Research Article

Journal of Environmental Nanotechnology

High-Efficiency Microfluidic Channels for Enhanced Nanoparticle Behavior in Sustainable Fluids

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Received: 23.09.2024 Accepted: 20.12.2024 Published: 30.12.2024
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ABSTRACT

In this study, it focuses specifically on the microfluidic channel. And the way of approaching the pattern through literature. The pattern provides the mixing in an enhanced manner. To meet the requirement of efficient mixing part of simulation that it influenced through iteration. The provision of 3D design that entails the simulation of such patterned mesh. To get the integrated pattern towards the single mold that facilitates the channel for fluid flow that tenses toward mixing. It can be studied through simulation and iteration. The study includes iterative literature and simulation to make it fine tune channel design and target better mixing conditions. Specifically on nanoparticles such as neem to impact it. Through the 3D design and simulation, a structure of mesh pattern was developed, which acts as origin for mold that promotes or facilitates the effective flow of fluid. That induces turbulence and improves mixing within the microchannel; it enables particle distribution. The iteration process plays a crucial role in improving the entire efficiency, with every iteration bringing channel closer to desired performance. These findings are the instrument for experiments studies on channel design. This work delves into the optimization of microfluidic channels for nanoparticle synthesis, focusing on advanced design patterns to improve mixing efficiency. Using Neem extract and silver nitrate at varying concentrations, the study explores how the microfluidic device facilitates effective nanoparticle synthesis. The iterative design and simulation processes play a crucial role in achieving the desired mixing conditions. The findings offer valuable insights for future experimental studies and applications in nanoparticle synthesis. The focus lies in optimizing the microfluidic channels to mix better, especially for nanoparticle synthesis using Neem extract and silver nitrate. Focus on iterative design, simulation, and 3D modeling to improve microfluidic performance. Develop sophisticated mesh patterns in the microfluidic channels to cause turbulence and enhance fluid mixing. Use of 3D design and simulation to optimize the design of channel structure to produce the best flow of fluid and homogeneous particle distribution. The objective is to fill the gap that exists between computational design and the actual applications to improve the efficiency of microfluidic systems in real nanoparticle synthesis.

Keywords: Microfluidic channel; Neem extract; Optimization; Nanoparticle synthesis; 3D design; Silver nitrate.

1. INTRODUCTION

The development of microfluidic devices is crucially advanced in the part of nano mixing. To design the microfluidic device, the lithography 3D printing (Razavi *et al.* 2020) was utilized. To maintain laminar flow, to be ensured for smooth high-resolution features are required. The fabricated device was used to integrate silver nitrate nanoparticles from plant extract and solution on ferric chloride. The mixing efficiency was evaluated by UV spectroscopy. The current study shows that the design and fabrication of resin-based printing may result in the pouring of the PDMS into the mold and facilitate curing (Tony *et al.* 2023). Microfluidic devices have become essential in nano mixing applications, where precision and control over fluid flow are critical. This study employs lithography and 3D printing techniques to design a microfluidic device that maintains laminar flow and features high-resolution channels. The device facilitates the integration of silver nitrate nanoparticles synthesized from plant extracts, with the efficiency of mixing assessed through UV spectroscopy. This approach aims to enhance the nanoparticle synthesis process by providing a controlled environment for fluid interactions. The study highlights the benefits of resin-based 3D printing in achieving high-resolution features and laminar flow, which are vital for consistent nanoparticle dispersion. The comparison of different methods, such as ultrasonic agitation and surfactants, aims to optimize the mixing process and improve overall efficiency. Under the ambience the oxide or any surfactant is utilized instead of ultrasonic cation. These are the objective process to be established after curing. That might be taken under flow of fluid in laminar (Pawinanto *et al.* 2019; Stroock *et al.* 2002).

The advancement in microfluidic devices concerns the crucial role of enhancing the mixing efficiency of nanoparticles, certainly in field of nanotechnology, a Resin based 3D printing technique was employed to design and fabricate the microfluidic device. This method ensures precise, high-resolution features that maintain laminar flow within the channels, preventing unwanted turbulence and promoting efficient fluid mixing. Ferrous oxide nanoparticles were synthesized from plant extract (Jiang *et al.* 2014). A ferric chloride solution was also extracted. Mixing efficiency was rigorously evaluated using UV rays, a method that providing quantitative insights into the extent of mixing in a provision. The process is crucial for application requiring homogenous dispersion within the fluid. While providing precise control at the microscale, scaling up the same processes for industrial applications becomes complex and usually inefficient. the small size of channels limits overall production rates for nanoparticles, which is an important drawback in large-scale applications. compatibility issues between microfluidic materials and bio-fluids and precise in-situ monitoring increase the complexity. These limitations can be overcome by advancements in the scalable microfluidic technology, stronger device materials, and processes for repeatedly preparing the bio-extracts. Further studies can explore the synthesis of new functional materials, targeting broader application. Real time monitoring technologies were integrated to such sensors in the device, which certainly enhance the quality of production of nanoparticles.

2. DESIGN AND FABRICATE THE MICROFLUIDIC DEVICE

2.1 Introduction

The microfluidic tool for creating nano-sized formulations was meticulously planned and engineered to ensure precise control over fluid movement and effective mixing. CAD software played a crucial role in designing a digital model of the microfluidic device, incorporating features specifically suited for nano-formulation. The design of the microfluidic tool for nanoparticle formulation required careful planning to ensure precise fluid control and effective mixing (Ward *et al.* 2015; Kulkarni *et al.* 2020). CAD software played a pivotal role in creating a detailed digital model of the microfluidic device, incorporating serpentine mixers and mixing chambers to enhance efficiency. The transition from the digital model to a physical device involved photolithography and soft lithography techniques, which enabled the accurate replication of microfluidic features onto PDMS. This process ensures that the final device achieves the necessary fluid dynamics for controlled nanoparticle synthesis. The model featured microchannels with carefully defined dimensions to facilitate smooth fluid flow and optimal interaction between the solutions. Additionally, elements such as serpentine mixers and mixing chambers were included to enhance mixing efficiency and produce uniform nanoparticles. Once the design was optimized, the next steps involved translating the digital model into a functional microfluidic device using advanced fabrication techniques (Whui Dhong Wong *et al*, 2024). Photolithography and soft lithography were employed to create the mold of the microfluidic features on a substrate. This mold was then used to transfer the pattern onto a material like PDMS (polydimethylsiloxane), chosen for its biocompatibility, ease of use, and suitability for microfluidic applications. The soft lithography process involved pouring PDMS over the mold, curing it to solidify, and then bonding it to a glass substrate to complete the microfluidic device (Niculescu *et al.* 2022). This approach ensured that the micro channels and mixing chambers were precisely replicated and capable of achieving the desired fluid dynamics. To assess the effectiveness of the microfluidic design, silver nitrate nanoparticles were synthesized by mixing ferric chloride and plant extract solutions within the microchannels. The synthesis process was carefully monitored in a hands-on manner to observe the formation of nanoparticles (Gimondi *et al.* 2023). This real-time observation allowed for the evaluation of the microfluidic device's performance in producing nanoparticles with the intended size and uniformity. The detailed design and fabrication process ensured that the microfluidic device possessed the necessary characteristics for controlled nanoparticle synthesis, providing valuable insights into the efficiency and accuracy of the nano-formulation process. In the microfluidic systems, high surface-to-volume ratio accelerates chemical reactions and thus makes it faster than synthesis methods that use bulk. The mesh patterns and design features of microchannels induce turbulence, making it easier for the particles to distribute evenly and avoid agglomeration, hence making better-quality nanoparticles.

2.2 3D Modelling

A low-cost methodology was adopted for fabricating the mold by utilizing printed circuit board (PCB) technology. This approach allowed for a cost-effective and efficient production process. The design incorporated a serpentine herringbone pattern with pillars and pits within a Y-shaped micromixer, which was fabricated with dimensions of 53 x 70 x 12 mm. The use of PCB technology enabled precise and accurate etching of the micromixer features onto the board. Fusion 360 software was used to design the microchannels, ensuring they met the specifications for effective fluid mixing (Nady *et al.* 2021). The design process involved simulating fluid dynamics to refine the channel dimensions before fabrication. This iterative approach improved the final product's performance in terms of fluid mixing and channel efficiency. The microchannels, essential for the optimal function of the micromixer, were meticulously designed using Fusion 360. This design software provided the tools necessary to create detailed and accurate models of the microchannels, ensuring that they met the required specifications for effective fluid mixing and flow. The design process involved defining the geometrical parameters of the channels, including their width, depth, and arrangement, to achieve the desired mixing efficiency (Bezelya *et al.* 2023).

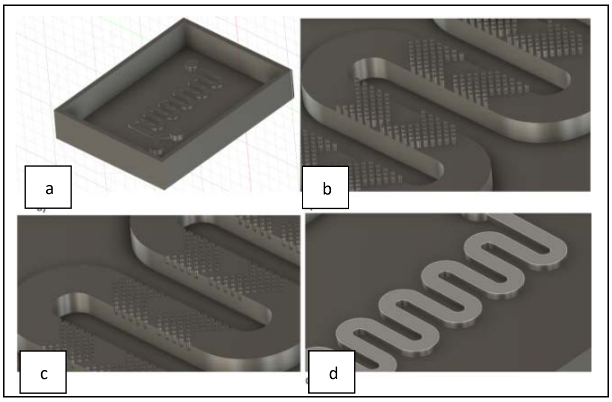

Fig. 1: Design optimization of serpentine patterned channel mold (a), Serpentine Pits (b), Pillar and control channel (c,d) using Fusion 360

By employing Fusion 360, the design team was able to simulate and analyse the fluid dynamics within the micro mixer before fabrication. This allowed for adjustments and optimizations to be made in the design phase (Yu *et al.* 2016; Rhoades *et al.* 2020), reducing the likelihood of issues during the manufacturing process. The combination of PCB technology for mold fabrication and advanced CAD software for design ensured that the final micro mixer was both functional and cost-effective. The resulting micro mixer demonstrated improved performance in terms of fluid mixing and channel efficiency, highlighting the effectiveness of the adopted methodology. A computer-aided design (CAD) software as shown in Fig. 1. This comprehensive 3D modelling tool allowed to produce precise digital models of the device's microchannels, chambers, and internal fluidic network (Kee *et al.* 2008; Hu *et al,* 2021). Fusion 360 intuitive interface enabled the precise design of complicated elements, ensuring the microfluidic device's operation and manufacturability. This approach allowed for full adjustment of the device's flow dynamics and mixing characteristics prior to physical manufacturing, which considerably improved the overall efficiency and success of the research.

2.3 Fabrication of Micro Mixer

The micromixer was fabricated using a combination of 3D printing and soft lithography. The initial exploration for fabricating the microfluidic device utilized an FDM wavelength of 405mm. However, upon closer inspection of the printed mold, fine lines corresponding to the layer-by-layer deposition inherent to FDM technology were observed as shown in Fig. 2. These surface imperfections were deemed unsuitable for the microfluidic application as they could potentially disrupt the laminar flow within the microchannels (Hu *et al*, 2020; Niculescu *et al*, 2021).

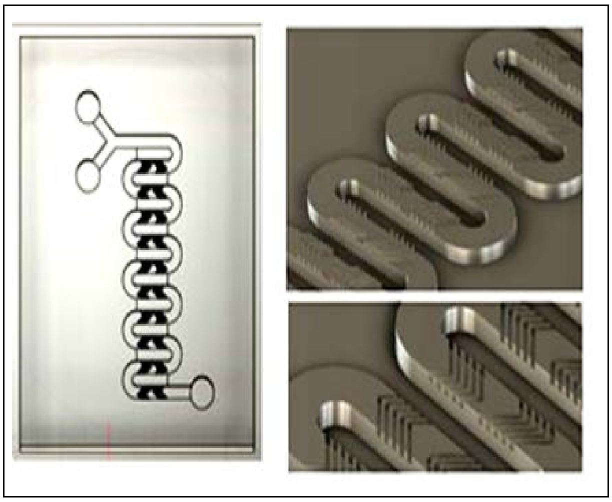

Fig. 2: Pattern Stroocks ridge and grooves

Therefore, to achieve the smooth surface finish necessary for optimal fluid flow characteristics, stereo lithography apparatus (SLA) 3D printing approach was adopted. The synthesis of $AgNO_3$ nanoparticles involved the use of Neem extract and silver nitrate solutions (Batubara *et al*, 2023). Microfluidics supports the use of natural and bio-based materials, such as plant extracts, for eco-friendly nanoparticle synthesis. The nanoparticles were synthesized within the microfluidic device, with the process monitored under controlled conditions. Different concentrations and mixing conditions were explored to optimize nanoparticle formation. The study also evaluated the effects of ultrasonic agitation on mixing efficiency and made iterative adjustments to improve the synthesis process (Xu L *et al*, 2020). The goal was to achieve uniform nanoparticles and better control over particle properties. Neem extract is being used primarily as the principal precursor in the synthesis of nanoparticles intended for microfluidic channels containing several bioactive compounds acting as natural reducing and stabilizing agents. The introduction of compounds along with $AgNO_3$ permits the reduction of silver ions, Ag^+, thus forming eco-friendly silver nanoparticles, AgNPs. In such a controlled environment, comprehensive and uniform integration of Neem extract with silver nitrate will be ensured as a basis for adequate chemical reactions as well as consistent formation of nanoparticles. Optimized flow conditions should be appropriately managed to prevent aggregation of nanoparticles, ensuring well-dispersed and stable nanoparticle entities. The microfluidic channels present a very controlled and efficient situation for the synthesis of high-quality silver nanoparticles using Neem extract.

SLA offers higher resolution and smoother surface finishes compared to FDM, making it the preferred choice for fabricating the final microfluidic device. The precise 3D model was subsequently translated into a tangible mold using a Stereo lithography (SLA) 3D printer shown in Fig. 3. In contrast to Fused Deposition Modelling (FDM) printers that utilize filament material, SLA printers leverage to flight-curable liquid resin. SLA printing offers superior resolution, making it highly suitable for fabricating microchannels with precise dimensions.

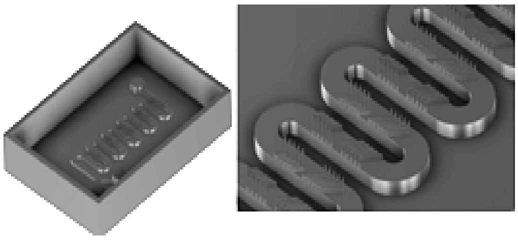

Fig. 3: Observation of fine lines when magnified into the FDM-based 3D print

These microchannels play a vital role in promoting chaotic advection, a phenomenon where the fluid interface is stretched and folded repeatedly within the channels, leading to enhanced mixing efficiency. Following the 3D printing process, the mold was used as a template for a soft lithography step involving polydimethylsiloxane (PDMS). This technique effectively encloses the microfluidic channels within the fabricated micromixer, ensuring that the channels are fully sealed and functional for the intended microfluidic applications. The result is a robust microfluidic device with well-defined channels that facilitate controlled fluid flow and mixing.

The PDMS was carefully poured onto the mold and then cured in an oven at 50 °C for a minimum of 12 hours. This curing process resulted in the formation of an accurate replica of the micromixer design. Once the PDMS had fully cured and solidified, the next step was to finalize the microfluidic device by bonding a glass piece to the PDMS layer. This was achieved using plasma bonding, which involves exposing the surface to high-energy plasma, which activates the surfaces and creates a permanent seal. First, the CAD model of the micromixer was generated. The mold was prepared using PDMS followed by plasma bonding with glass (Seo *et al.* 2012; Zhu *et al.* 2020). Techniques such as soft lithography, 3D printing, and laser micromachining can be used to create very precise shapes of microchannel designs that can be customized a lot. New channels with snake-like patterns, spiral shapes, or mesh-based mixers are good at mixing and making uniform nanoparticles.

2.4 $AgNO_3$ Nanoparticles

Here the Nanoparticle utilized for mixing under ambience condition is taken $AgNO_3$ instead of silver nitrate the oxide react as surfactant that provide the ultrasonic cation to facilitate the mixing for furthermore enhanced mixing the iteration was taken to be to be progressed (Kumari SA *et al*, 2022). The Newtonian fluid is taken for the sample material that it performs the cheaper ionic liquids under periodic influence. Then, the optimal percent of mixing is only obtained by oxide and ceramic particles. The contaminated spherical shape that retains its shape, size and texture for particle properties to get the proper mixing comparatively even better with active mixing. Silver nitrate (AgNO3) is used in the concentration from 0.001M to 0.01M. Neem extract concentrations are prepared as a percentage weight/volume solution as 1% to 5% w/v was used in this mixing efficiency. Then, conventional particles are mixed in optimized percentage through ultrasonic cation under the similarity with surfactant.

3. RESULTS AND DISCUSSIONS

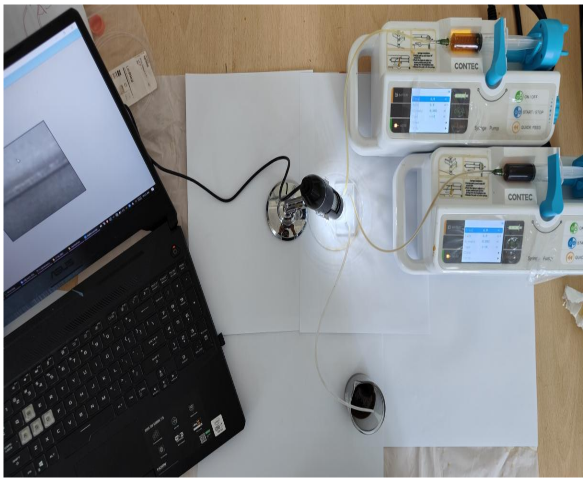

Fig. 4: Setup showing a USB microscopic camera capturing the flow of $AgCl_3$ Solution and plant extract solution from the infusion pump

The microfluidic setup for $AgNO_3$ nanoparticle synthesis employed a controlled and observable environment, as shown in Fig. 4. Two syringe pumps were utilized to precisely deliver precursor solutions at predetermined flow rates. One syringe pump contained a 10 mL syringe filled with silver nitrate ($AgNO_3$) solution, while the other held a 10 mL syringe filled with plant extract solution. These solutions were mixed in a 1:1 ratio within a PDMS microfluidic device. The device was positioned under a USB microscopic camera, allowing real-time observation and recording of the mixing process and any color changes occurring during the reaction between $AgNO_3$ and the plant extract. Small-diameter tubing connected the syringes to the inlet ports of the PDMS mold and facilitated the controlled flow of the mixed solution out of the device into a small collection beaker (Cao *et al.* 2021). By adjusting the flow rates controlled by the syringe pumps, the experiment explored the impact of different mixing speeds on the efficiency of $AgNO_3$ nanoparticle formation.

3.1 Mixing Efficiency of Micromixer

UV-Vis spectral analysis was performed for the synthesized $AgNO_3$ nanoparticles, and absorption maxima were recorded at wavelengths between 200 and 500 nm using a UV-Vis spectrophotometer. The UV-Vis spectra of silver nitrate nanoparticles synthesized using G. Sylvestre plant extract are shown in Fig. 5.

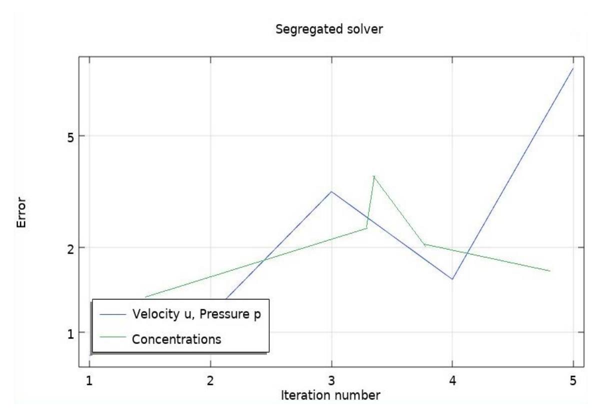

Fig. 5: UV-visible spectroscopy was used to evaluate the concentration and velocity in serpentine and Y-shaped microchannels

As seen in Fig. 5, a characteristic absorption peak around 275-300 nm is observed, implying the formation of silver nanoparticles. The formation of nanoparticles in the serpentine micromixer was monitored at different flow rates, namely 10 ml/hr, 1 ml/hr, and 0.5 ml/hr. An increase in peak intensity was observed as the flow rate was reduced to 0.5 ml/hr. Additionally, in comparison with the Y-shaped channel, the serpentine micromixer exhibited better efficiency in synthesizing the nanoparticles.

4. CONCLUSION AND FUTURE SCOPE

4.1 Conclusion

From the study of microfluidics and nanoparticles, the employed solutions for the mixing process demonstrated interesting results. The design and development of microfluidic devices for oxide nanoparticle synthesizing showed an efficient model, along with design techniques that help to enhance the process. One key element in this study was the use of 3D printing technology, which offers a more advanced CAD model that optimizes the structure of mixers and channels. This is especially critical as it helps to ensure that the fluid dynamics and mixing efficiency are maintained throughout the experiment. Without proper design, the fluid's movement would be disrupted, leading to less reliable results. Additionally, the use of UV light proved to be an important factor in the synthesis of iron oxide nanoparticles. The UV light helped to ensure the success of the synthesis process, providing a more stable and consistent production of nanoparticles. The comparison between the serpentine micromixer and a normal channel revealed that the serpentine micromixer exhibited a much better performance in the mixing and synthesizing process.

Fig. 6: Microscopic image of Patterned ridges and grooves

The design of the serpentine micromixer allowed for better control over the flow and mixing of fluids, leading to more efficient production of nanoparticles. This study highlights the potentiality of nanoparticle synthesis in a microfluidic environment. It demonstrates that such systems can provide a highly reproducible environment and ambience that is desirable for large-scale production. The controlled mixing of solutions and the ability to observe the process in real-time make microfluidic devices ideal for nanoparticle synthesis. With further optimizations, these systems could become a standard method for producing nanoparticles in a consistent and reliable manner. The integration of microfluidics and 3D printing in this field shows promise for future developments (shown in Fig. 6), particularly in ensuring the scalability and efficiency of nanoparticle production. The use of human design techniques, such as CAD models, alongside UV light for synthesis ensures that these systems can be continually improved.

4.2 Future Scope

The research in the future can expand this study into different approaches to exploring channel geometries and materials for optimization to further synthesis. The intervention of sensors within the microfluidic devices would permit real-time monitoring of reacting control over the size and composition of the particles. In addition, scaling increases productivity on progress, that clearly controlled by valuable application industries. Further studies are also investigated by synthesizing a broad range of particles and materials. This enables the development of functional materials that enable deployment of functional materials to fields like drug delivery, catalyst and environment remediation.

Further studies can explore the synthesis of new functional materials, Targeting broader applications. The use of materials for constructing microfluidic devices, such as biocompatible or conductive polymers, could open the domain of application. Systems that are not only synthesis nanoparticles effectively but also adapt with biomedical application or environmental monitoring systems. In terms of scaling, the research can extend towards industrial scale production by adapting fluidic platforms where the mass production of functional nanomaterials is required. Real time monitoring technologies were integrated into such sensors in the device which certainly enhances the quality of production of nanoparticles.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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