliminating the need to use gas cylinders; have biomimetic hydraulic resistance, allowing operation at natural pressure and eliminating the need for blood pumps; and provide increased gas-exchange capacity. If all of these benefits are implemented in microfluidic devices and the remaining challenges are resolved, artificial lungs could revolutionize the field of pulmonary rehabilitation.

Plants also have a complex vascular system of capillaries that transports water and nutrients [16]. For example, channels in leaves, which are the main organ for photosynthesis in plants, can deliver nutrients to the rest of the plant. This feature was used in [17] to create artificial systems with built-in microfluidic channels and an improved ability to respond to environmental changes. Plants respond to environmental signals through movement, which inspired researchers to incorporate temperature, humidity, and light-sensitive materials into a device with foldable geometry. The principle underlying such a convertible microsystem can potentially be extended to applications that require interactions between the environment and devices, such as dynamic artificial vasculature and shape-adaptive flexible electronics.

These are just a few examples of the prospects for the application of microfluidic processes. To fully realize this potential and achieve this, some technical and technological challenges must be overcome. Some of these include the control and management of microscale flows, liquid distribution on small surfaces, and the integration of microfluidic systems with other technologies, as well as the use of artificial intelligence and machine learning to more precisely control the developed devices. With the development of technology, the ability to create more complex microfluidic systems is improving, which opens new horizons for their use in bioinspired technologies.

Microfluidic processes play an important role in the development of bioinspired technologies. Their ability to copy natural physical and chemical processes opens up broad prospects for the development of innovative methods and technologies that can become indispensable in medicine, analytics, pharmacology, biotechnology, ecology, and other significant fields. The study and application of microfluidic processes in bioinspired technologies plays a key role for the scientific community, the rapid development of science in the context of new challenges, and threats faced by Russia. Overcoming these challenges will ensure the technological sovereignty of Russia.

FUNDING

This work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. C. Rivet, H. Lee, A. Hirsch, et al., Chem. Eng. Sci. **66**, 1490 (2011). https://doi.org/10.1016/j.ces.2010.08.015
2. V. Ortseifen, M. Viefhues, L. Wobbe, and A. Grünberger, Front. Bioeng. Biotechnol **8**, 1 (2020).
3. W. Liu and Y. Zhu, Anal. Chim. Acta **1113**, 66 (2020). https://doi.org/10.3389/fbioe.2020.589074
4. A. Bohr, S. Colombo, and H. Jensen, *Microfluidics for Pharmaceutical Applications* (Elsevier, Norwich, 2019), p. 425. https://doi.org/10.1016/B978-0-12-812659-2.00016-8
5. X. Zhu, W. Kun, H. Yan, et al., Environ. Sci. Technol. **56**, 711 (2022). https://doi.org/10.1021/acs.est.1c03899
6. H. S. Santana, Jr. J. L. Silva, B. Aghel, and J. Ortega-Casanova, SN Appl. Sci. **2**, 395 (2020). https://doi.org/10.1007/s42452-020-2176-7
7. L. Chronopoulou et al., "Microfluidic synthesis of PLGA nanocarriers for the controlled delivery of bioactive compounds in plants of agronomic interest," in *Proceedings of International Conference on Applied Nanotechnology and Nanoscience, 2021.* https://hdl.handle.net/11573/1562280
8. Z. Fattahi and M. Hasanzadeh, TrAC Trends Anal. Chem. **152**, 116637 (2022). https://doi.org/10.1016/j.trac.2022.116637
9. O. A. Ibrahim, M. Navarro-Segarra, P. Sadeghi, et al., Chem. Rev. **122**, 7236 (2022). https://doi.org/10.1021/acs.chemrev.1c00499
10. E. Carrasco, J. Gomez-Cruz, M. Serrano-Berrueco, et al., IEEE Open J. Antennas Propag. **3**, 425 (2022). https://doi.org/10.1109/OJAP.2022.3166232
11. C. Rossi and D. Esteve, Sens. Actuators, A **120**, 297 (2005). https://doi.org/10.1016/j.sna.2005.01.025
12. G. V. Kaigala, R. D. Lovchik, and E. Delamarche, Angew. Chem., Int. Ed. **51**, 11224 (2012). https://doi.org/10.1002/anie.201201798
13. M. K. Pugsley and R. Tabrizchi, J. Pharmacol. Toxicol. Methods **44**, 333 (2000). https://doi.org/10.1016/S1056-8719(00)00125-8
14. B. Sebastian and P. S. Dittrich, Annu. Rev. Fluid Mech. **50**, 483 (2018). https://doi.org/10.1146/annurev-fluid-010816-060246
15. J. A. Potkay, Lab. Chip **14**, 4122 (2014). https://doi.org/10.1039/C4LC00828F
16. W. J. Lucas, A. Groover, R. Lichtenberger, et al., J. Integr. Plant. Biol. **55**, 294 (2013). https://doi.org/10.1111/jipb.12041
17. Y. Pan, Zh. Yang, Ch. Li, et al., Sci. Adv. **8**, 1 (2022). https://doi.org/10.1126/sciadv.abo1719

Translated by D. Novikova