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EDITED AND REVIEWED BY
Jonathan Cooper,
University of Glasgow, United Kingdom

*CORRESPONDENCE
Anne-Laure Deman,
anne-laure.deman-him@univ-lyon1.fr
Maïwenn Kersaudy-Kerhoas,
m.kersaudy-kerhoas@hw.ac.uk

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Part of the problem or part of the solution? An interdisciplinary action call for more research on the environmental sustainability of lab-on-a-chip and point-of-care devices

Anne-Laure Deman[1]*, Rosanne M. Guijt[2], Collins Otieno Odhiambo[3], Zibusiso Ndlovu[4] and Maïwenn Kersaudy-Kerhoas[5]*

[1]Universite Claude Bernard Lyon 1, Centre National de Recherche Scientifique (CNRS), INSA Lyon, Ecole Centrale de Lyon, CPE Lyon, Institut des Nanotechnologies de Lyon (INL), Villeurbanne, France, [2]Centre for Regional and Rural Futures, Deakin University, Geelong, Australia, [3]African Society for Laboratory Medicine, Addis Ababa, Ethiopia, [4]Southern African Medical Unit, Medecins Sans Frontieres, Johannesburg, South Africa, [5]School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, United Kingdom

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Introduction

The concept of the lab-on-a-chip, at the core of many point-of-care or point-of use environmental or human diagnostic products, is intricately linked to the idea of single-use. The need for decentralisation, convenient diagnostic solutions has led to the design and production of centimeter scale, disposable devices, used once, then discarded.

This approach has increased the amount of generated waste beyond laboratories and into the communities where adequate disposal maybe is inadequate. Have we unwittingly created a "technological trap" resulting in unintended, additional, and potentially avoidable, waste (Søgaard Jørgensen et al., 2024)? Thus, a legitimate question is "are we part of the solution or part of the problem?" How can we ensure that the social benefits of such solutions are not delivered at the expense of an environmental impact that might take years to be fully appreciated? How big of a problem does the lab-on-a-chip waste represent? Can a single-use approach be reversible, or can it be alleviated through materials or methods choices? Most of the environmental sustainability of a single-use device is locked at the design stage and material choice is one of the many contributing factors to the environmental impact of the device. Can we identify applications where single use can be avoided, or can the impact of single use devices be minimized through material and design choices?

Importantly, a transition to alternative materials and reagents is not just an engineering problem. Beyond the functional aspects, there are significant economic and regulatory implications to consider. We are calling for engineers, economists, healthcare professionals, manufacturers, regulators and policymakers to join forces and work together to answer this Grand Challenge: how do we reduce the amount of waste created by the lab-on-a-chip and point-of-care devices industry?

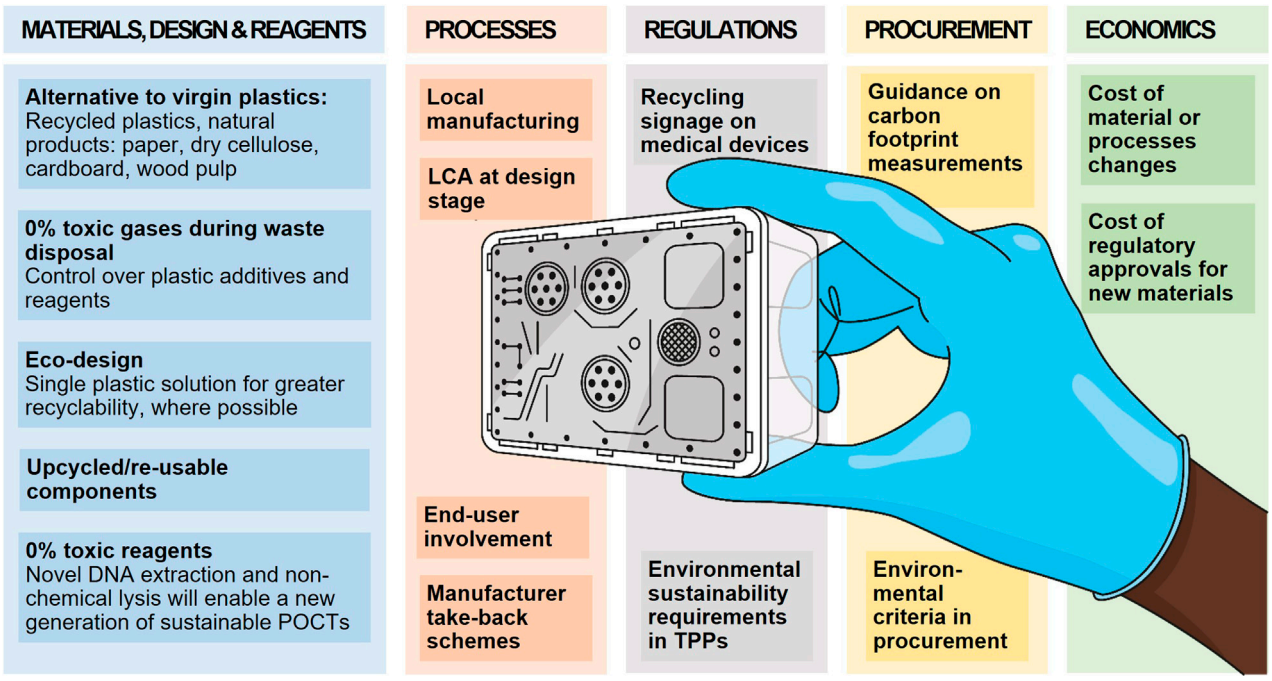

FIGURE 1
High-level roadmap for microfluidic, lab-on-chip, and point-of-care industry environmental sustainability

Environmental impact of the lab-on-a-chip and point-of-care industry

The environmental impact of lab-on-a-chip devices in the point-of-care or point-of-need industry is arguably difficult to assert, as no studies have been conducted to quantify this yet.

At the inception of the lab-on-chip field, a microfluidic approach was touted as the possibility to reduce reagents and solvent consumption. However, how much of this, still hold true? To yield meaningful results microfluidic devices often need similar amounts of sample and reagents than would be used in a bench assay. That is certainly the case when comparing to the use of liquid handling robots capable of handling microvolumes, with arguably less paraphernalia than most microfluidic-based devices.

The majority of point-of-need and point-of-care industry uses petroleum-based plastics (Campbell et al., 2021; Ongaro et al., 2022; Core, 2023). We also know that the industry is in full expansion to the need for decentralized healthcare. According to various reports, the microfluidic market sits at an estimated $11 billion and is projected to grow at an average rate of 10% CAGR. Meanwhile the point-of-care market is worth $32 billion with a CAGR of 11.5%. Whilst the exact production volumes have not been reported, it is clear the production equates waste at the end of the life cycle. An open question is how much of the industry produce single-use versus re-useable products. Similarly, the distribution of different end-of-life processes (incineration, landfill or recycling) for point-of-care and point-of-use devices are unknown, however, the toxic effect of plastic incineration or landfill on environmental, human and animal health is well documented (Odhiambo et al., 2021; Street et al., 2022; Bidashimwa et al., 2023). Preventing the use of petrochemical plastics has the potential of significant carbon savings in the industry, but also reduces toxic effects on human, animal and environmental health. Plastic pollution from the diagnostic industry is also a social justice issue, which affects predominantly the Global South. Manufacturers (predominantly from western or global north) have shied away from responsible practice and distribute products with unclear disposal indications (Street et al., 2022).

Sustainability research and action

Over the last 5 years, awareness of environmental sustainability in the medical sector has risen, partly due to the pandemic, which highlighted the impact of medical waste as the broader public observed the widespread disposal of masks, other PPE, and diagnostic kits (Adyel et al., 2020; Glasziou et al., 2020).

There has been several attempts to raise awareness about end-of-use issues and waste specifically in the sector of lab-on-a-chip and point-of-care diagnostics (Ongaro et al., 2022; Core, 2023; Street et al., 2022). However as commented elsewhere, there is a reluctance particularly from the global health field, to acknowledge the issue of pollution (Bidashimwa et al., 2023).

Developing green processes means questioning our own laboratory practices. What is the carbon footprint of research activities in academic laboratories related to these activities and the amount of waste generated? Purchases and travel are the two main sources of CO_2e emissions in laboratories, and the carbon footprint can reach 10 t CO_2e per researcher in the fields of physics, biology or engineering. How can we reduce it? Several initiatives,

such as *mygreenlab. org*, *Labo 1.5* in France, or *LEAF* (Laboratory Efficiency Assessment Framework) in the United Kingdom are schemes proposing methods for assessing the carbon footprint and actions that lab users can take to save plastics, water, energy and other resources. What would it mean in practice for a microfluidic lab? What are the waste streams like for our sector of activity?

Several editors have also launched new journals or manuscripts collection focusing on sustainability: example, the American Chemical Society launched "*Sustainable Chemistry and Engineering*" in 2013, Nature created "*Nature Sustainability*" in 2018, and Taylor and Francis have created the "*International Journal of Sustainable Engineering*", in 2024. In the meantime, the Royal Society of Chemistry (RSC) has launched a new cross-journals collection called "*Sustainable Laboratories*".

These activities, while laudable, remain niche, and the same big questions are still there and more work is needed to understand the impact of the industry, and what can, and should be done in academia and industry.

Call for action

What research is needed to improve sustainability in the sector? Here we lay out here some key pointers for a high level road-map (Figure 1).

We need a better understanding of the life cycle of lab on a chip and point-of-care devices and opportunities for local and circular solutions

Research in this area focus mainly on the design, with little consideration for the end-of-life leaving the door open to unintended consequences. We need research reports post-use attitudes and quantifying wastage in various settings. Bringing "garbology" experts to understand why we do not put an emphasis on end-of-life, and how to change these attitudes, for example, by changing education curriculums, encouraging academics to consider the impact of technology at the design stage (Schofield et al., 2021).

Life Cycle Assessments (LCA) are standardised method to quantitatively assess environmental impacts. While they were an unreliable tool a decade ago, they now benefit from a larger pool of experts, reliable software, better comparison framework and a dedicated standard (ISO, 2006). LCAs could be deployed to understand which stage of the product has the most environmental impact, and guide further research.

We need research to understand the opportunity for circularity in the sector. Could we use recycled materials to make these devices? Could used devices be segregated, collected, dismantled and re-used or recycled?

LCA and other types of environmental analysis, can also help us identify the need for manufacturing methods that significantly lower energy input or wastage. The geographical location of the organisations involved in the manufacturing, use and end-of-life of devices, play a significant role in a product's overall carbon footprint. Devices are often assembled, or sub-assembled in one geographical region, then sea or air freighted for final assembly in another region, shipped to their place of use, and sometimes shipped again to their "graveyard" destination. This additional travel can lead to a major increase in carbon footprint (Willoughby, 2022). It would be interesting to know the share of transport in typical microfluidic, lab-on-chip or point-of-care devices, to review local manufacturing solutions to date and barriers challenging more local manufacturing, cutting on unnecessary transport. There may also be an opportunity to investigate the use of local materials and the development of standardized processes that are able to produce equivalent devices using local natural resources or waste streams (Brito-Pereira et al., 2023).

We need new materials for lab-on-a-chip and point-of-care devices

The environmental challenges raised by the democratization of single-use LOCs require the scientific community to seek alternative solutions to hydrocarbon-based plastics. Replacing these materials with bio-sourced and biodegradable polymers as body material for the microdevices is a promising perspective. What specifications must these materials meet to produce eco-responsible LoCs? From a purely functional perspective, they must meet the specific requirements of LoCs, being (i) micro-patternable, with feature resolution enabling a wide range of applications (from a few µm to a few mm), (ii) impermeable for transporting aqueous solutions, (iii) bondable to obtain watertight systems, in certain cases (iv) transparent for microscopic observation, and (v) biocompatible when needed. In addition, the manufacturing processes associated with these materials must be ideally low in energy requirement.

The extraction, production, and processing methods must limit the use of techniques and products that are harmful to the environment. The transport associated with the entire production chain must be considered and encouraged to favor local resources. Finally, the pollution resulting from their degradation or combustion must be considered. Furthermore, sourcing biomaterials must not lead to new imbalances: resources must be sufficiently available not to be depleted. Another approach that has been little explored in the sector is the use of industrial by-products and waste streams currently produced by industry.

Different biopolymers have been trialed. Cellulose-based LoCs, using paper microfluidic principles, have already led to numerous tests, although few have been commercialised (Noviana et al., 2021). Cellulose-based devices are not suitable for all types of applications, particularly those involving cells, and unfortunately are too often packaged in plastic cases. Further upstream research has explored the use of other bio-based polymers such as poly (lactic acid) (PLA) (Ongaro et al., 2020), derived from renewable, plant-based sources such as corn starch or sugar cane; zein, obtained as a by-product from the production of ethanol from corn and transformed into resin (Hsiao et al., 2011); silk, produced from *bombyx mori* cocoons (Zhao et al., 2016); chitosan, a polysaccharide derived from chitin, that can be extracted from waste generated by the seafood industry (Zimmer et al., 2024); shellac, secreted by the *Kerria Lacca* insect, a species of cochineal (Lausecker et al., 2016); and wood (Andar et al., 2019).

These examples highlight the diverse possibilities for replacing standard petrochemical polymers in the manufacture of LoCs. While technological challenges remain—such as material reactivity with aqueous solutions and the complexity and environmental impact of their production processes—all present promising prospects. By tailoring their industrialization to local resource availability and specific applications, these alternatives could collectively contribute to the production of eco-responsible LoCs. The use of recycled materials is another solution, proposed for prototyping or production of lab on a chip of point-of-care. Whilst recycling does not eliminate dependence on non-renewable raw materials, it could be part of the solution, at least in the short term.

For example, lateral flow assay manufacturers have attempted efforts to curb plastic use, removing plastic cassettes or producing cassettes out of bio-based materials rather than petroleum derived materials (Gavi.org, 2024; Morris and Haworth, 2022).

We need safe, non-toxic reagents and chemistry

Material consideration should not be limited to housings, they should be extended to reagents (Agrawal et al., 2021), which brings direct chemical exposure with potential significant impacts on the environmental, human and animal health. Sleeman et al. (2018) calculated that more than 30 million HIV VL tests were estimated to be performed globally, generating approximately 924,000 L of effluent chemical waste and 2.1 million kg annually (Sleeman et al., 2018). The World Health Organisation and the African Society for Laboratory Medicine, have highlighted the problem surrounding the waste management, in particular in resource-limited settings and poor infrastructure, which unfairly exacerbate the problems, resulting in poor compliance to biosafety and biosecurity requirements (Odhiambo et al., 2021). This is further compounded by the lack of availability or generalized policy and guidelines that not specifically address the pollutants, and do not address the selection of waste disposal options. As point-of-care kits are rapidly commodified there is less information about the content of the test kits and specific waste instructions following test completion. In terms of the production of wet chemistry for use in point-of-care diagnostic devices, it is worth pointing out that the synthesis of affinity ligands such as aptamers, oligonucleotides and peptides also large amounts of environmentally challenging solvent, which also need to be addressed (Kopach and Andrews, 2022; Andrews et al., 2021).

For example, the dangers of guanidine thiocyanate (GTC), has been highlighted by yet many nucleic acid extraction kits and lab on chip devices still use this reagent. The diagnostic industry is coming up, albeit slowly, with solutions: Cepheid is trying to address amount of GTC in their cartridges, while Global Access Diagnostics uses HCL instead. Companies and laboratories have already spent time and money modifying existing protocols to use less toxic solvents and more environmentally friendly tools and techniques, researchers should be mindful of adopting those where possible. We need to list and prioritise toxic reagents to target research in reducing them, replacing them with efficient but safer alternatives. Peer-review has a role to play, in suggesting alternatives to toxic reagents and solvents and calling out environmentally damaging practices.

We need better understanding of regulatory and procurement frameworks and economics associated with sustainable solutions

The use of new materials or new methods in the sector of microfluidic, lab-on-chip and point-of-care devices brings the question of regulations for these new or transformed products, in particular in the medical industry, but not solely. What materials are allowed to be used in regulated environments? What documentation and processes are involved in a material change, and how much a typical material change cost?

Procurement rules for diagnostic devices are likely to be changed in coming years, with greater emphasis on product carbon footprint. Policymakers worldwide are increasingly mandating greater sustainability for single-use products, as exemplified by public procurement programs like the United States' BioPreferred Programme, Asian Development Bank, and the EU's Green Public Procurement (GPP) framework. In the US, the Environmental Protection Agency (EPA) now mandates that federally-affiliated healthcare facilities prioritize sustainable products. In this context, designing point-of-care testing (POCT) technologies for safe and sustainable disposal is both an ethical imperative for the industry and a chance for scientific innovation. We need more research on the impact of regulatory or procurement frameworks on the type of materials that can be used in microfluidic, lab-on-chip and point-of-care device sector.

Economics will have the final say. A key challenge for bio-derived and recycled materials is their typically smaller production scale compared to petrochemical counterparts, which benefit from economies of scale. Economists need to pinpoint the production scale at which alternative materials or processes become economically viable. Without a major policy shift—such as imposing a pollution tax that holds manufacturers accountable for their carbon footprint—new materials, methods, and processes must compete economically with the *status quo*.

Conclusion

The expansion of the microfluidic and point-of-need sector drives production, which in turn, creates the accumulation of a new kind of waste, that exacerbates existing waste streams. This technological trap shows that more emphasis on end-of-life should be put at the design stage.

We are calling for more interdisciplinary investigative research in the waste created by this industry, research in materials, methods and systems to reduce the environmental impact of products, research in regulatory and procurement frameworks and economics associated with the creation of sustainable solutions. This requires a transdisciplinary approach together with a clear roadmap.

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References

Adyel, T. M., Roberts, D., DeSalle, R., and Tishkoff, S. (2020). Accumulation of plastic waste during COVID-19. *Science* 369 (6509), 1314–1315. doi:10.1126/science.abd9925

Agrawal, A., Keçili, R., Ghorbani-Bidkorbeh, F., and Hussain, C. M. (2021). Green miniaturized technologies in analytical and bioanalytical chemistry. *Trac. Trends Anal. Chem.* 143, 116383. doi:10.1016/J.TRAC.2021.116383

Andar, A., Hasan, M. S., Srinivasan, V., Al-Adhami, M., Gutierrez, E., Burgenson, D., et al. (2019). Wood microfluidics. *Anal. Chem.* 91 (17), 11004–11012. doi:10.1021/acs.analchem.9b01232

Andrews, B. I., Antia, F. D., Brueggemeier, S. B., Diorazio, L. J., Koenig, S. G., Kopach, M. E., et al. (2021). Sustainability challenges and opportunities in oligonucleotide manufacturing. *J. Org. Chem.* 86 (1), 49–61. doi:10.1021/acs.joc.0c02291

Bidashimwa, D., Hoke, T., Huynh, T. B., Narkpitaks, N., Priyonugroho, K., Ha, T. T., et al. (2023). Plastic pollution: how can the global health community fight the growing problem? *BMJ Glob. Health* 8 (Suppl. 3), e012140. doi:10.1136/BMJGH-2023-012140

Brito-Pereira, R., Silva Macedo, A., Ribeiro, C., Cardoso, V. F., and Lanceros-Méndez, S. (2023). Natural indigenous paper substrates for colorimetric bioassays in portable analytical systems: sustainable solutions from the rain forests to the great plains. *ACS Appl. Mater Interfaces* 15 (40), 46747–46755. doi:10.1021/acsami.3c11928

Campbell, S. B., Wu, Q., Yazbeck, J., Liu, C., Okhovatian, S., and Radisic, M. (2021). Beyond polydimethylsiloxane: alternative materials for fabrication of organ-on-a-chip devices and microphysiological systems. *ACS Biomater. Sci. Eng.* 7 (7), 2880–2899. doi:10.1021/acsbiomaterials.0c00640

Core, G. (2023). Lab-on-a-chip—fostering a sustainable future. *Front. Lab. a Chip Technol.* 2 (Aug). doi:10.3389/frlct.2023.1239134

Gavi.org (2024). Eco-friendly diagnostic tests 'need global push. *VaccinesWork*. Available at: https://www.gavi.org/vaccineswork/eco-friendly-diagnostic-tests-need-global-push.

Glasziou, P. P., Sanders, S., and Hoffmann, T. (2020). Waste in Covid-19 research. *BMJ Clin. Res. ed.* 369, m1847. doi:10.1136/bmj.m1847

Hsiao, A., Luecha, J., Kokini, J., and Liu, L. (2011). "Green microfluidics made of corn proteins," in Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Boston, MA, United States, 30 August 2011 - 03 September 2011 (Piscataway, NJ, United States: EMBS). doi:10.1109/IEMBS.2011.6092072

ISO (2006). ISO 14040:2006 - environmental management – life cycle assessment – principles and framework. Available at: https://www.iso.org/standard/37456.html (Accessed November 16, 2024).

Kopach, M. E., and Andrews, B. I. (2022). Trimming synthetic peptide and oligonucleotide waste-lines. *Curr. Opin. Green Sustain. Chem.* 37, 100643. doi:10.1016/J.COGSC.2022.100643

Lausecker, R., Badilita, V., Gleißner, U., and Wallrabe, U. (2016). Introducing natural thermoplastic shellac to microfluidics: a green fabrication method for point-of-care devices. *Biomicrofluidics* 10 (4), 044101. doi:10.1063/1.4955062

Morris, M., and Haworth, D. (2022). Reducing the carbon footprint and plastic waste of LFTs: evidence-based opportunities. *Camb. Des.* Available at: https://www.cambridge-design.com/blog/how-to-reduce-the-carbon-footprint-and-plastic-waste-of-lfts/(Accessed November 14, 2024).

Noviana, E., Ozer, T., Carrell, C. S., Link, J. S., McMahon, C., Jang, I., et al. (2021). Microfluidic paper-based analytical devices: from design to applications. *Chem. Rev.* 121 (19), 11835–11885. doi:10.1021/acs.chemrev.0c01335

Odhiambo, C. O., Mataka, A., Kassa, G., and Ondoa, P. (2021). Managing laboratory waste from HIV-related molecular testing: lessons learned from African countries. *J. Hazard. Mater. Lett.* 2, 100030. doi:10.1016/J.HAZL.2021.100030

Ongaro, A. E., Di Giuseppe, D., Kermanizadeh, A., Miguelez Crespo, A., Mencattini, A., Ghibelli, L., et al. (2020). Polylactic is a sustainable, low absorption, low iutofluorescence alternative to other plastics for microfluidic and organ-on-chip applications. *Anal. Chem.* 92 (9), 6693–6701. doi:10.1021/acs.analchem.0c00651

Ongaro, A. E., Ndlovu, Z., Sollier, E., Otieno, C., Ondoa, P., Street, A., et al. (2022). Engineering a sustainable future for point-of-care diagnostics and single-use microfluidic devices. *Lab. Chip* 22 (17), 3122–3137. doi:10.1039/D2LC00380E

Schofield, J., Praet, E., Townsend, K. A., and Vince, J. (2021). COVID waste' and social media as method: an archaeology of personal protective equipment and its contribution to policy. *Antiquity* 95 (380), 435–449. doi:10.15184/AQY.2021.18

Sleeman, K., Hurlston, C. M., Diallo, K., Zeh, C., Riley, P., and Alexander, H. (2018). "Strengthening waste management during HIV viral load scale-up," in ASLM 2018 International Conference, Abuja, Nigeria, 10-14 December 2018, 107.

Søgaard Jørgensen, P., Jansen, R. E. V., Avila Ortega, D. I., Wang-Erlandsson, L., Donges, J. F., Österblom, H., et al. (2024). Evolution of the polycrisis: anthropocene traps that challenge global sustainability. *Philos. Trans. R. Soc. Lond. Ser. B, Biol. Sci.* 379 (1893), 20220261. doi:10.1098/RSTB.2022.0261

Street, A., Vernooij, E., and Rogers, M. H. (2022). Diagnostic waste: whose responsibility? *Glob. Health* 18 (1), 30–37. doi:10.1186/s12992-022-00823-7

Willoughby, A. (2022). The environmental impact of global supply chain logistics and bupplier selection. *drug Deliv.* 139, 30–34. Available at: https://ondrugdelivery.com/assessing-the-environmental-impact-of-global-supply-chain-logistics-and-supplier-selection/(Accessed: November 16, 2024).

Zhao, S., Chen, Y., Partlow, B. P., Golding, A. S., Tseng, P., Coburn, J., et al. (2016). Bio-functionalized silk hydrogel microfluidic systems. *Biomaterials* 93, 60–70. doi:10.1016/J.BIOMATERIALS.2016.03.041

Zimmer, M., Trombotto, S., Laurenceau, E., and Deman, A. L. (2024). Chitosan as an alternative to oil-based materials for the fabrication of lab-on-a-chip. *Micromachines (Basel)* 15 (3), 379. doi:10.3390/mi15030379