Int. J. Pharm. Investigation, 2025; 15(2):313-324.
https://www.jpionline.org

Review Article

A Comparative Review of 3D Printing Technologies and their Applications: A Systematic Review for Future of Medicine Fabrication

Muhammad Abid Mustafa*, Aqsa Malik, Eman Javed, Aliza Amjad, Sana Iqbal, Eman Mustafa, Namra Rasheed, Aqsa Shafiq, Muhammad Fahad, Maryam Mughal, Gohar Jaan, Nageen Ramzan

Department of Pharmaceutics, Faculty of Pharmaceutical Sciences, Lahore University of Biological and Applied Sciences, Lahore, PAKISTAN.

ABSTRACT

This review explores the role of additive manufacturing, particularly 3D printing, as an innovative approach in targeted drug delivery. It effectively addresses the limitations of traditional methods, such as high costs, complex geometrics and difficulties in individualized medications. The advent of 3D printing offers a modern solution, enabling the manufacturing of customized 3D objects from digital models. The approval of Spritam® (levetiracetam) by the FDA, the first additive manufacturing tablet, is a clear indication of the demand for 3D printing. This technique, which creates products layer-by-layer through a two-step process of data transfer and print head movement in all three dimensions, is gaining popularity. The review explores the diverse additive manufacturing methods applicable to drug delivery systems, including Fused Deposition Modeling (FDM), Stereo Lithography (SLA) and others. FDM, in particular, stands out for its creativity and cost-effectiveness. Beyond drug delivery, additive manufacturing has found applications in tissue engineering, manufacturing of complicated geometries, controlled-release systems and individualized medication for specific patient needs. The technology empowers the creation of intricate, customized structures loaded with drugs, demonstrating great potential for targeted therapies and personalized medicine.

Keywords: Modern Fabrication, Individualized Medicine, Dosage form printing, Nanotechnology, FDA Approved.

Correspondence:
Dr. Muhammad Abid Mustafa
Department of Pharmaceutics, Faculty of Pharmacy, Lahore University of Biological and Applied Sciences, Lahore, PAKISTAN.
Email: abidbhatti222@gmail.com
ORCID: 0009-0009-2851-3047

Received: 24-07-2024;
Revised: 02-09-2024;
Accepted: 05-11-2024.

INTRODUCTION

The pharmaceutical field is constantly exploring new approaches to drug delivery, with a particular focus on targeted delivery methods. Targeted delivery enhances patient safety and medication compliance. However, the conventional method is unable to fulfill individual patient needs due to their focus on mass production (Gaurkhede *et al*., 2021). Traditional methods, including encapsulation and compression, are expensive and struggle to produce highly complex medications. Additionally, they are ineffective in manufacturing personalized products (Tan *et al*., 2019). For this purpose, 3D printing, a rapidly expanding and revolutionary technology, can be employed to make additive items from electronic models (Glukhova *et al*., 2022). The 3D printing process involves two key steps: (1) transferring data from software to the 3D printer and (2) using the print head to repeatedly deposit material in layers, building the object one layer at a time (Ramya and Vanapalli, 2016). 3D printing technology gained significant attention in August 2015 when the FDA approved Spritam® (levetiracetam) as the first additive manufacturing tablet (Samiei, 2020). The pharmaceutical industry has recently shown a surge of interest in additive printing. This is due to 3D printing's unique capabilities, such as creating complex drug release patterns, intricate drug shapes and customized medications. Additionally, it enhances the effectiveness of drug loading into pharmaceutical products (Sen *et al*., 2020). 3D printing possesses several key features, including affordability, accessibility and the ability to produce objects in any conceivable shape. These potential positions 3D printing as a technology with significant probability for advancements in both the pharmaceutical and biomedical fields.[2] Three-dimensional printing is a rapid prototyping technique that creates products layer by layer. This enables the production of complex internal structures, such as hollow channels, internal walls and areas with varying materials and porosities. Besides, additive manufacturing allows the dispensation of multiple drugs within a single object, a capacity beyond the reach of traditional pharmaceutical manufacturing methods (Li *et al*., 2018). Contemporary advancements in 3D printing technology

OPEN ACCESS

Manuscript TECHNOMEDIA

DOI: 10.5530/ijpi.20250024

Publishing Partner : Manuscript Technomedia.[www.mstechnomedia.com]

have extended implementation in oral drug administration. This is notable because successful drug delivery requires leveraging modern technologies like 3D printing and nanotechnology while ensuring safe medication delivery (Pandey *et al.*, 2020). In tissue engineering and drug delivery, additive printing enables the creation of intricate and personalized structures infused with medication, which is especially advantageous for pediatric and geriatric patients (Jamróz *et al.*, 2018). 3D printing encompasses various techniques, such as Stereolithography (SLA), Fused Deposition Modeling (FDM), Powder Bed Fusion, Binder Jetting and Material Jetting. FDM is particularly notable for its versatility and affordability, making it the most commonly utilized method.

Several techniques are employed in the creation of 3D-printed objects, including Fused Deposition Modeling (FDM) (Nober *et al.*, 2019), Binder jet 3D printers (Sen *et al.*, 2020) Stereolithography (SLA) (Wang *et al.*, 2016), Extrusion-based modelling (Gaurkhede *et al.*, 2021). This review article examines how 3D printing has transformed the development of various Drug Delivery Systems (DDS), such as tablets, capsules, gels, novel dosage forms and transdermal patches. Additionally, 3D printing provides a unique capability to tackle the challenge of creating complex multi-drug tablets, where each drug is released according to a customized release profile (Khaled *et al.*, 2015).

Current research aims to provide a comprehensive review of 3D printing technologies used in drug delivery systems. This review will cover various 3D printing methods, including Fused Deposition Modeling (FDM), Stereo Lithography (SLA) and Digital Light Processing (DLP), among others. It will delve into how these techniques are applied to develop a range of drug delivery systems, such as multi-layered tablets, hydrogels, nanoparticles, liposomes, niosomes and transdermal patches. Additionally, the review will discuss the specific functionalities and practical applications of each 3D printing method in this context.

MATERIALS AND METHODS

The study took place over four months, from February 10, 2024, to June 10, 2024. Ethical approval was granted by the Research Ethics Committee at the University of Biological and Applied Sciences (UBAS) in Lahore, Pakistan, under reference number RMEC/AM/09791, ensuring adherence to ethical standards and guidelines. This review primarily utilized PubMed and Cochrane databases. The study protocols followed the PRISMA flow statement guidelines. Research studies were identified using keywords such as '3D Printing,' 'Future Fabrication,' 3D Printing Applications'' and '2010-2024'. Additionally, various electronic databases and manual searches on Google Scholar were conducted to collect relevant studies for this review. The inclusion criteria focused on studies conducted in English and studies on 3d printing, modern dosage form fabrication and its applications between 2010 and 2024 in different world regions. Only studies published in English were considered. The Prisma flow chart and appraisal tool for systematic review are given in Figure 1 and Table 1, respectively.

Exclusion Criteria

The exclusion criteria included:

- Conventional dosage form design.
- Traditional methods of formulation development.
- Research articles written in languages other than English.
- Studies conducted before 2010.

Data Extraction

The extracted data from the included studies comprised author details, the year of the study, the 3D printing device, its history, construction, fabrication procedure and application.

The PRISMA 2020 statement: an updated guideline for reporting systematic reviews.

For more information, visit:http://www.prisma-statement.org/

3D printing devices

Fused Deposition Modeling (FDM)

In 1988, Steven Scott Crump developed the Fused Deposition Modeling (FDM) method, later founding Stratasys and commercializing the process in the following year (Günaydın and Süleyman Türkmen, 2018). FDM has since become a widely used 3D printing technique for drug delivery systems (Goyanes *et al.*, 2015).

FDM facilitates the creation of hollow objects and dosage forms with varied drug release profiles, offering high-resolution and precise dosage control through computer settings (Goyanes *et al.*, 2015). The components of fused deposition modeling include a Filament roll from where the filament holds drug and polymer passes towards heated rollers. The heated material is released from the nozzle to a moveable base/platform, where 3D objects are prepared. The graphical representation of fused deposition modeling is shown in Figure 2.

Fused Deposition Modeling (FDM) operates by passing an extruded polymer filament through a heated coil, melting the polymer, which is then deposited onto a platform where it solidifies. By relying on these solidified layers, a 3D object is formed. FDM enables the creation of hollow objects and dosage forms with varying drug release profiles by adjusting the formulation's infill density or surface area-to-volume ratio. This technique, known as Hot-Melt Extrusion (HME), is commonly used in the pharmaceutical industry to integrate drugs within a carrier matrix at the molecular level, allowing for

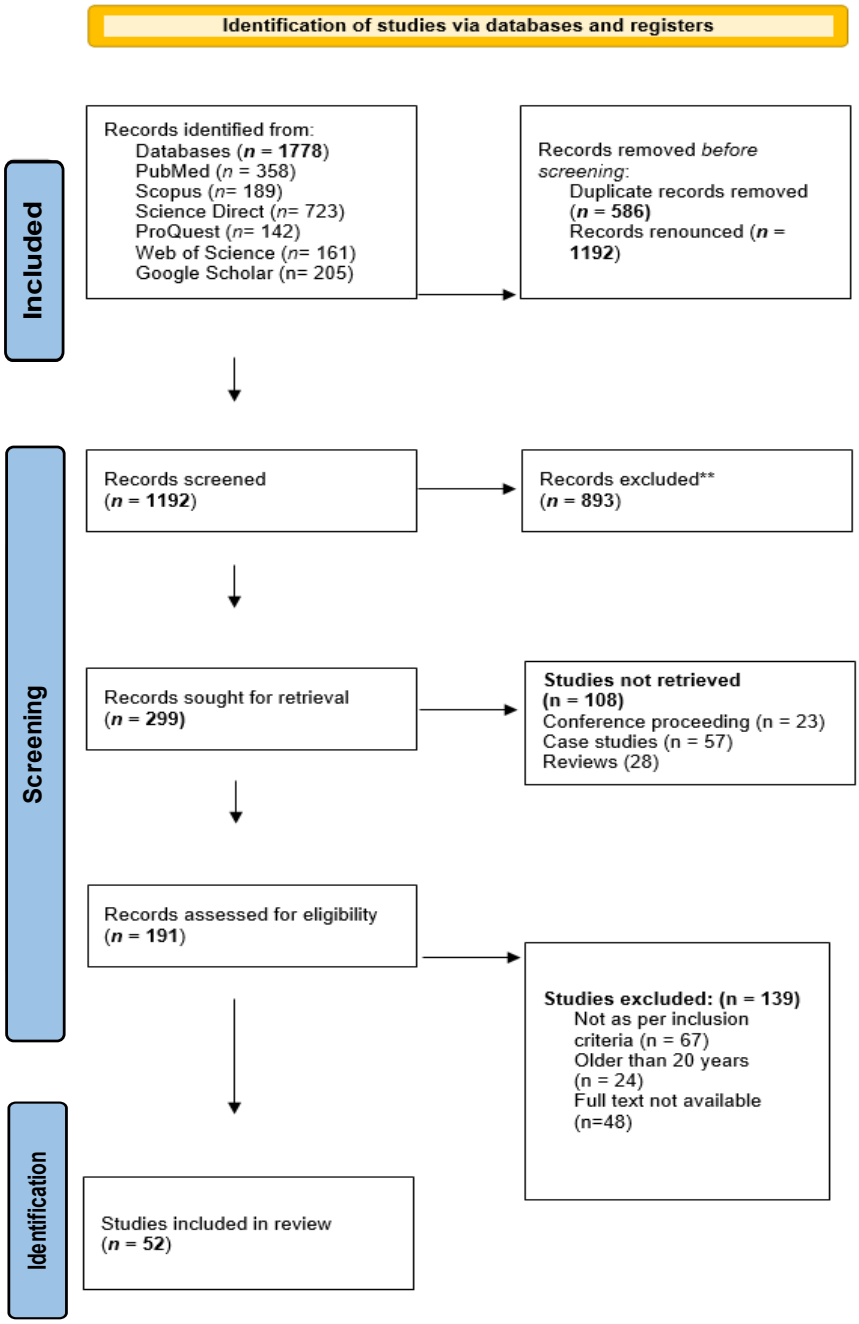

Figure 1: PRISMA flow diagram for systematic review.

the development of solid solutions for drug delivery systems with higher drug-loading capacity (Goyanes *et al.*, 2015).

Microfluidics is used for nanoparticles, with reactors essentially made from conventional materials. 3D printing is being used, with fused deposition modeling being a less expensive option (Bressan *et al.*, 2019). Fused deposition modeling, in which an extruded polymer crosses through a heating coil. The polymer softens by heat and then is placed onto a plate to solidify. Then, layers of hardened polymer are deposited and form a 3D object. This printing method can form hollow objects and dosage forms in different drug release profiles. The final step involves adjusting the surface area-to-volume ratio or infill density of the formulation. Compared to earlier printing methods, FDM 3D printing provides higher resolution and allows for improved dosage precision, which can be readily adjusted by modifying computer settings (Goyanes *et al.*, 2015).

Selective Laser Sintering technique (SLS)

SLS, a 3D printing technique, is utilized for the development of innovative solid dosage forms (Fina *et al.*, 2018). At room temperature, this method is advantageous for producing objects with good resolution (Fina *et al.*, 2017).

The study's objective is to show that SLS is easy to use to form novel solid dosage forms with instant drug release qualities to

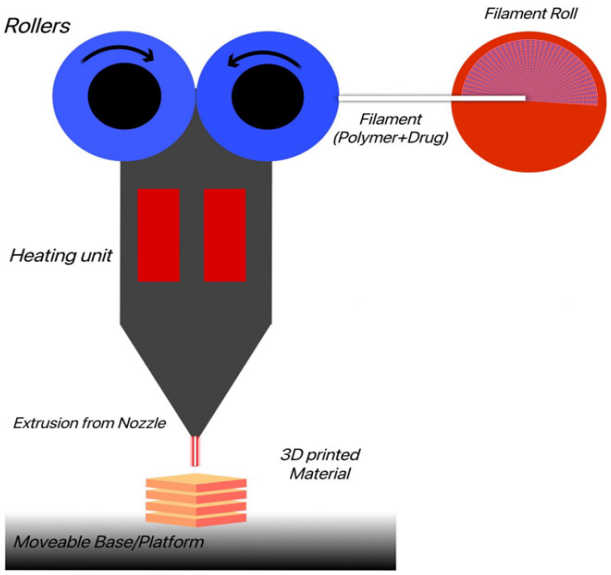

Figure 2: Fused Deposition Modelling.

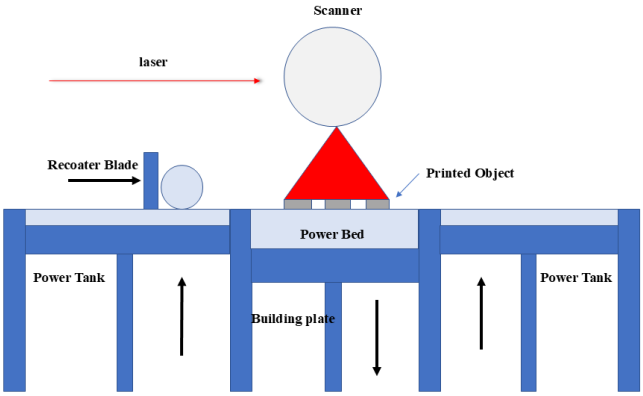

Figure 3: Selective Laser Sintering.

make the oral disintegrating formulations (Fina *et al.*, 2018). The components of SLS are a Laser, scanner, recoated blade, power bed, power tank and building plate as shown in Figure 3 (Fina *et al.*, 2017).

Copolymers and polymers were combined individually with colorant and 5% active ingredient. The powder mixtures were then printed using SLS technology to form printlet. Printlets hold active ingredients, which have recently been produced by using various 3-D printing processes called stereolithography. Drug-containing photopolymerizable polymer solution is solidified using a laser with SLA technology. At room temperature, this method has the advantage of forming objects with good resolution (Fina *et al.*, 2017).

Stereolithography (SLA)

Stereolithography is a fast, economical, one-step method for producing multi-scale aspects and combining them with

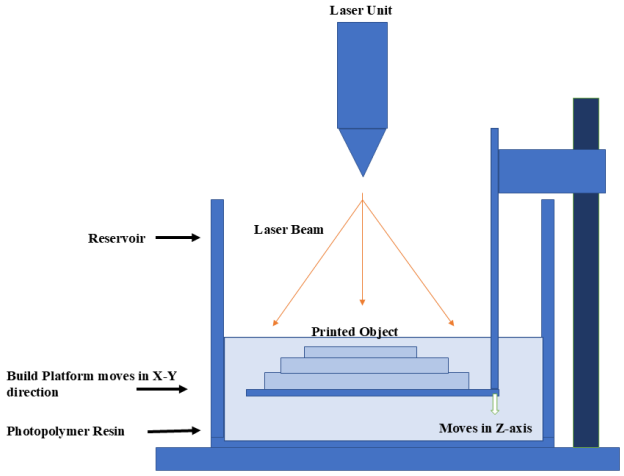

Figure 4: Stereo Lithography (SLA).

microfluidic-microneedle devices at the same time (Yeung *et al.*, 2019). Among the various forms of 3D printing, Stereo Lithography (SLA) stands out for its capability to create objects through the formation of interconnected polymer matrices via resin cross-linking (Cho *et al.*, 2018).

3D printing has emerged as a powerful technique for fabricating 3D nanogels. Nanogels are hydrogels formed by cross-linking nanoscopic micelles dispersed in a liquid medium. Most nanogels are produced by incorporating drug(s) or photo-initiator-loaded nanoparticles, liposomes, or nano-emulsions into hydrogels using 3D printing methods (Cho *et al.*, 2018). To enhance the capabilities of Stereo Lithography (SLA), components typically include a resin vat, UV chamber, biocompatible resins and composite materials, as illustrated in Figure 4 (Yeung *et al.*, 2019).

Stereolithography exhibits a vat polymerization process. In resin vat, the laser is directed to a certain depth, resulting in localized polymerization and consequent solidification. The intensity of the light source, scanning speed, exposure time, quantity of polymer and photo-initiator employed and various other factors collectively determine the energy imparted by the laser during SLA printing. Layer-by-layer solidification proceeds until a complete, three-dimensional object is produced (Wang *et al.*, 2016). A new composite substance with added metal is necessary to enhance the SLA application and mechanical properties. Ag nanoparticles are a promising class of nanofillers for obtaining composites with optical and electrical properties, hence expanding the range of applications for SLA into domains such as biomedical or electronic.

In the manufacturing of patches, the solidification of liquid resin to obtain the desired object in the SLA method relies on photopolymerization. Solidification is continued until solid; the 3D object is manufactured (Wang *et al.*, 2016). An SLA printer and Class IIa biocompatible resin were utilized to create a microfluidic-enabled microneedle device. The product

Table 1: ZEE tool for studies assessment (Appraisal tool).

Parameters	Study 1 (Gaurkhede *et al.*, 2021)	Study 2 (Tan and Maniruzzaman, 2019)	Study 3 (Glukhova *et al.*, 2022)	Study 4 (Li *et al.*,2018)	Study 5 (Sen *et al.*, 2020)	Study 6 (Nober et l.,2019)	Study 7 (Wang *et al.*, 2016)	Study 8 (Khaled *et al.*, 2015)	Study 9 (Erkus *et al.*, 2023)	Study 10(Petrová *et al.*, 2024)	Study 11(Yeung *et al.*, 2019)	Study 12 (Chen *et al.*, 2022)	Study 13 (Bressan *et al.*, 2019)	Study 14(Valencia *et al.*, 2022)	Study 15 (Sharma *et al.*, 2022)	Study 16 (Goyanes *et al.*, 2015)	Study 17 (Pereira *et al.*, 2019)	Study 18 (Fina *et al.*, 2018)	Study 19 (Fina *et al.*, 2017)	Study 20 (Cho and Jammalamadaka, 2018)	Study21 (Chan *et al.*, 2024)	Study 22 (He *et al.*, 2023)	Study 23 (Ballacchino *et al.*, 2021)	Study 24 (Wang *et al.*, 2016)	Study 25 (Arcaute and Mann, 2010)	Study 26 (Curti and Kirby, 2024)	Study 27 (Xu *et al.*, 2020)	Study 28 (Linares *et al.*, 2023)	Study 29 (Eosoly *et al.*, 2010)	Study 30 (Pandav and Karanwad, 2024)
Are study objectives specific?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Is the study design suitable for aims?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Was the basic data adequately described?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Were results internally consistent?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Were the results presented for all the analyses described in the methods?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Are discussion and conclusions justified by results?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Were the limitations of the study discussed?	×	✓	✓	✓	✓	×	×	×	×	×	×	×	×	×	✓	×	×	×	×	×	×	×	×	×	✓	×	×	×	×	×
Is there any conflict of interest that might affect study findings?	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×

Parameters	Study 31 (Fina *et al.*, 2017) (Fina *et al.*, 2017)	Study 32 (Lekurwale and Karanwad, 2022)	Study 33 (Fina *et al.*, 2018)	Study 34 (Adamov *et al.*, 2022)	Study 35(Kadry *et al.*, 2019)	Study36 (Xu *et al.*, 2021)	Study 37 (Wu *et al.*, 2019)	Study 38 (Yang *et al.*,2020)	Study 39 (Madžarević, 2021)	Study 40 (Xu *et al.*, 2021)	Study 41 (Li *et al.*, 2022)	Study 42 (Papadimitriou *et al.*, 2022)	Study 43 (Xenikakis and Tsongas, 2021)	Study 44 (Cristaldi *et al.*, 2021)	Study 45 (Cristaldi, 2020)	Study 46 (De Grandi *et al.*, 2022)	Study 47 (He *et al.*, 2023)	Study 48 (Tan and Maniruzzaman, 2018)	Study 49 (Cailleaux and Sanchez-Ballester, 2021)	Study 50 (Mathew *et al.*, 2020)	Study51 (Pires *et al.*, 2020)	Study 52(Khalid, 2022)
Are study objectives specific?	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Is the study design suitable for aims?	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Was the basic data adequately described?	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Were results internally consistent?	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Were the results presented for all the analyses described in the methods?	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Are discussion and conclusions justified by results?	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Were the limitations of the study discussed?	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Is there any conflict of interest that might affect study findings?	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×

underwent preprocessing using 3D printer preparation software and was designed using Computer-Aided Design (CAD) software. To enhance productivity and quality, the object was positioned at a 45º angle. To optimize the stiffness and strength of the microneedle patch, SLA-printed components were cleaned in isopropyl alcohol for 5 min and then cured in a UV chamber with a 405nm wavelength at 80ºC for 20 min. A single-piece, three-dimensional microfluidic device with a multi-inlet and integrated hollow microneedle array was produced using SLA 3D printing. Underneath the construction platform is an optical window through which the printer in use applies UV light, enabling additive manufacturing of the intended model through the layer-after-layer curing of photopolymer resin inside the resin tank (Yeung *et al.*, 2019).

Digital Light Processing (DLP)

It is a 3D printing technique based on photopolymerization. By this technique, irradiation photopolymer hardens layer by layer as the sections of the model are stick out onto the liquid photopolymer's surface by the digital micromirror element (Erkus *et al.*, 2023).

Digital light processing is a helpful technique for producing a digital workflow for personalized medicine. There is evidence of its effectiveness in applications in biomedical areas such as dental prostheses and tissue engineering (Yang *et al.*, 2020). The initial functional component is a digital micromirror device made of several adjustable mirror sizes of microns, as shown in Figure 5.

This method employs light sources that direct light onto photosensitive material using an array of chipsets based on optical microelectromechanical technology. A rotating mirror controls the path of light, projecting it onto photosensitive resins. The resolution of digital light processing-based 3D printing is determined by the projection plane, which is modified by the DMD (Digital Micromirror Device) and lens. Ultimately, digital

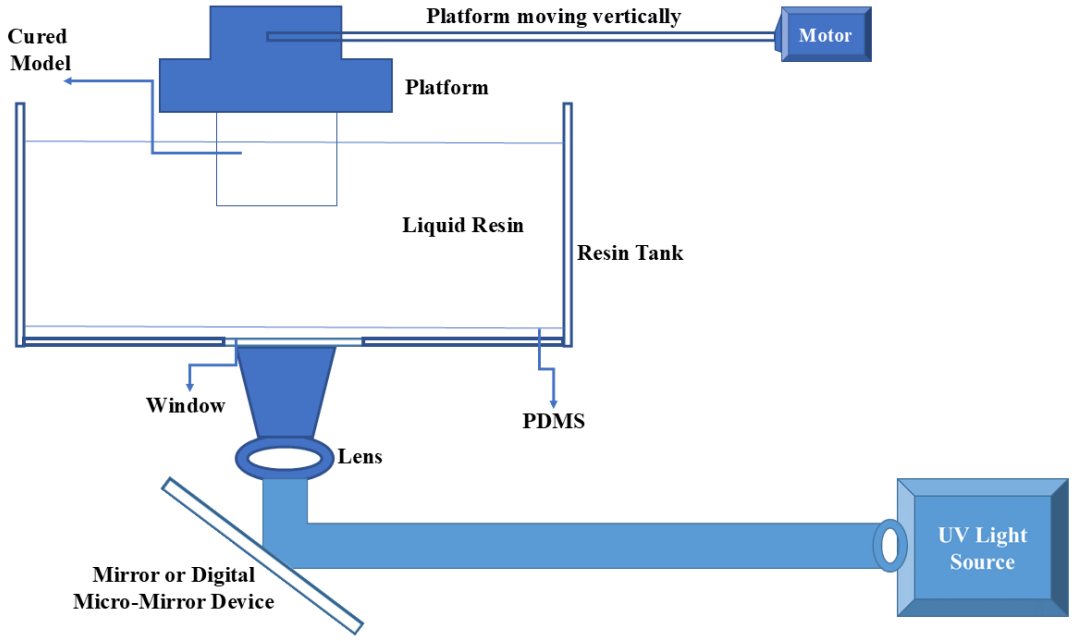

Figure 5: Digital Light Processing.

light processing achieves high-resolution (Zhang *et al.*, 2020). Microneedles were prepared with the help of a computer-aided program named Tinker CAD. After printing, every patch consisted of 36 conical microneedles measuring 1mm in diameter and 1.5 mm in height. After being changed to STL format, the design was connected to the Lumen X 3D printer. In the printing process, a solvent and resin are utilized. Following printing, the patch was gently removed, rinsed in 70% ethanol and then exposed to a UV chamber for 1 min (Petrová *et al.*, 2024). In contrast to other techniques, DLP is less susceptible to oxygen inhibition. As compared to the rest of the 3D printing techniques, DLP provides higher resolution and faster printing (Erkus *et al.*, 2023). Rapid modifications to the final patch's size and shape are another merit of employing DLP printing, contrary to the conventional method (Petrová *et al.*, 2024).

LCD-printed microfluidic devices

LCD 3D printing, combined with specially formulated ink, paves the way for anyone, anywhere, to access high-resolution formulating of ready-to-use microfluidic and organ-on-a-chip devices. This technology even holds promise for the preparation of liposomes (He *et al.*, 2023).

The liposomes made with microfluidics have better encapsulation efficiency than other techniques (Ballacchino *et al.*, 2021). Printer platform, printed object, resin vat, power switch, USB port, LED source, touch screen and platform securing knob as shown in Figure 6 (Ballacchino *et al.*, 2021).

The designed microfluidic devices were used in this work to manufacture liposomes. It entails the fabrication of various microfluidic structures, particularly Y-shaped mixers, featuring different configurations with two inlets and one outlet. A continuous flow of lipids in an alcohol solution and another in a wet solution pass through separate channels. Liposome production is achieved by merging these two channels where the streams converge. Therefore, the mixing is determined by the diffusion process occurring at the boundary between liquids, resulting in the formation of micelles as the lipids precipitate in the wet solutions, followed by the formation of liposomes (Ballacchino *et al.*, 2021).

3D-printed Reactor-in-a-Centrifuge (RIAC) device

RIAC is a simple, pump-free technique that requires a 3D-printed flow-through reactor and is powered by a standard centrifuge (Andrea *et al.*, 2021).

The RIAC device is used to formulate liposomes and silver nanospheres, which are used in the production of nanoparticles (Andrea *et al.*, 2021). The components used in the formulation of liposomes are the reservoir, centrifuge tube, polymer stabilizer and test tube, as shown in Figure 7 (He *et al.*, 2023).

Another device is a 3D-printed RIAC device in which a single reservoir was pipetted with a lipid solution of 2 mL, which contained different molar ratios of stabilizer, solubilizer, surfactant, polymer stabilizer and membrane stabilizer to produce liposomes and optimize the formulation parameters. After being preheated to the appropriate temperature, Deionized water was transferred into the second reservoir. Additionally, 6 mL of water was added to the bottom of a 50 mL centrifuge tube containing the RIAC. This water addition was aimed at reducing

the tendency of liposomes to aggregate. Increasing this volume beyond 6 mL would not significantly alter the properties of the liposomes. However, modifying production parameters such as time (between 1000 and 2000 cf) and centrifugal force would further decrease the concentration of liposomes in the final product (He *et al.*, 2023).

Applications of 3d Printed Devices

Fused Deposition Modelling (FDM)

FDM provides cost-effectiveness, design flexibility and exceptional reproducibility in pharmaceutical production procedures (Tan *et al.*, 2018). This technology aids the production of complicated geometries swiftly from digital design without any necessity of moulds or other traditional industrial procedures (Cailleaux *et al.*, 2021). FDM printing technology can be utilized in the development of Controlled-release and floating gastroretentive tablets. Due to its accuracy, versatility and ease of use in producing various dosage forms, including implants, capsules, films and adhesives, 3D printing by fused deposition modeling contains great potential for therapeutic customization (Pires *et al.*, 2020). Solid dispersions can enhance the solubility of APIs by utilizing suitable polymers. Combining solid dispersions with FDM offers new technological possibilities that address the challenge of low API solubility (Khalid and Billa, 2022).

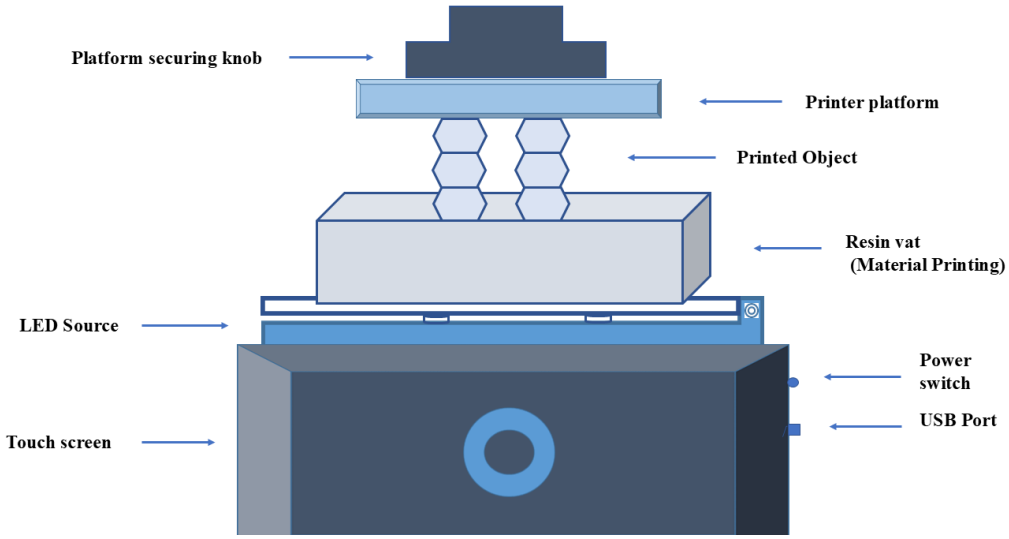

Figure 6: LCD Printed Microfluidic Device.

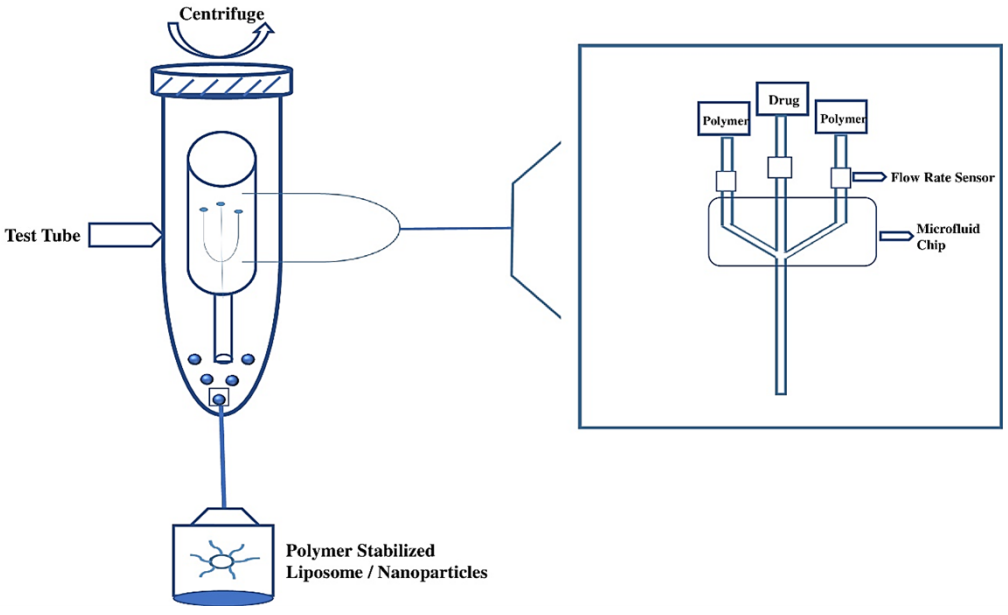

Figure 7: Reactor in a centrifuge (RIAC) Device.

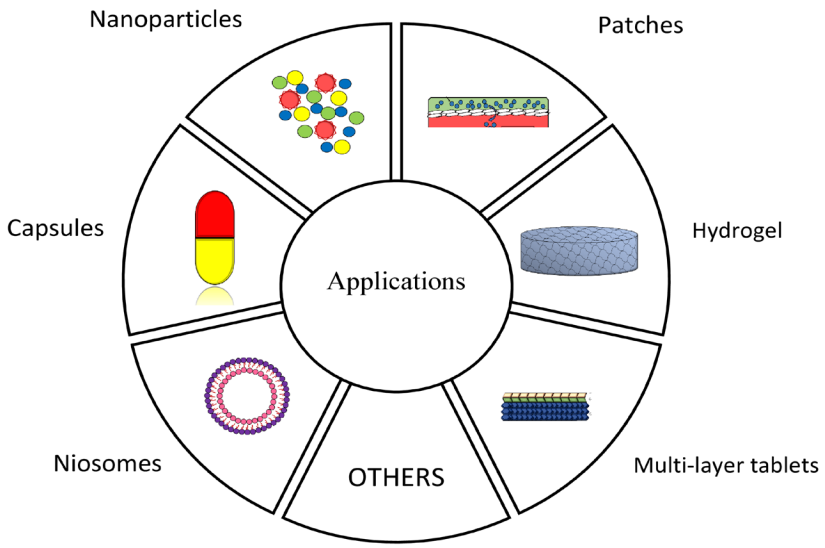

Figure 8: Application of 3D Printing Devices.

Stereolithography (SLA)

SLA is used for the development of controlled-release drug delivery (Xu *et al*., 2020). It finds applications in the field of tissue engineering. SLA is used to develop multi-material 3-D structures with specified characteristics (Arcaute and Mann, 2010). SLA is also used for thermolabile drugs and avoids flowability issues (Arcaute *et al*., 2010). SLA can form printable resins (Linares *et al*., 2023).

Selective Laser Sintering (SLS)

SLS printers are capable of producing bilayer objects. In industries, SLS is used for different manufacturing processes, such as plastic, metallic and ceramic products. The necessity of excipients and solvents can be minimized. Also, it recycles and reprocesses feedstock. SLS is used to form porous scaffolds with intricate geometries both internally and externally. SLS devices produce SLS-mediated hollow capsular shells (Linares *et al*., 2023).

Digital Light Processing (DLP)

DLP is effective for establishing a digital workflow in personalized medicine, as evidenced by its applications in biomedical fields such as dental prostheses and tissue engineering. Hydrogel, microneedles and dental models can be manufactured (Pandav *et al*., 2024). Drug delivery systems such as nose patches, intravaginal rings, oral dosage forms, bladder devices, microneedles and dental implants can be produced with the help of DLP (Adamov *et al*., 2022). It is also used in computational imaging, multiplexing and hyperspectral imaging (Xu *et al*., 2021). Designing acrylate-based photosensitive resin through 4D printing can be done through DLP (Kadry *et al*., 2019).

LCD 3D Printer

Liquid Crystal Display (LCD) technology is utilized to manufacture solid oral dosage forms, where active substances can be blended with photopolymer before printing and encapsulated within solidified matrices (Wu *et al*., 2019). In mobile-based pharmaceutical supply systems it is clearly advantageous for patients who live far away, as it improves access to healthcare by allowing them to receive their medications directly (Madžarević and Ibrić, 2021). Liquid crystal display 3D printing helps in the formulation of different placebo moulds of VOR tablets (Xu *et al*., 2021). Microneedle arrays are successfully constructed employing 3D printing methods such as liquid crystal display (Papadimitriou *et al*., 2022). By using a liquid crystal display, the human microneedles were fabricated, which provides the accuracy that is essential for microstructures like human Microneedles (Papadimitriou *et al*., 2022).

Reactor in a Centrifuge (RIAC)

The efficacy and accuracy of the reactors were demonstrated through the production of inorganic and organic nanoparticles. It is used in the formulation of nanoscale liposomes within the required size range, that is, diameter (80-300 nm). It is also used to produce silver nanospheres at selected operational settings, which have significance in drug delivery for infectious and cancerous disease treatment and imaging techniques. Cationic liposomes have become a necessary DDS due to the advancement in the fields of gene therapy and mRNA-based vaccines. Due to their compatibility and effectual transfection, results have led to the development of functionalized liposomal formulation through RIAC. RIAC is used to formulate liposomes and silver nanospheres (Andrea *et al*., 2021). The graphical representation of the 3d printing application is illustrated in Figure 8.

CONCLUSION

This review comprehensively explored the development procedures and diverse applications of 3D printing technologies in fabricating a range of drug delivery systems. From FDM-printed controlled-release tablets to DLP-manufactured microneedles, 3D printing offers unparalleled flexibility and customization compared to traditional methods. Notably, 3D printing empowers the creation of personalized medicine, a prospect previously limited by conventional manufacturing. While challenges like high costs and complex material requirements remain, 3D printing undoubtedly presents a transformative platform for the pharmaceutical industry, paving the way for more precise, patient-centric and on-demand drug delivery systems.

ACKNOWLEDGEMENT

We want to extend our sincere gratitude to the Deanship of the Faculty of Pharmaceutical Sciences at Lahore University of Biological and Applied Sciences (UBAS) for providing the necessary resources and support that made this research possible. Their commitment to fostering academic excellence has been invaluable.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ABBREVIATIONS

FDM: Fused Deposition Modeling; **RIAC:** Reactor in a centrifuge; **SLA:** Stereo lithography; **DLP:** Digital Light Processing; **HME:** Hot-melt extrusion; **DDS:** Drug delivery system; **LCD:** Liquid Crystal Display; **CAD:** Computer-Aided Design; **DMD:** Digital Micromirror Device; **FDA:** Food and drug administration; **Ag:** Silver.

REFERENCES

Adamov, I., Stanojević, G., & Medarević, D., … BII journal of. (2022a)•Elsevier [Internet]. undefined. Formulation and characterization of immediate-release oral dosage forms with zolpidem tartrate fabricated by digital light processing (DLP) 3D printing technique. ElsevierI Adamov, G Stanojević, D Medarević, B Ivković, D Kočović, D Mirković, S IbrićInternational journal of pharmaceutics p. 2022. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0378517322006019

Adamov, I., Stanojević, G., & Medarević, D., … BII journal of. (2022b)•Elsevier [Internet]. undefined. Formulation and characterization of immediate-release oral dosage forms with zolpidem tartrate fabricated by digital light processing (DLP) 3D printing technique. ElsevierI Adamov, G Stanojević, D Medarević, B Ivković, D Kočović, D Mirković, S IbrićInternational journal of pharmaceutics p. 2022. Retrieved July 17, 2024. https://www.sciencedirect.com/science/article/pii/S0378517322006019

Andrea Cristaldi, D., Labanca, A., Donal Pottinger, T., Owen, J., Stulz, E., Zhang, X., & Carugo, D. (2021). 3D printed reactor-in-a-centrifuge (RIAC): Making flow-synthesis of nanoparticles pump-free and cost-effective. Chemical Engineering Journal, 425, 3D. https://doi.org/10.1016/j.cej.2021.130656

Arcaute, K., & Mann, B. (2010)•Elsevier [Internet]. biomaterialia RWA, 2010 undefined. Stereolithography of spatially controlled multi-material bioactive poly (ethylene glycol) scaffolds. ElsevierK Arcaute, B Mann, R WickerActa biomaterialia, 2009 Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S1742706109003559

Arcaute, K., Mann, B., & Wicker, R. (2010). Stereolithography of spatially controlled multi-material bioactive poly(ethylene glycol) scaffolds. Acta Biomaterialia, 6(3), 1047–1054. https://doi.org/10.1016/j.actbio.2009.08.017

Ballacchino, G., Weaver, E., & Mathew, E., ... RDIJ of. undefined. Manufacturing of 3D-printed microfluidic devices for the synthesis of drug-loaded liposomal formulations p. 2021. mdpi.comG Ballacchino, E Weaver, E Mathew, R Dorati, I Genta, B Conti, DA LamprouInternational Journal of Molecular Sciences, 2021•mdpi.com [Internet]. [cited 2024 Jul 29]; Available from: https://www.mdpi.com/1422-0067/22/15/8064

Ballacchino, G., Weaver, E., Mathew, E., Dorati, R., Genta, I., Conti, B., & Lamprou, D. A. (2021). Manufacturing of 3d-printed microfluidic devices for the synthesis of drug-loaded liposomal formulations. International Journal of Molecular Sciences, 22(15). https://doi.org/10.3390/ijms22158064

Bressan, L., Robles-Najar, J., Adamo, C., … R. Q. M. (2019)•Elsevier [Internet]. 2019 undefined. 3D-printed microfluidic device for the synthesis of silver and gold nanoparticles. ElsevierLP Bressan, J Robles-Najar, CB Adamo, RF Quero. BMC, DP de Jesus, JAF da SilvaMicrochemical journal. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0026265X18314425

Bressan, L. P., Robles-Najar, J., Adamo, C. B., Quero, R. F., Costa, B. M. C., de Jesus, D. P., & da Silva, J. A. F. (2019). 3D-printed microfluidic device for the synthesis of silver and gold nanoparticles. Microchemical Journal, 146, 1083–1089. https://doi.org/10.1016/j.microc.2019.02.043

Cailleaux, S., & Sanchez-Ballester, N., ... YGJ of controlled. (2021)•Elsevier [Internet]. undefined. Fused deposition modeling (FDM), the new asset for the production of tailored medicines. ElsevierS Cailleaux, NM Sanchez-Ballester, YA Gueche, B Bataille, I SoulairolJournal of controlled release p. 2021. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0168365920306374

Cailleaux, S., Sanchez-Ballester, N. M., Gueche, Y. A., Bataille, B., & Soulairol, I. (2021). Fused deposition modeling (FDM), the new asset for the production of tailored medicines. Journal of Controlled Release, 330, 821–841. https://doi.org/10.1016/j.jconrel.2020.10.056

Chan, A. K. C., Ranjitham Gopalakrishnan, N., Traore, Y. L., & Ho, E. A. (2024). Formulating biopharmaceuticals using three-dimensional printing. Journal of Pharmacy and Pharmaceutical Sciences, 27, 12797. https://doi.org/10.3389/jpps.2024.12797

Chen, Z., Wu, H., Zhao, S., Chen, X., Wei, T., Peng, H., & Chen, Z. (2022, September 5). 3D-printed integrated ultrasonic microneedle array for rapid transdermal drug delivery. Molecular Pharmaceutics, 19(9), 3314–3322. https://doi.org/10.1021/acs.molpharmaceut.2c00466

Cho, H., & Jammalamadaka, U. (2018). Materials KT, 2018 undefined. Nanogels for pharmaceutical and biomedical applications and their fabrication using 3D printing technologies. H Cho, U Jammalamadaka, K TappaMaterials, 2018. mdpi.com. mdpi.com [Internet] Retrieved July 29, 2024. https://www.mdpi.com/1996-1944/11/2/302

Cho, H., Jammalamadaka, U., & Tappa, K. (2018). Nanogels for pharmaceutical and biomedical applications and their fabrication using 3D printing technologies. Materials, 11(2). https://doi.org/10.3390/ma11020302

Cristaldi, D. Continuous-flow reactors for large-scale production of nanoparticles. 2020 Retrieved July 29, 2024. https://eprints.soton.ac.uk/474658/

Cristaldi, D., Labanca, A., Pottinger, T., … JOCE. 2021 undefined, 3d printed reactor-in-a-centrifuge (RIAC): Making flow-synthesis of nanoparticles pump-free and cost-effective. ElsevierDA Cristaldi, A Labanca, TD Pottinger, J Owen, E Stulz, X Zhang, D CarugoChemical Engineering Journal, 2021•Elsevier [Internet]. [cited 2024 Jul 29]; Available from: https://www.sciencedirect.com/science/article/pii/S1385894721022427.

Curti, C., & Kirby, D. (2024)•Elsevier [Internet]. Pharmaceutics CRIJ of, 2024 undefined. Systematic screening of photopolymer resins for stereolithography (SLA) 3D printing of solid oral dosage forms: Investigation of formulation factors on. ElsevierC Curti, DJ Kirby, CA RussellInternational. Journal of Pharmaceutics. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0378517324000966

Curti, C., Kirby, D. J., & Russell, C. A. (2024). Systematic screening of photopolymer resins for stereolithography (SLA) 3D printing of solid oral dosage forms: Investigation of formulation factors on printability outcomes. International Journal of Pharmaceutics, 653, 123862. https://doi.org/10.1016/j.ijpharm.2024.123862

De Grandi, D., Meghdadi, A., & LuTheryn, G., advances DCR. (2022). undefined. Facile production of quercetin nanoparticles using 3D printed centrifugal flow reactors. D De Grandi, A Meghdadi, G LuTheryn, D CarugoRSC advances, 2022 p. 2022. pubs.rsc.org. pubs.rsc.org [Internet] Retrieved July 29, 2024. https://pubs.rsc.org/en/content/articlehtml/2022/ra/d2ra02745c

Eosoly, S., Brabazon, D., & Lohfeld, S. (2010)•Elsevier [Internet]. biomaterialia LLA, 2010 undefined. Selective laser sintering of hydroxyapatite/polyε-caprolactone scaffolds. ElsevierS Eosoly, D Brabazon, S Lohfeld, L LooneyActa biomaterialia. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S1742706109002992

Erkus, H., Bedir, T., Kaya, E., & Tinaz, G. Materialia OG, 2023 undefined. Innovative transdermal drug delivery system based on amoxicillin-loaded gelatin methacryloyl microneedles obtained by 3D printing. Elsevier [Internet]. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S2589152923000285

Erkus, H., Bedir, T., Kaya, E., Tinaz, G. B., Gunduz, O., Chifiriuc, M.-C., & Ustundag, C. B. (2023). Innovative transdermal drug delivery system based on amoxicillin-loaded gelatin methacryloyl microneedles obtained by 3D printing. Materialia, 27. https://doi.org/10.1016/j.mtla.2023.101700

Fina, F., Goyanes, A., & Gaisford, S. (2017)•Elsevier [Internet]. of ABI journal, 2017 undefined. Selective laser sintering (SLS) 3D printing of medicines. ElsevierF Fina, A Goyanes, S Gaisford, AW BasitInternational journal of pharmaceutics. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0378517317305902

Fina, F., Goyanes, A., Gaisford, S., & Basit, A. W. (2017). Selective laser sintering (SLS) 3D printing of medicines. International Journal of Pharmacy, 529(1-2).

Fina, F., Goyanes, A., & Madla, C., … AAI journal of, 2018. undefined. 3D printing of drug-loaded gyroid lattices using selective laser sintering. ElsevierF Fina, A Goyanes, CM Madla, A Awad, SJ Trenfield, JM Kuek, P Patel, S Gaisford, AW BasitInternational journal of pharmaceutics, 2018•Elsevier [Internet]. [cited 2024 Jul 29]; Available from: https://www.sciencedirect.com/science/article/pii/S0378517318303545.

Fina, F., Madla, C., & Goyanes, A., … JZI journal of, 2018. undefined. Fabricating 3D printed orally disintegrating printlets using selective laser sintering. ElsevierF Fina, CM Madla, A Goyanes, J Zhang, S Gaisford, AW BasitInternational journal of pharmaceutics, 2018•Elsevier [Internet]. [cited 2024 Jul 29]; Available from: https://www.sciencedirect.com/science/article/pii/S0378517318300966.

Fina, F., Madla, C. M., Goyanes, A., Zhang, J., Gaisford, S., & Basit, A. W. (2018). Fabricating 3D printed orally disintegrating printlets using selective laser sintering. International Journal of Pharmaceutics, 541 (1–2), 101–107. https://doi.org/10.1016/j.ijpharm.2018.02.015

Gaurkhede, S. G., Osipitan, O. O., Dromgoole, G., Spencer, S. A., Pasqua, A. J. D., & Deng, J. (2021). 3D printing and dissolution testing of novel capsule shells for use in delivering acetaminophen. Journal of Pharmaceutical Sciences, 110(12), 3829–3837. https://doi.org/10.1016/j.xphs.2021.08.030

Glukhova, S., Molchanov, V., . . . Y. C. C. 2022 undefined. Green nanocomposite gels based on binary network of sodium alginate and percolating halloysite clay nanotubes for 3D printing. ElsevierSA Glukhova, VS Molchanov, YM Chesnokov, BV Lokshin, EP Kharitonova, OE PhilippovaCarbohydrate Polymers, 2022•Elsevier [Internet]. [cited 2024 Jul 29]; Available from: https://www.sciencedirect.com/science/article/pii/S0144861722000108.

Glukhova, S. A., Molchanov, V. S., Chesnokov, Y. M., Lokshin, B. V., Kharitonova, E. P., & Philippova, O. E. (2022). Green nanocomposite gels based on binary network of sodium alginate and percolating halloysite clay nanotubes for 3D printing. Carbohydrate Polymers, 282, 119106. https://doi.org/10.1016/j.carbpol.2022.119106

Goyanes, A., Chang, H., & Sedough, D., ... GHI journal of. (2015)•Elsevier [Internet]. undefined. Fabrication of controlled-release budesonide tablets via desktop (FDM) 3D printing. ElsevierA Goyanes, H Chang, D Sedough, GB Hatton, J Wang. A Buanz, S Gaisford, AW BasitInternational journal of pharmaceutics p. 2015. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0378517315303082

Goyanes, A., Chang, H., Sedough, D., Hatton, G. B., Wang, J., Buanz, A., Gaisford, S., & Basit, A. W. (2015). Fabrication of controlled-release budesonide tablets via desktop (FDM) 3D printing. International Journal of Pharmaceutics, 496(2), 414–420. https://doi.org/10.1016/j.ijpharm.2015.10.039

He, Y., De Grandi, D. D., Chandradoss, S., Lutheryn, G., Cidonio, G., Nunes Bastos, R., Pereno, V., & Carugo, D. (2023). mdpi.com [Internet] Cited July 29, 2024. Rapid production of nanoscale liposomes using a 3D-printed reactor-in-A-centrifuge: Formulation, characterisation and super-resolution imaging. mdpi.com. Micromachines, 14(9), 1763. https://www.mdpi.com/2072-666X/14/9/1763. https://doi.org/10.3390/mi14091763

He, Y., Grandi, D., Chandradoss, S., & Micromachines, G. L. (2023). 2023 undefined. Rapid production of nanoscale liposomes using a 3D-printed reactor-in-A-centrifuge: Formulation, characterisation and super-resolution imaging. Y He, DD Grandi, S Chandradoss, G LuTheryn, G cidonio, R Nunes Bastos, V PerenoMicromachines. mdpi.com. mdpi.com [Internet]. Retrieved July 29, 2024. https://www.mdpi.com/2072-666X/14/9/1763

Jamróz, W., Szafraniec, J., Kurek, M., & Jachowicz, R. (2018). 3D printing in pharmaceutical and medical applications – Recent achievements and challenges. Pharmaceutical Research, 35(9), 176. https://doi.org/10.1007/s11095-018-2454-x

Kadry, H., Wadnap, S., & Xu, C. (2019)•Elsevier [Internet]. Pharmaceutical FAEJ of, 2019 undefined. Digital light processing (DLP) 3D-printing technology and photoreactive polymers in fabrication of modified-release tablets. ElsevierH Kadry, S Wadnap, C Xu, F AhsanEuropean. Journal of Pharmaceutical Sciences. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0928098719301794

Kadry, H., Wadnap, S., Xu, C., & Ahsan, F. (2019). Digital light processing (DLP)3D-printing technology and photoreactive polymers in fabrication of modified-release tablets. European Journal of Pharmaceutical Sciences, 135, 60–67. https://doi.org/10.1016/j.ejps.2019.05.008

Khaled, S., Burley, J., & Alexander, M., ... JYI journal of. (2015)•Elsevier [Internet]. undefined. 3D printing of tablets containing multiple drugs with defined release profiles. ElsevierSA Khaled. JC, MR Alexander, J Yang, CJ RobertsInternational journal of pharmaceutics p. 2015. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0378517315300855

Khaled, S. A., Burley, J. C., Alexander, M. R., Yang, J., & Roberts, C. J. (2015). 3D printing of tablets containing multiple drugs with defined release profiles. International Journal of Pharmaceutics, 494(2), 643–650. https://doi.org/10.1016/j.ijpharm.2015.07.067

Khalid, G. (2022). Pharmaceutics NB, 2022 undefined. Solid dispersion formulations by FDM 3D printing—A review. GM Khalid, N BillaPharmaceutics, 2022. mdpi.com. mdpi.com [Internet] Retrieved July 29, 2024. https://www.mdpi.com/1999-4923/14/4/690

Khalid, G. M., & Billa, N. (2022). Solid dispersion formulations by FDM 3D printing—A review. Pharmaceutics, 14(4). https://doi.org/10.3390/pharmaceutics14040690

Lekurwale, S., & Karanwad, T. (2022)•Elsevier [Internet]. Medicine SBA of 3D P, 2022 undefined. Selective laser sintering (SLS) of 3D printlets using a 3D printer comprised of IR/red-diode laser. ElsevierS Lekurwale, T Karanwad, S BanerjeeAnnals of 3D printed medicine. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S2666964122000108

Li, Q., Guan, X., Cui, M., Zhu, Z., Chen, K., Wen, H., Jia, D., Hou, J., Xu, W., Yang, X., & Pan, W. (2018). Preparation and investigation of novel gastro-floating tablets with 3D extrusion-based printing. International Journal of Pharmaceutics, 535 (1–2), 325–332. https://doi.org/10.1016/j.ijpharm.2017.10.037

Li, S., Pang, J., Hong, S., Chen, X., Shao, S., Wang, H., Lao, H., Xiong, L., Wu, H., Yang, W., Yang, F., . . . Yang, F., ... HWEJ of, et al. (2022). A novel technology for preparing the placebos of vortioxetine hydrobromide tablets using LCD 3D printing. ElsevierS. European Journal of Pharmaceutics and Biopharmaceutics, 178, 159–167. https://doi.org/10.1016/j.ejpb.2022.07.001 Li, J Pang, S Hong, X Chen, S Shao, H Wang, H Lao, L Xiong, H Wu, W Yang, F YangEuropean Journal of Pharmaceutics and Biopharmaceutics, 2022•Elsevier [Internet]. [cited 2024 Jul 29]; Available from: https://www.sciencedirect.com/science/article/pii/S0939641122001394

Linares, V., Casas, M., & Huwyler, J. Delivery ICJ of D, 2023 undefined. Stereolithographic 3D printing: Formulation design based on percolation thresholds. Elsevier [Internet]. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S1773224723009516

Linares, V., Casas, M., Huwyler, J., & Caraballo, I. (2023). Stereolithographic 3D printing: Formulation design based on percolation thresholds. Journal of Drug Delivery Science and Technology, 90. https://doi.org/10.1016/j.jddst.2023.105099

Madžarević, M. (2021)•Elsevier [Internet]. Sciences SIEJ of P, 2021 undefined. Evaluation of exposure time and visible light irradiation in LCD 3D printing of ibuprofen extended release tablets. ElsevierM Madžarević, S IbrićEuropean. Journal of Pharmaceutical Sciences. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0928098720304760

Madžarević, M., & Ibrić, S. (2021). Evaluation of exposure time and visible light irradiation in LCD 3D printing of ibuprofen extended release tablets. European Journal of Pharmaceutical Sciences, 158, 105688. https://doi.org/10.1016/j.ejps.2020.105688

Mathew, E., Pitzanti, G., & Larrañeta, E. Pharmaceutics. 3D printing of pharmaceuticals and drug delivery devices, DL p. 2020 undefined. mdpi.com [Internet]. Retrieved July 29, 2024. https://www.mdpi.com/1999-4923/12/3/266?TB_iframe=trueandwidth=921.6andheight=921.6

Nober, C., Manini, G., & Carlier, E., … JRI journal of, 2019. undefined. Feasibility study into the potential use of fused-deposition modeling to manufacture 3D-printed enteric capsules in compounding pharmacies. ElsevierC Nober, G Manini, E Carlier, JM Raquez, S Benali, P Dubois, K Amighi, J GooleInternational journal of pharmaceutics, 2019•Elsevier [Internet]. [cited 2024 Jul 29]; Available from: https://www.sciencedirect.com/science/article/pii/S0378517319306258.

Nober, C., Manini, G., Carlier, E., Raquez, J.-M., Benali, S., Dubois, P., Amighi, K., & Goole, J. (2019). Feasibility study into the potential use of fused-deposition modeling to manufacture 3D-printed enteric capsules in compounding pharmacies. International Journal of Pharmaceutics, 569, 118581. https://doi.org/10.1016/j.ijpharm.2019.118581

Pandav, G., & Karanwad, T. (2024)•Elsevier [Internet]. of SBJ of the MB, 2024 undefined. Sketching feasibility of additively manufactured different size gradient conventional hollow capsular shells (HCSs) by selective laser sintering (SLS): From design to. ElsevierG Pandav, T Karanwad, S BanerjeeJournal of the mechanical behavior of biomedical materials. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S1751616124000250

Pandav, G., Karanwad, T., & Banerjee, S. (2024). Sketching feasibility of additively manufactured different size gradient conventional hollow capsular shells (HCSs) by selective laser sintering (SLS): From design to applications. Journal of the Mechanical Behavior of Biomedical Materials, 151, 106393. https://doi.org/10.1016/j.jmbbm.2024.106393

Pandey, M., Choudhury, H., Fern, J. L. C., Kee, A. T. K., Kou, J., Jing, J. L. J., Her, H. C., Yong, H. S., Ming, H. C., Bhattamisra, S. K., & Gorain, B. (2020). 3D printing for oral drug delivery: A new tool to customize drug delivery. Drug Delivery and Translational Research, 10(4), 986–1001. https://doi.org/10.1007/s13346-020-00737-0

Papadimitriou, P., Andriotis, E., Fatouros, D., & Micromachines, D. T. (2022). 2022 undefined. Design and prototype fabrication of a cost-effective microneedle drug delivery apparatus using fused filament fabrication, liquid crystal display and semisolid. EG Andriotis, D Fatouros, D TzetzisMicromachines. mdpi.comP Papadimitriou. mdpi.com [Internet]. Retrieved July 29, 2024. https://www.mdpi.com/2072-666X/13/8/1319

Papadimitriou, P., Andriotis, E. G., Fatouros, D., & Tzetzis, D. (2022). Design and prototype fabrication of a cost-effective microneedle drug delivery apparatus using fused filament fabrication, liquid crystal display and semi-solid extrusion 3D printing technologies. Micromachines, 13(8). https://doi.org/10.3390/mi13081319

Pereira, B., Isreb, A., & Forbes, R., ... FDEJ of. 2019 undefined. Temporary plasticiser: A novel solution to fabricate 3D printed patient-centred cardiovascular 'Polypill'architectures. ElsevierBC Pereira, A Isreb, RT Forbes, F Dores, R Habashy, JB Petit, MA Alhnan, EF OgaEuropean Journal of Pharmaceutics and Biopharmaceutics, 2019•Elsevier [Internet]. [cited 2024 Jul 29]; Available from: https://www.sciencedirect.com/science/article/pii/S0939641118313109.

Petrová, E., Chvíla, S., Štěpánek, F., Zbytovská, J., & Lamprou, D. A. (2024). Imiquimod nanocrystal-loaded dissolving microneedles prepared by DLP printing. Drug Delivery and Translation Research.

Pires, F., Alves-Silva, I., & Pinho, L., ... JCIJ of. (2020)•Elsevier [Internet]. undefined. Predictive models of FDM 3D printing using experimental design based on pharmaceutical requirements for tablet production. ElsevierFQ Pires, I Alves-Silva, LAG Pinho, JA Chaker. LL Sa-Barreto, GM Gelfuso, T GratieriInternational. Journal of Pharmaceutics p. 2020. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0378517320307122

Pires, F. Q., Alves-Silva, I., Pinho, L. A. G., Chaker, J. A., Sa-Barreto, L. L., Gelfuso, G. M., Gratieri, T., & Cunha-Filho, M. (2020). Predictive models of FDM 3D printing using experimental design based on pharmaceutical requirements for tablet production. International Journal of Pharmaceutics, 588, 119728. https://doi.org/10.1016/j.ijpharm.2020.119728

Ramya, A., & Vanapalli, S. L. (2016). 3D printing technologies in various applications. International Journal of Mechanical Engineering and Technology, 7(3).

Samiei, N. (2020). Recent trends on applications of 3D printing technology on the design and manufacture of pharmaceutical oral formulation: A mini review. Beni-Suef University Journal of Basic and Applied Sciences, 9(1). https://doi.org/10.1186/s43088-020-00040-4

Sen, K., Manchanda, A., & Mehta, T., … AMI journal of, 2020. undefined. Formulation design for inkjet-based 3D printed tablets. ElsevierK Sen, A Manchanda, T Mehta, AWK Ma, B ChaudhuriInternational journal of pharmaceutics, 2020•Elsevier [Internet]. [cited 2024 Jul 29]; Available from: https://www.sciencedirect.com/science/article/pii/S0378517320304142.

Sen, K., Manchanda, A., Mehta, T., Ma, A. W. K., & Chaudhuri, B. (2020). Formulation design for inkjet-based 3D printed tablets. International Journal of Pharmaceutics, 584, 119430. https://doi.org/10.1016/j.ijpharm.2020.119430

Sharma, P. K., Choudhury, D., Yadav, V., Murty, U. S. N., & Banerjee, S. (2022, December). 3D printing of nanocomposite pills through desktop vat photopolymerization (stereolithography) for drug delivery reasons. 3D Printing in Medicine, 8(1), 3. https://doi.org/10.1186/s41205-022-00130-2

Tan, D., & Maniruzzaman, M. (2018). Pharmaceutics AN, 2018 undefined. Advanced pharmaceutical applications of hot-melt extrusion coupled with fused deposition modelling (FDM) 3D printing for personalised drug delivery. DK Tan, M Maniruzzaman, A NokhodchiPharmaceutics. mdpi.com. mdpi.com [Internet]. Retrieved July 29, 2024. https://www.mdpi.com/1999-4923/10/4/203

Tan, D., & Maniruzzaman, M. (2019). Polymers AN, 2019 undefined. Development and optimisation of novel polymeric compositions for sustained release theophylline caplets (PrintCap). ComDK Tan, M Maniruzzaman, A NokhodchiPolymers. MDPI. mdpi.com [Internet]. Retrieved July 29, 2024. https://www.mdpi.com/2073-4360/12/1/27

Tan, D. K., Maniruzzaman, M., & Nokhodchi, A. (2018). Advanced pharmaceutical applications of hot-melt extrusion coupled with fused deposition modelling (FDM) 3D printing for personalised drug delivery. Pharmaceutics, 10(4). https://doi.org/10.3390/pharmaceutics10040203

Tan, D. K., Maniruzzaman, M., & Nokhodchi, A. (2019). Development and optimisation of novel polymeric compositions for sustained release theophylline caplets (PrintCap) via FDM 3D printing. Polymers, 12(1). https://doi.org/10.3390/polym12010027

Valencia, L., Herrera, M., & de la Mata, M. Polymers A de L, 2022 undefined. Synthesis of silver nanocomposites for stereolithography: In situ formation of nanoparticles. mdpi.com [Internet]. Retrieved July 29, 2024. https://www.mdpi.com/2073-4360/14/6/1168

Wang, J., Goyanes, A., & Gaisford, S. (2016)•Elsevier [Internet]. of ABI journal, 2016 undefined. Stereolithographic (SLA) 3D printing of oral modified-release dosage forms. ElsevierJ Wang, A Goyanes, S Gaisford, AW BasitInternational journal of pharmaceutics. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0378517316302150

Wang, J., Goyanes, A., Gaisford, S., & Basit, A. W. (2016). Stereolithographic (SLA) 3D printing of oral modified-release dosage forms. International Journal of Pharmaceutics, 503 (1–2), 207–212. https://doi.org/10.1016/j.ijpharm.2016.03.016

Wu, H., Chen, P., Yan, C., & Cai, C. Design YSMand, 2019 undefined. Four-dimensional printing of a novel acrylate-based shape memory polymer using digital light processing. ElsevierH Wu, P Chen, C Yan, C Cai, Y ShiMaterials, and Design, 2019•Elsevier [Internet]. [cited 2024 Jul 29]; Available from: https://www.sciencedirect.com/science/article/pii/S0264127519301418.

Wu, H., Chen, P., Yan, C., Cai, C., & Shi, Y. (2019). Four-dimensional printing of a novel acrylate-based shape memory polymer using digital light processing. Materials and Design, 171. https://doi.org/10.1016/j.matdes.2019.107704

Xenikakis, I., & Tsongas, K., ... ETIJ of. (2021)•Elsevier [Internet]. undefined. Fabrication of hollow microneedles using liquid crystal display (LCD) vat polymerization 3D printing technology for transdermal macromolecular delivery. ElsevierI Xenikakis, K Tsongas, EK Tzimtzimis, CK Zacharis, N Theodoroula, EP KalogianniInternational. Journal of Pharmaceutics p. 2021. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S0378517321001071

Xenikakis, I., Tsongas, K., Tzimtzimis, E. K., Zacharis, C. K., Theodoroula, N., Kalogianni, E. P., Demiri, E., Vizirianakis, I. S., Tzetzis, D., & Fatouros, D. G. (2021). Fabrication of hollow microneedles using liquid crystal display (LCD) vat polymerization 3D printing technology for transdermal macromolecular delivery. International Journal of Pharmaceutics, 597, 120303. https://doi.org/10.1016/j.ijpharm.2021.120303

Xu, X., Awwad, S., & Diaz-Gomez, L. Pharmaceutics CAL, 2021 undefined. 3D printed punctal plugs for controlled ocular drug delivery. mdpi.comX Xu, S Awwad, L Diaz-Gomez, C Alvarez-Lorenzo, S Brocchini, S Gaisford, A GoyanesPharmaceutics, 2021•mdpi.com [Internet]. [cited 2024 Jul 29]; Available from: https://www.mdpi.com/1999-4923/13/9/1421

Xu, X., Awwad, S., Diaz-Gomez, L., Alvarez-Lorenzo, C., Brocchini, S., Gaisford, S., Goyanes, A., & Basit, A. W. (2021). 3d printed punctal plugs for controlled ocular drug delivery. Pharmaceutics, 13(9). https://doi.org/10.3390/pharmaceutics13091421

Xu, X., Robles-Martinez, P., Madla, C., . . . F. J. A. (2020)•Elsevier [Internet]. 2020 undefined. Stereolithography (SLA) 3D printing of an antihypertensive polyprintlet: Case study of an unexpected photopolymer-drug reaction. ElsevierX Xu, P Robles-Martinez, CM Madla, F Joubert. A Goyanes, AW Basit, S GaisfordAdditive manufacturing. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S2214860419314356

Xu, X., Robles-Martinez, P., Madla, C. M., Joubert, F., Goyanes, A., Basit, A. W., & Gaisford, S. (2020). Stereolithography (SLA) 3D printing of an antihypertensive polyprintlet: Case study of an unexpected photopolymer-drug reaction. Additive Manufacturing, 33. https://doi.org/10.1016/j.addma.2020.101071

Xu, X., Seijo-Rabina, A., & Awad, A., ... CRIJ of. (2021)•Elsevier [Internet]. undefined. Smartphone-enabled 3D printing of medicines. ElsevierX Xu, A Seijo-Rabina, A Awad, C Rial. S Gaisford, AW Basit, A GoyanesInternational. Journal of Pharmaceutics p. 2021. Retrieved July 29, 2024. https://www.sciencedirect.com/science/article/pii/S037851732101005X

Xu, X., Seijo-Rabina, A., Awad, A., Rial, C., Gaisford, S., Basit, A. W., & Goyanes, A. (2021). Smartphone-enabled 3D printing of medicines. International Journal of Pharmaceutics, 609, 121199. https://doi.org/10.1016/j.ijpharm.2021.121199

Yang, Y., Zhou, Y., Lin, X., & Yang, Q. (2020). Pharmaceutics GY, 2020 undefined. Printability of external and internal structures based on digital light processing 3D printing technique. Lin, Q Yang, G YangPharmaceutics, X. mdpi.comY Yang, Y Zhou. mdpi.com [Internet]. Retrieved July 29, 2024. https://www.mdpi.com/1999-4923/12/3/207?trk=public_post_main-feed-card-text

Yang, Y., Zhou, Y., Lin, X., Yang, Q., & Yang, G. (2020). Printability of external and internal structures based on digital light processing 3D printing technique. Pharmaceutics, 12(3). https://doi.org/10.3390/pharmaceutics12030207

Yeung, C., Chen, S., King, B., Lin, H., King, K., Akhtar, F., Diaz, G., Wang, B., Zhu, J., Sun, W., Khademhosseini, A., & Emaminejad, S. (2019). A 3D-printed microfluidic-enabled hollow microneedle architecture for transdermal drug delivery. pubs.aip.org [Internet]. Retrieved July 29, 2024. https://pubs.aip.org/aip/bmf/article/13/6/064125/238862. Biomicrofluidics, 13(6), 064125. https://doi.org/10.1063/1.5127778

Zhang, J., Hu, Q., Wang, S., Tao, J., & Gou, M. (2020). Digital light processing based three-dimensional printing for medical applications. International Journal of Bioprinting, 6(1), 242. https://doi.org/10.18063/ijb.v6i1.242

Cite this article: Mustafa MA, Malik A, Javed E, Amjad A, Iqbal S, Mustafa E. A Comparative Review of 3D Printing Technologies and their Applications: A Systematic Review for Future of Medicine Fabrication. Int. J. Pharm. Investigation. 2025;15(2):313-24.