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Cost-Effective Fabrication of Polydimethylsiloxane (PDMS) Microfluidics for Point-of-Care Application

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ABSTRACT

Microfluidics fabrication pertains to the construction of small-scale devices and systems that manipulate and control small volumes of fluids. This process involves precise engineering and manufacturing procedures aimed at designing and producing these devices, which find applications in healthcare, environmental monitoring, and chemical analysis. The present study showcases an inexpensive approach to fabricate microfluidics channels using PDMS biopolymer and soft lithography technique to achieve laminar fluid flow. Initially, a robust and adhesive mold was created by fabricating a master template using several layers of SU-8 5 and SU-8 2015 negative photoresists. Subsequently, PDMS microfluidics channels were replicated and sealed onto a glass substrate through plasma bonding treatment. High-power microscopy images and profilometer analyses demonstrated successful fabrication with minimal deviation from the initial designs and the fabricated devices (less than 0.07 mm, less than 0.6°). Both the SU-8 master template and PDMS replicate displayed average microchannel height values and surface roughness of 100 µm and 0.26 µm or lower, respectively. Additionally, the fluid test confirmed laminar flow without any leakage post plasma oxidation, indicating the completion of an efficient and cost-effective fabrication process.

Keywords: *SU-8 photoresist, Fabrication, PDMS, Microfluidics, Soft Lithography, Point-of-care analysis*

1. INTRODUCTION

Microfluidics is a field of study focused on the behavior, manipulation, and control of fluids in small-scale systems. These systems typically consist of channels and chambers with dimensions ranging from micrometers to millimeters, with channel sizes typically between 10 and 100 µm [1]. The unique characteristics of fluids at the microscale enable precise control and manipulation, offering possibilities for miniaturized systems in various sectors such as biology, chemistry, pharmaceuticals, and engineering. One of the major advantages of microfluidics technology is the ability to perform complex experiments and analyses using small amounts of sample and reagents, resulting in cost reduction and rapid high-throughput testing. Some well-known instances of microfluidic devices encompass microvalves, microchannels, micromixers, and micropumps. In constructing microfluidic devices, inorganic materials, such as glass, silicon, and ceramics, and polymer-based materials, including polymethyl methacrylate (PMMA), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polycarbonate, polystyrene, are suitable. Nonetheless, the intricate, expensive, and time-intensive manufacturing procedures associated with these materials present constraints that restrict the widespread adoption of these microfluidic analytical devices in our society. Some disadvantages include incompatibility for optical detection in the visible and ultraviolet regions for silicon [2], [3], as well as issues with dimensional stability, porosity, brittleness, and optical properties that can hinder seamless integration of ceramics into a comprehensive microsystem [4], [5]. The production of glass microfluidic chips has been reported as costly despite the relative affordability of glass, often necessitating time-consuming, labor-intensive processes, and potential cleanroom preparations [6], [7]. Rigid polymers also pose inherent variability such as deformation during the heated sealing process, which makes them unsuitable for large-scale production [8], [9].

Polydimethylsiloxane (PDMS), a silicon-based bioorganic polymer, has gained attention as a suitable material for microfluidics fabrication due to its ability to produce devices quickly and inexpensively without requiring specialized clean room facilities [10]. PDMS offers several favorable properties, including biocompatibility, low cost, non-toxicity, thermo-tolerant, optical transparency, minimal autofluorescence, and the ability to be molded into complex shapes with high resolution [11], [12]. PDMS is also adaptable for integrating fluidic valves, establishing leak-proof connections, detecting subtle forces like biomechanical interactions from cells and facilitating gas delivery for cell culture on microfluidics devices. PDMS replicas can also be easily bonded to a glass substrate through plasma treatment, creating a sealed microfluidics

device. In producing a cost-effective fabrication of PDMS microfluidics, several strategies can be employed to achieve this objective. Firstly, utilizing simple fabrication techniques like soft lithography can reduce costs. Soft lithography involves creating a mold from a master template and replicating the microfluidics channels using PDMS. This method requires minimal equipment and can be performed in a standard laboratory setting. Secondly, optimizing the design of the microfluidics device can minimize material waste and reduce costs. By carefully considering the channel layout and dimensions, it is possible to maximize the number of devices that can be fabricated from a single batch of PDMS, thus reducing expenses. Implementing standardized protocols for fabrication processes also contributes to cost savings by enhancing reproducibility and scalability of microfluidics device production. Additionally, integrating additional functions into a single device maximizes the utility and value of PDMS microfluidics [13]. For instance, incorporating sensing elements or on-chip valves into the microfluidics design eliminates the need for extra components and reduces overall fabrication costs.

The primary motivation behind device miniaturization was to enhance device performance by scaling down analytical systems and making them suitable for point-of-care applications. This study employed passive flow control to simplify operation by designing microscale devices that utilize natural forces such as gravity, suction, and capillary action, eliminating the need for external power sources. The fabrication process involved creating a master template on a glass substrate using a negative epoxy-based photoresist (SU-8) through conventional lithography with a designed photomask and UV light exposure. The master template can be utilized indefinitely as long as the SU-8 remains intact on the substrate [14]. Subsequently, the master template was replicated using PDMS through the cost-effective soft lithography technique, which does not require a fully cleanroom environment [15], [16]. After channel formation, they were sealed using plasma bonding treatment. PDMS replicas can be sealed through reversible or irreversible methods. Reversible sealing relies on Van der Waals interactions, allowing for conformal sealing with a planar surface. In contrast, irreversible sealing necessitates plasma treatment to oxidize the PDMS surface and modify its properties [17].

2. METHODOLOGY

2.1. Chemicals, Materials, and Apparatus

Photomask for microfluidics was designed on Autodesk AutoCAD 2007 software and was printed on a special inkjet transparency using HP 1515 Deskjet printer for a high-resolution but low-cost method. Negative photoresist SU-8 5 (for thickness ≤7 μm), and SU-8 2015 (for thickness ≥40 μm), as well as resist developer were all purchased from MicroChem, USA. Standard laboratory glass microscope slide (25.4 × 76.2 mm) was used as a substrate for the master template. Distilled water and Isopropyl alcohol used in the fabrication of master templates were also of standard laboratory grade. Apparatus involved in the fabrication of SU-8 master template include a spin coater (Laurell WS-650MZ-23NPP, USA), a mask aligner (MIDAS MDA-400M, Korea), and a hot plate (WISETHERM HP30D, Indonesia). PDMS microfluidics was fabricated using SylgardTM 184 Silicone Elastomer Kit that was purchased from The Dow Chemical Company, USA, on a standard laboratory glass watch glass. Piranha solution was prepared carefully in a ratio of 1:3 of hydrogen peroxide to sulfuric acid. Apparatus involved in the fabrication of PDMS microfluidics channels include a plasma preen system (Plasma-Preen® II-862, USA), and a pressurized incubator (Constance XMTD-8222, Germany).

2.2. Fabrication of Master Template Using Negative Photoresist SU-8

Microfluidics photomasks were designed in two patterns, a simple Y-junction, and a mixer by U-turn. Both designs contain two inlets and one outlet. However, compared to the Y-junction which only has one straight main channel, the mixer by U-turn has a channel that has five turns for the sample to flow through. The inlets and outlets were both designed with a radius of 0.5, and 1.0 mm, respectively. In addition, the overall size for each design is <20 mm in length, which enabled a number of devices to be fabricated in a single batch. In this study, the photomask consists of 8 microfluidics chips that are easily fitted onto a 100 ± 0.2 mm silicon wafer. The channel layouts and dimensions were also designed to serve as a miniaturized, portable device, and thus minimizing the use of reagents and material waste, effectively reducing cost. Dimension and specification of the patterns are shown in Figure 1 and Table 1.

The photolithography process was performed with some modifications to ensure high-quality fabrication [12]. Initially, the pattern transfer from the mask to the glass slide was accomplished to create the SU-8 master template. A thorough cleaning of a microscope slide was done using a piranha solution. SU-8 5 was then coated onto the glass substrate with specific settings to achieve a thickness of 7μm: the spread cycle was gradually increased to 500 rpm at an acceleration of 100 rpm/s for 40 s, followed by a spin cycle at 2000 rpm for 30 s, and then ramped down for an additional 40 s. The glass slide was pre-baked at 65 °C for 2 min and soft-baked at 95 °C for 5 min to ensure resist adhesion. To promote adhesion further, two additional layers of SU-8 2015 were coated onto the glass slide with specific settings to achieve a thickness of 38 μm: the spread cycle was ramped up to 500 rpm at an acceleration of 100 rpm/s for 40 s, followed by a spin cycle at 1000 rpm for 30 s, and then scaled down for another 30 s. The glass microscope slide was pre-baked at 65 °C for 2 min and soft-baked at 95 °C for 5 min. The next step involved transferring the photomask patterns onto the coated glass slides. The glass slides were aligned on the mask aligner and exposed to UV light for 120 s to solidify. The glass slide was then baked at 65 °C for 1 min and another 1 min at 95 °C. After a few minutes at room temperature, the patterns were developed using SU-8 developer for 4 min. Because SU-8 is a negative photoresist, the exposed area solidified during UV light exposure, and the covered area was etched during development. It is important to control the developing time to avoid overdevelopment or underdevelopment, as the SU-

8 master template will be used for channel formation using PDMS afterwards. Once developed, the glass slide was washed twice with isopropyl alcohol to remove any residue SU-8 and clean the surface.

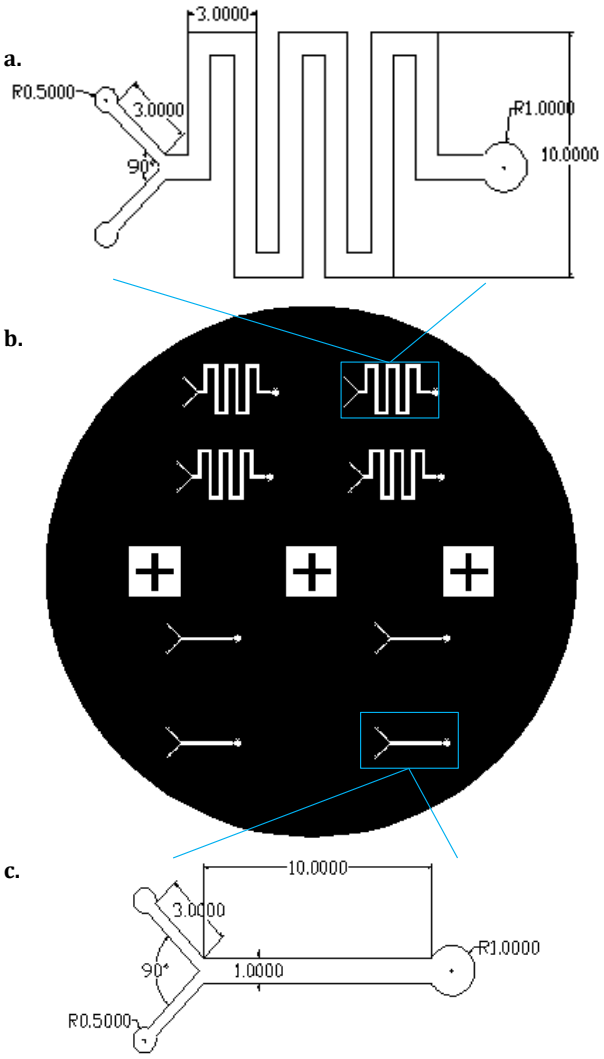

Figure 1. Dimension of the microfluidics designs (mm): (a) the overall mask design; (b) the mixer U-turn design; (c) the simple Y-junction design.

Table 1 Size and dimension of the photomask patterns designed on the AutoCAD software

Design	Simple Y-junction	Mixer U-turn
Inlet length	3 mm	3 mm
Inlet radius	0.5 mm	0.5 mm
Inlet angle	90°	90°
Channel length	10 mm	11 mm
Channel width	1 mm	1 mm
Outlet radius	1 mm	1 mm

2.3. Fabrication of Microfluidics Microchannels Using PDMS Biopolymer

Following SU-8 master template fabrication, PDMS was molded onto it using the soft lithography technique, which is considered the fastest and most cost-effective method since a fully cleanroom environment is not necessary [15], [16]. Prior to molding, the SU-8 master template was cleaned with isopropyl alcohol and rinsed with purified water to remove contaminants from the surface. A PDMS mixture was prepared by combining PDMS and a curing agent in a 10:1 ratio. The mixture was stirred gently for 10 to 15 min until it turned milky, and bubbles appeared. The cleaned SU-8 master template was placed facing up in a glass container, and the PDMS slurry was poured onto it, covering the surface. The PDMS was cured at 65 °C for 45 to 60 min in a pressurized incubator, then allowed to cool before being removed from the master template. The cured PDMS was carefully placed on a fresh glass slide and subjected to plasma bonding treatment, where both surfaces of the PDMS and glass were exposed to oxygen plasma for 90 sec at 250 W and 60 mTorr to create a stable structure for the microfluidic channels. The plasma treatment ensured an irreversible bond between PDMS and glass, preventing channel leakage.

2.4. Overall Process of the Two-Step Fabrication of Microfluidics Device

A process flow diagram depicting the complete two-step fabrication process for the master template using lithography and the formation of the master template through soft lithography is shown in Figure 2. Additionally, Figure 3 illustrates the equipment used for the fabrication of the SU-8 master template and PDMS replica. Dimension inspection was conducted using conventional lenses and high-power microscopy (HPM) at various inspection points. The interior structure was analyzed using a 3D surface profilometer (DektakXT Stylus Profilometer, Bruker, USA) to assess structural integrity, thickness, and surface roughness of both devices. Leakage testing was performed with food colorant to evaluate fluid delivery and biocompatibility, confirming the successful fabrication. All experiments were carried out in a standard laboratory setting, with conventional photolithography performed in a semiconductor yellow booth cleanroom, while soft lithography of PDMS microfluidics was conducted on an open laboratory bench.

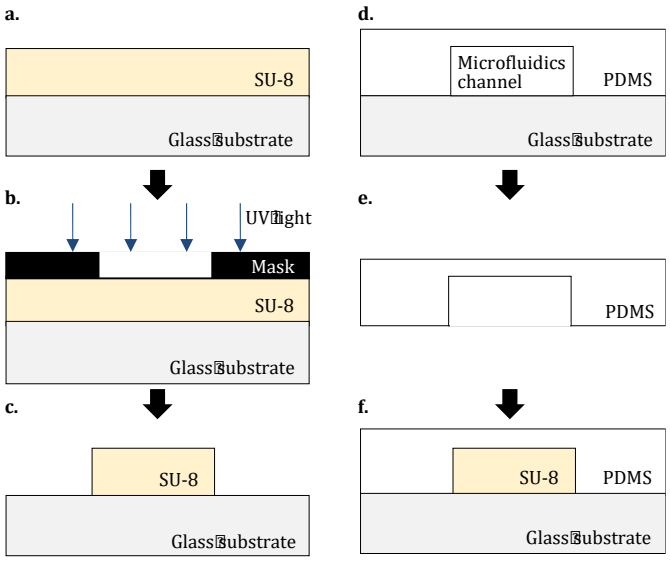

Figure 2. Fabrication of microfluidics channels: (a) deposition of SU-8 on a glass slide to form determined layers on top where spin coating takes place; (b) pattern transfer by UV light exposure using a mask aligner; (c) etching and pattern development using SU-8 developer; d. PDMS replication of the master template; (e). cured PDMS that was peeled off; (f) plasma bonding of PDMS microfluidics on a glass substrate to create the microchannels.

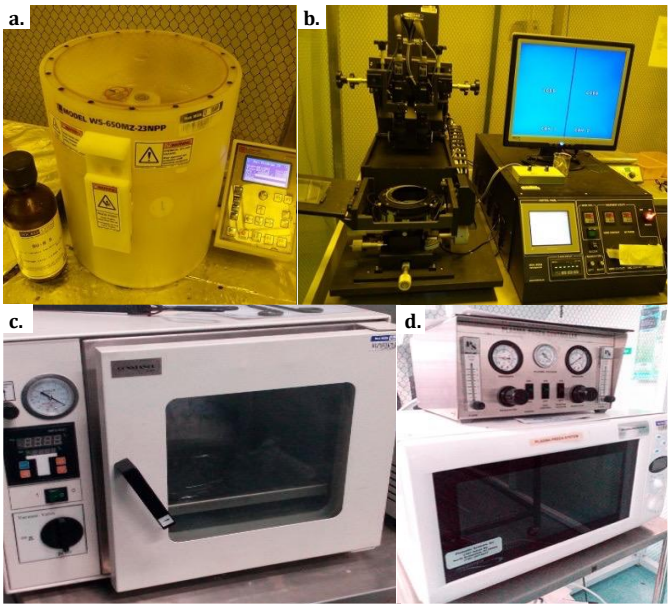

Figure 3. Apparatus involved in the fabrication of microfluidics: (a) a spin coater; (b) a mask aligner; (c) a pressurized incubator; and (d) a plasma system.

3. RESULTS AND DISCUSSION

3.1. Morphological Analysis of PDMS Microfluidics

Figure 4 displays images taken under a conventional lens of the photomask design and the microfluidic devices before and after successful fabrication. Figure 5 exhibits images of several inspection points of both the SU-8 master templates and the PDMS replicas of the two designs, captured using HPM. There was a slight variation in dimensions between the original design and after the lithography process, attributed to possible incomplete removal of excess SU-8 during development. It is important to note that despite the slight variation in dimensions resulting from the lithography process, these differences were deemed insignificant, with measurements falling within the margin of error (<0.07 mm, <0.6°).

This implies that the observed deviations did not have a substantial impact on the overall functionality and performance of the fabricated microfluidic devices. However, it is recommended to further investigate the fabrication process to ensure consistent and precise replication of the original design parameters, potentially refining the development steps to minimize such variations in the future. The peeled-off PDMS from the SU-8 master template closely resembled the dimensions outlined in Table 2.

Table 2 Size and dimension of the simple Y-junction design before and after fabrication

Design	AutoCAD	SU-8 master template	PDMS replicate
Inlet radius	0.5 mm	0.4998 mm	0.4984 mm
Inlet angle	90°	90.5°	95.8°
Channel width	1 mm	1.0347 mm	1.0684 mm

Table 3 Size and dimension of the mixer U-turn design before and after fabrication

Design	AutoCAD	SU-8 master template	PDMS replicate
Inlet radius	0.5 mm	0.5240 mm	0.4767 mm
Inlet angle	90°	91.8°	95.4°
Channel width	1 mm	1.1772 mm	1.0654 mm

An important aspect of microfluidic fabrication is the design and creation of the master template. The design was printed onto a transparency mask using a high-resolution printer to ensure a high-quality mask that transfers patterns onto the SU-8 for master template formation. This master template serves as the mold for creating microfluidics channels using PDMS. PDMS was chosen for this study due to its desirable characteristics, such as cost-effectiveness and easy adhesion to glass, enabling both reversible and irreversible sealing. In this experiment, irreversible sealing was employed to mitigate the risk of leakage during the introduction of reagents into the microfluidic channels.

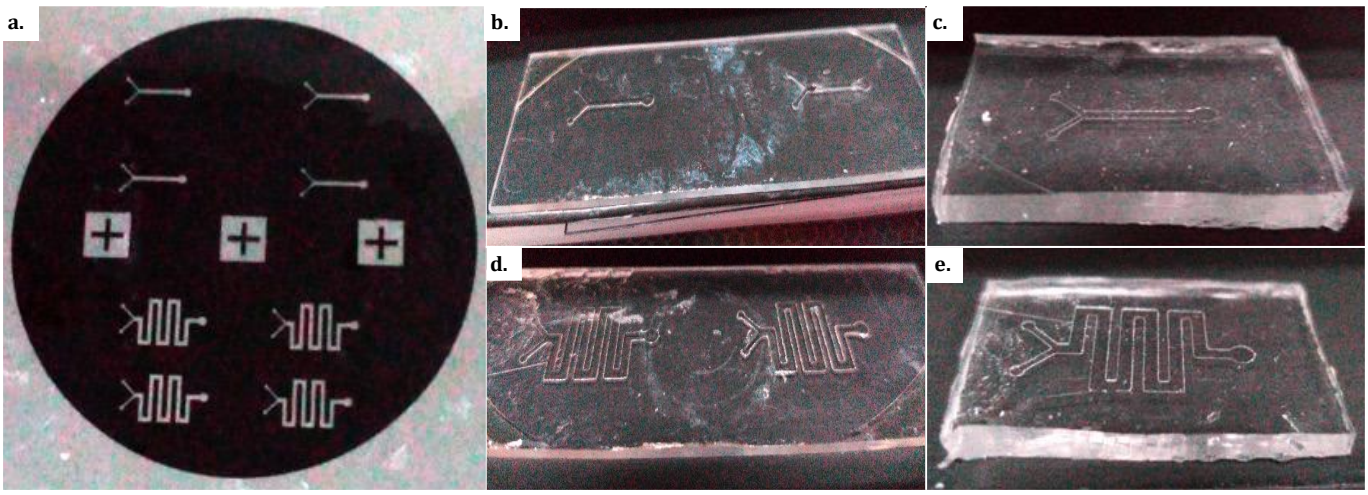

Figure 4. Design for microfluidics: (a) the overall printed photomask, (b) the SU-8 master template, and (c) the PDMS replicate of a simple Y-junction design, as well as (d) the SU-8 master template and (e). the PDMS replicate of a mixer by U-turn design.

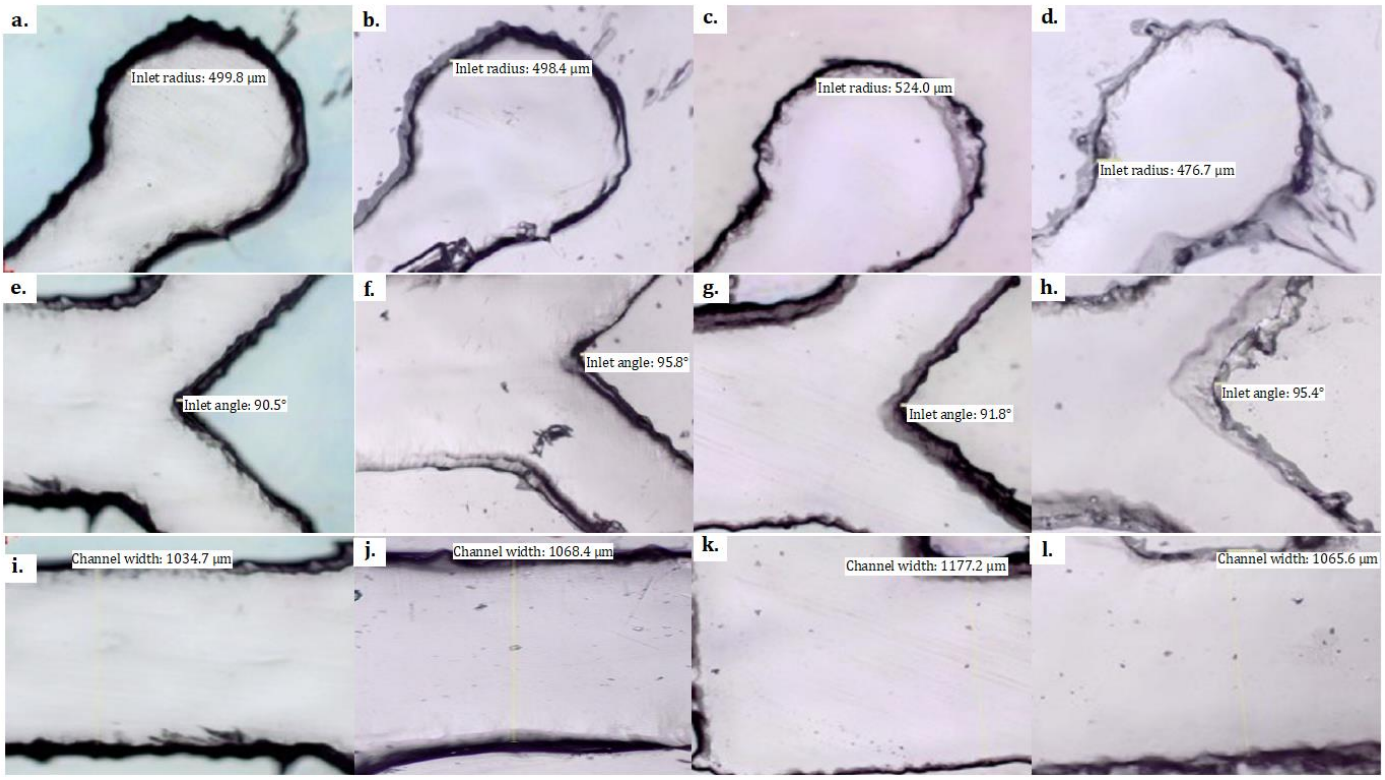

Figure 5. Images from high-power microscope of simple Y-junction design: six images from the left, and mixer by U-turn design: six images from the right, for SU-8 master templates: (a), (c), (e), (g), (i), (k), and microfluidics replicates: (b), (d), (f), (h), (j), (l).

3.2. 3D Profilometer Analysis

Profilometer analysis provides valuable information about the dimensions, geometry, surface topography, and structural integrity of microfluidic channels and devices. It allows precise measurement of surface irregularities, including peaks, valleys, and waviness, by recording deviations from the ideal flatness. Figure 6 and 7 illustrates 3D profilometer measurements for all the fabricated samples, including the thickness of the SU-8 master templates, channel depth of the PDMS replicas, and surface roughness of both templates and replicas. The thickness of the SU-8 master templates and the channels depth of the PDMS microfluidics were found to be approximately 100 µm for both designs, aligning with the application of microfluidics for manipulating fluids in small volumes within 100 µm. Surface roughness measurements indicated that the SU-8 surface was relatively uniform with slight unevenness, observed as an increased frequency of waves and shorter distance between waves. However, the surface roughness was not significant, with oscillations ranging between 0.11–0.32 µm. Although there is room for improving the fabrication process to increase surface smoothness, this study demonstrated successful microfluidic fabrication as the minor irregularities were within <0.5 µm.

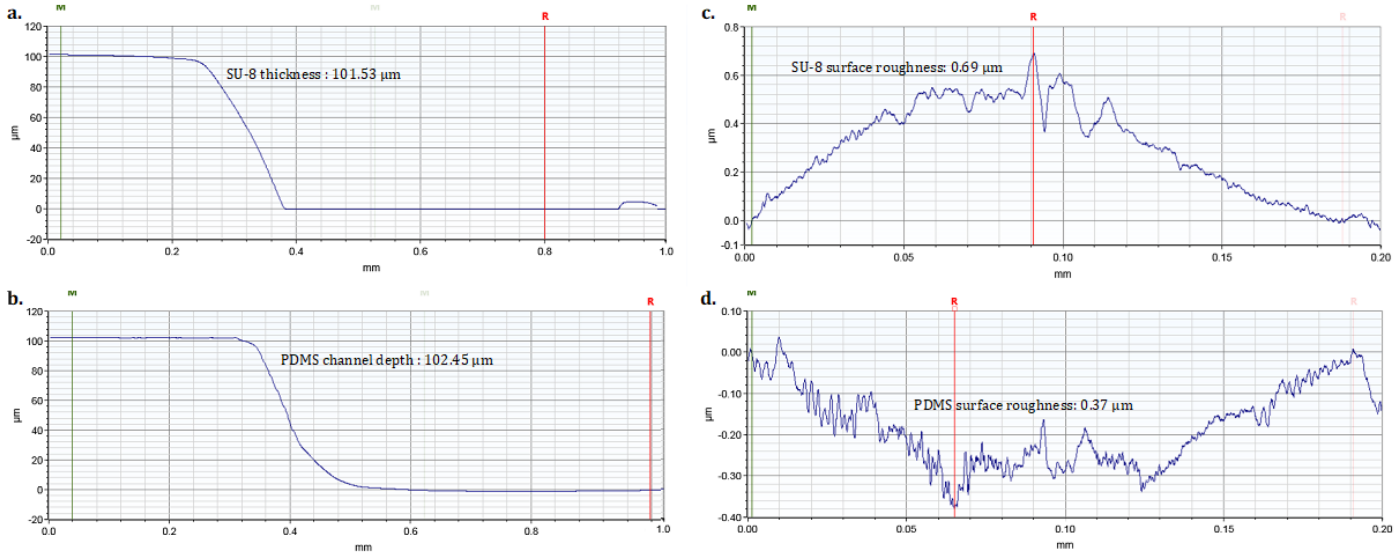

Figure 6. 3D Profilometer assessments for simple Y-junction design.

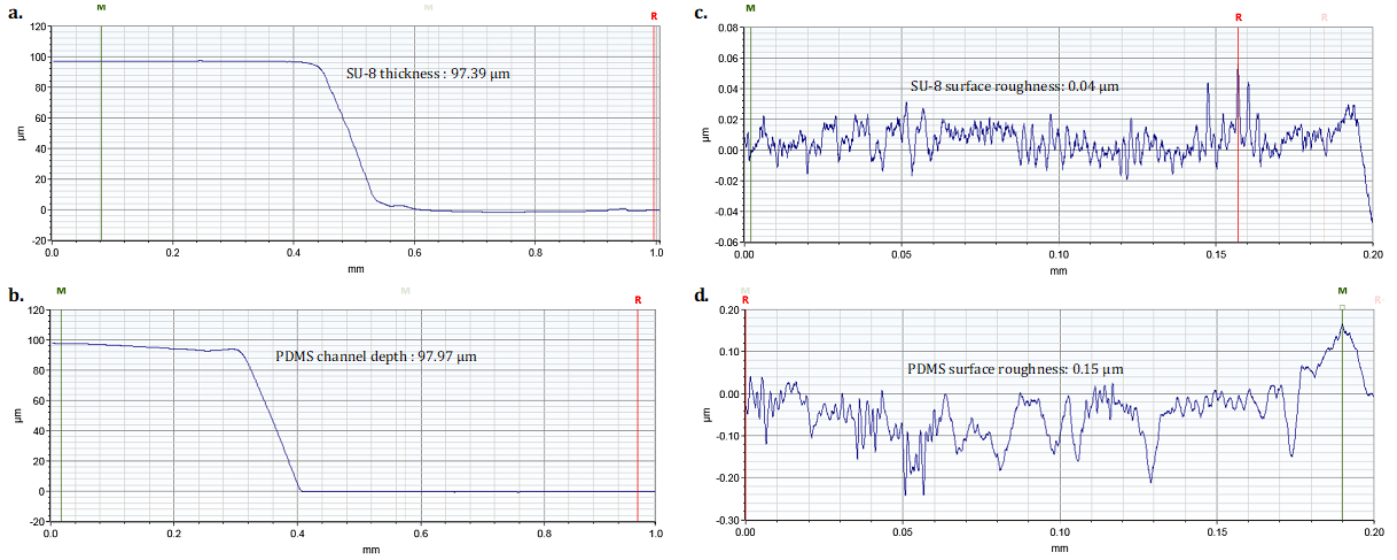

Figure 7. 3D Profilometer assessments for mixer by U-turn design.

3.3. Plasma Bonding and Fluid Test for Biocompatibility

Figure 8 presents the fabricated PDMS microfluidics devices sealed on new slides post plasma bonding treatment. Figure 9 illustrates fluid flow inside the microfluidics devices upon introduction of a food dye, with no observed leakage, confirming the success of fabrication.

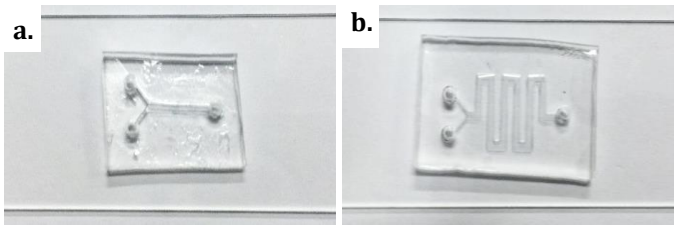

Figure 8. Microfluidics devices bonded to a glass substrate ready to be used.

Plasma treatment induces surface modification of PDMS, initially possessing a hydrophobic surface that repels water. Upon exposure of the microfluidic channel to oxygen during plasma treatment, the surface transitions to a hydrophilic nature, thereby attracting water [18]. In the conducted experiment, fluid is introduced into the microfluidics through initial pressure exerted by a micropipette. The plasma bonding technique effectively seals the microfluidics channels, preventing leakage. Plasma oxidation serves to modify the surface of the PDMS microfluidics by introducing silanol groups. As a result, the fluid flows smoothly with minimal resistance, adhering to the oxidized channel walls in a unidirectional manner. The fluid flow can be described by Navier-Stokes equations, considering both inertial and viscous properties of the fluid [19]. However, in low Reynolds number microfluidic applications such as the fabricated devices in this study, inertial effects can be ignored, leading to the simplified Stokes equation or creeping flow approximation. This approximation assumes a low Reynolds number,

$$Re = \rho UL/\mu, \quad (1)$$

which describes the ratio of inertial to viscous forces for a liquid of density ρ, and viscosity μ, in a flow with characteristic length L, and characteristic velocity U,

is very low. And thus, the Stokes equation linearizes the Navier-Stokes equations and only considers the viscous properties of the fluid, describing the flow of fluids in microfluidics systems under laminar conditions.

$$-\nabla P + \mu\nabla^2 u + f = 0, \quad (2)$$

$$\nabla \cdot u = 0, \quad (3)$$

where μ represents the dynamic viscosity of the fluid, ∇ is the gradient operator, u is velocity, *P* is the pressure and f is the body force. This assumption is valid for the small length scales and low flow velocities involved in microfluidic systems [20].

Due to the micro-sized nature of the fabricated microfluidics devices, the Reynolds number is extremely low (<10) [21], enabling consideration of laminar flow within the microfluidics channels of both designs.

In terms of the processing time, the simple Y-junction design exhibited a shorter duration compared to the mixer by U-turn design during the fluid test, suggesting laminar flow characterized by smooth and predictable fluid motion where the inertial forces are negligible compared to the viscous forces. In contrast, the longer channel path of the mixer by U-turn design presents opportunities for diffusion and reaction kinetics, making it well-suited for applications requiring extended reagent mixing and reaction durations. Biomedical sensors integrated with microfluidics, aimed at detecting bacterial DNA in saliva, or pathogenic microorganisms can benefit from the enhanced reaction kinetics and detection sensitivity afforded by the mixer's increased interaction length between reagents [22]–[26]. Both designs offer unique advantages based on flow characteristics and processing times for diverse sensor applications.

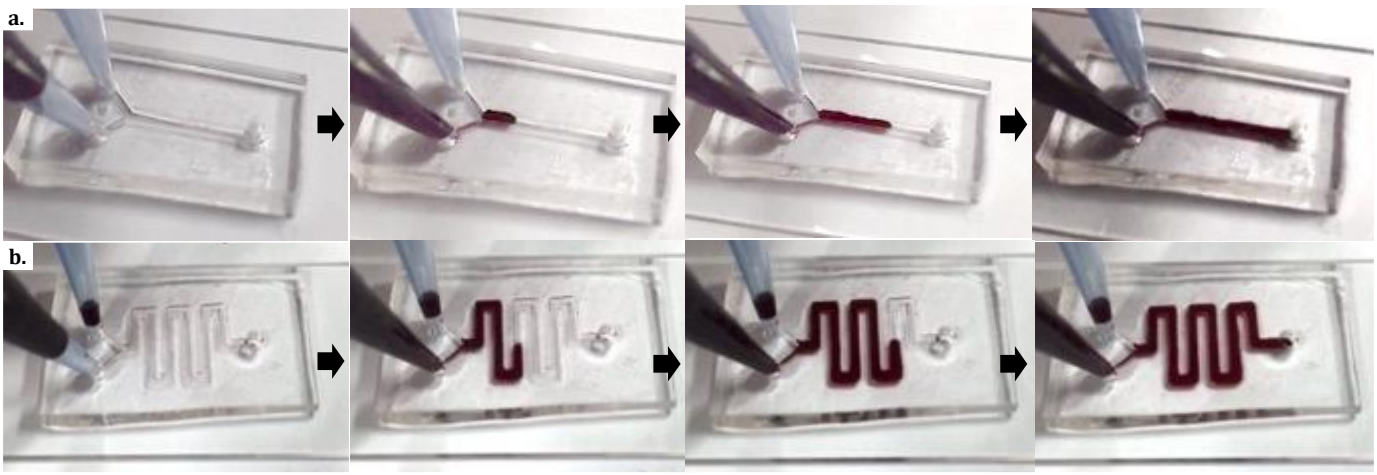

Figure 9. Fluid flow test of microfluidics devices demonstrated no leakage: (a) simple Y-junction design, (b) mixer by U-turn design.

4. CONCLUSION

Microfluidics technology is a versatile and valuable tool for downsizing devices, finding applications in numerous fields such as microbiology, agriculture, forensics, and point-of-care biomedical analysis. This study presents an intelligent and cost-effective method for fabricating PDMS microfluidics suitable for point-of-care applications. The utilization of AutoCAD software for pattern design and a regular desktop inkjet printer for high-resolution transparency printing makes the process accessible and convenient. By employing multi-layered SU-8 master templates, the fabrication technique achieves strong adhesion, reusability, and high-quality pattern transfer through photolithography. Soft lithography of PDMS allows for flexible and biocompatible fabrication with a short processing time. The fabricated PDMS microfluidics devices exhibit microchannels with a height of approximately 100 μm and a planar surface, characterized by a surface roughness of ≤0.26 μm, which are desirable for point-of-care applications. The small size of microfluidics enables laminar flow, ensuring quick and efficient reactions within the channels. The tight and irreversible seal achieved through plasma bonding enables the PDMS microfluidics device to withstand higher pressure during fluid introduction. Further enhancements and modifications to the design and fabrication process can be implemented to tailor microfluidics devices for specific applications.

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REFERENCES

[1] M. D. Tarn and N. Pamme, "Microfluidics," in *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering*, Elsevier, 2014. doi: 10.1016/B978-0-12-409547-2.05351-8.

[2] J. Hwang, Y. H. Cho, M. S. Park, and B. H. Kim, "Microchannel Fabrication on Glass Materials for Microfluidic Devices," *International Journal of Precision Engineering and Manufacturing*, vol. 20, no. 3, pp. 479–495, Mar. 2019, doi: 10.1007/s12541-019-00103-2.

[3] J. P. Martins, G. Torrieri, and H. A. Santos, "The importance of microfluidics for the preparation of nanoparticles as advanced drug delivery systems," *Expert Opin Drug Deliv*, vol. 15, no. 5, pp. 469–479, May 2018, doi: 10.1080/17425247.2018.1446936.

[4] J. B. Nielsen, R. L. Hanson, H. M. Almughamsi, C. Pang, T. R. Fish, and A. T. Woolley, "Microfluidics: Innovations in Materials and Their Fabrication and Functionalization," *Anal Chem*, vol. 92, no. 1, pp. 150–168, Jan. 2020, doi: 10.1021/acs.analchem.9b04986.

[5] A. Singh, C. K. Malek, and S. K. Kulkarni, "Development in microreactor technology for nanoparticle synthesis," *Int J Nanosci*, vol. 09, no. 01n02, pp. 93–112, Feb. 2010, doi: 10.1142/S0219581X10006557.

[6] S. B. Campbell, Q. Wu, J. Yazbeck, C. Liu, S. Okhovatian, and M. Radisic, "Beyond Polydimethylsiloxane: Alternative Materials for Fabrication of Organ-on-a-Chip Devices and Microphysiological Systems," *ACS Biomater Sci Eng*, vol. 7, no. 7, pp. 2880–2899, Jul. 2021, doi: 10.1021/acsbiomaterials.0c00640.

[7] J. Hwang, Y. H. Cho, M. S. Park, and B. H. Kim, "Microchannel Fabrication on Glass Materials for Microfluidic Devices," *International Journal of Precision Engineering and Manufacturing*, vol. 20, no. 3, pp. 479–495, Mar. 2019, doi: 10.1007/s12541-019-00103-2.

[8] Z. Wu, X. Chen, Z. Wu, Q. Zhang, and Q. Gao, "Experimental study of fabricating a four-layers Cantor fractal microfluidic chip by CO2 laser system," *Microsystem Technologies*, vol. 25, no. 4, pp. 1251–1256, Apr. 2019, doi: 10.1007/s00542-018-4060-6.

[9] N. Ling, J. S. Lee, and N. Y. Lee, "Solvent-assisted low-temperature and low-pressure poly (methylmethacrylate) bonding coupled with selective microchannel hydrophobic coating for reliable sealing," *Sens Actuators A Phys*, vol. 265, pp. 168–173, Oct. 2017, doi: 10.1016/j.sna.2017.08.023.

[10] S. Hemmilä, J. V. Cauich-Rodríguez, J. Kreutzer, and P. Kallio, "Rapid, simple, and cost-effective treatments to achieve long-term hydrophilic PDMS surfaces," *Appl Surf Sci*, vol. 258, no. 24, pp. 9864–9875, Oct. 2012, doi: 10.1016/j.apsusc.2012.06.044.

[11] R. Luttge, "Basic technologies for microsystems," in *Nano- and Microfabrication for Industrial and Biomedical Applications*, Elsevier, 2016, pp. 11–54. doi: 10.1016/B978-0-323-37828-4.00002-9.

[12] A. Ayoib, U. Hashim, S. C. B. Gopinath, V. Thivina, and M. K. M. Arshad, "Design and fabrication of PDMS microfluidics device for rapid and label-free DNA detection," *Applied Physics A*, vol. 126, no. 3, p. 193, Mar. 2020, doi: 10.1007/s00339-020-3337-7.

[13] A. Ayoib *et al.*, "Low cost design and fabrication of PDMS microfluidics micromixers for DNA extraction," *2017 IEEE Regional Symposium on Micro and Nanoelectronics (RSM)*, pp. 227–230, Aug. 2017, doi: 10.1109/RSM.2017.8069158.

[14] P. K. Dey, B. Pramanick, A. RaviShankar, P. Ganguly, and S. Das, "Microstructuring of SU-8 Resist for MEMS and Bio-Applications," *International Journal on Smart Sensing and Intelligent Systems*, vol. 3, no. 1, pp. 118–129, Jan. 2010, doi: 10.21307/ijssis-2017-384.

[15] S. K. Tiwari, S. Bhat, and K. K. Mahato, "Design and Fabrication of Low-cost Microfluidic Channel for Biomedical Application," *Sci Rep*, vol. 10, no. 1, p. 9215, Jun. 2020, doi: 10.1038/s41598-020-65995-x.

[16] A. Ayoib, U. Hashim, M. K. M. K. Arshad, and V. Thivina, "Soft lithography of microfluidics channels using SU-8 mould on glass substrate for low cost fabrication," *IECBES 2016 - IEEE-EMBS Conference on Biomedical Engineering and Sciences*, pp. 226–229, 2016, doi: 10.1109/IECBES.2016.7843447.

[17] W. Schrott, M. Svoboda, Z. Slouka, M. Přibyl, and D. Šnita, "PDMS microfluidic chips prepared by a novel casting and pre-polymerization method," *Microelectron Eng*, vol. 87, no. 5–8, pp. 1600–1602, May 2010, doi: 10.1016/j.mee.2009.10.049.

[18] T. Trantidou, Y. Elani, E. Parsons, and O. Ces, "Hydrophilic surface modification of PDMS for droplet microfluidics using a simple, quick, and robust method via PVA deposition," *Microsyst Nanoeng*, vol. 3, no. 1, p. 16091, Apr. 2017, doi: 10.1038/micronano.2016.91.

[19] J. Guan, J. Liu, X. Li, J. Tao, and J. Wang, "Stokes flow in a two-dimensional micro-device combined by a cross-slot and a microfluidic four-roll mill," *Zeitschrift für angewandte Mathematik und Physik*, vol. 66, no. 1, pp. 149–169, Feb. 2015, doi: 10.1007/s00033-013-0396-z.

[20] M. Huang, S. Fan, W. Xing, and C. Liu, "Microfluidic cell culture system studies and computational fluid dynamics," *Math Comput Model*, vol. 52, no. 11–12, pp. 2036–2042, Dec. 2010, doi: 10.1016/j.mcm.2010.01.024.

[21] T. A. Duncombe, A. M. Tentori, and A. E. Herr, "Microfluidics: reframing biological enquiry," *Nat Rev Mol Cell Biol*, vol. 16, no. 9, pp. 554–567, Sep. 2015, doi: 10.1038/nrm4041.

[22] V. Thivina, U. Hashim, M. K. Md. Arshad, A. R. Ruslinda, A. Ayoib, and N. K. S. Nordin, "Design and fabrication of Interdigitated Electrode (IDE) for detection of Ganoderma boninense," in *IEEE International Conference on Semiconductor Electronics, Proceedings, ICSE*, 2016. doi: 10.1109/SMELEC.2016.7573588.

[23] N. K. S. Nordin, U. Hashim, A. Ayoib, and V. Thivina, "Surface morphological and electrical characterization of silicon nanowires (SiNWs) by conventional photolithography method," in *Proceedings of the 2017 IEEE Regional Symposium on Micro and Nanoelectronics, RSM 2017*, 2017. doi: 10.1109/RSM.2017.8069142.

[24] D. Zhang, H. Bi, B. Liu, and L. Qiao, "Detection of Pathogenic Microorganisms by Microfluidics Based Analytical Methods," *Anal Chem*, vol. 90, no. 9, pp. 5512–5520, May 2018, doi: 10.1021/acs.analchem.8b00399.

[25] A. Ayoib, U. Hashim, and S. C. B. S. C. B. Gopinath, "Automated, high-throughput DNA extraction protocol for disposable label free, microfluidics integrating DNA biosensor for oil palm pathogen, Ganoderma boninense," *Process Biochemistry*, vol. 92, no. January, pp. 447–456, May 2020, doi: 10.1016/j.procbio.2020.02.003.

[26] A. Ayoib, U. Hashim, S. C. B. Gopinath, and M. K. Md Arshad, "DNA extraction on bio-chip: history and preeminence over conventional and solid-phase extraction methods," *Appl Microbiol Biotechnol*, vol. 101, no. 22, pp. 8077–8088, Nov. 2017, doi: 10.1007/s00253-017-8493-0.