Additive Manufacturing Excellence: A Review of 3D Printing Process in Precise Drug Delivery for Personalized Medicine

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ABSTRACT

Three-dimensional Printing (3DP), as an additive manufacturing technique, has emerged as a promising technology for the production of personalized medicine, tissue organ development, customized implants, complex drug release profile, anatomical model for surgical preparation, engineering components, setting it apart from conventional manufacturing methods. Precision medicines have acquired a foothold in the Healthcare sector pharmaceutical sector thanks. Integrating 3D Printing with AI Platform can amplify its potential by improving the customization, efficiency and safety. 3D printing involves the establishment of a three-dimensional object, in a layer upon layer manner using various computer software. Digital fabrication technology referred to as 3DP or additive manufacturing, produces physical objects by incrementally adding materials according to a geometric model. It creates new opportunities for improving efficacy, safety, and convenience of medicines. The major technological platforms of 3D printing researched on in the pharmaceutical sector include inkjet printing, binder jetting, fused filament fabrication, selective laser sintering, stereolithography, and pressure-assisted microsyringe. To broaden the applications of 3D printed components, greater emphasis should be placed on creating cost-effective printer technologies and materials that are compatible with these printers. The technology operates by sequentially depositing material from a computer-aided design (CAD) model into the production of an object. Applications of 3D printing integrated customized delivery and devices include dose personalization, multidrug composition, modified release system, medical implants, and particular demographic-specific customization. The present paper presents a comprehensive overview of various 3DP technologies, detailing their advantages, disadvantages, applications, & the materials utilized in industries like manufacturing.

1. Introduction

By layering on material, Three-dimensional Printing (3DP), also referred to as additive manufacturing, is a ground-breaking technology that turns digital models into tangible objects. The fabricating of drugs layer by-layer with thickness ranges between 0.001 to 0.1 inches by the 3D printer is a unique feature that enables the modification of shapes, pattern, or fill density which consequently results in improvement of the geometric complexity of the drugs. The complex geometries enable the controlled release of the drugs and more tailor dosing specific to the patient. Currently, there is an accelerating emergence of realization for applications and studies on drug delivery using this technology since the first 3D-printed orodispersible tablet Spritam® (levetiracetam) anti-epileptic drug was approved by the Food and Drug Administration (FDA) in 2015. 3D printing has given pharmacists the ability to quickly produce customized pharmaceutical formulations by modifying their design using computer-aided design (CAD) file. Personalized medication can also be applied by printing single solid dosage form that contains multiple APIs to treat patients suffering from multiple diseases, avoiding the administration of multiple medications. 3DP is incredibly effective & adaptable because it develops objects from ground up, contrary to traditional manufacturing techniques that frequently involve removing material from a larger block or molding it into shape. Originally invented in 1980s, 3DP has quickly advanced & is currently employed in a variety of sectors, comprising healthcare, consumer goods, aerospace, as well as automotive.

As object's blueprint, a CAD model is the initial step in process. Upon reading digital file, printer applies layers of material comprising resin, metal, or plastic until object is completely formed. With this technique, intricate geometries & personalized goods that would be hard or impossible to accomplish utilizing conventional methods could be manufactured. Three-dimensional printing technology itself has a digital gene and its entire process can be applied in precision medicine, including image acquisition, segmentation, modeling, printing, post-processing, and quality control, which can be referred to as full chain application. So, it has a wide range of market demand in the medical field, and its industrial scale continues to expand. According to the report of Acumen Research and Consulting, the global market size of medical 3D printing applications was USD 2.8 billion in 2022. It is estimated that the market size will reach USD 11 billion by 2032, with a compound annual growth rate of 16.6% from 2023 to 2032.

Reduced material waste, faster production times, with capacity for developing highly customized products are merely some of the many benefits that 3DP offers. Although it could decrease the consumption of resources and decrease the environmental impact of production, it is also becoming more widely acknowledged for its potential in sustainable manufacturing. 3DP is projected to become even more important in determining direction of manufacturing in future as technology develops, providing fresh opportunities for creativity as well as effectiveness. [1-3]

Developing the basic design of the part to be modelled is the initial step in the 3DP process. 3D printer-compatible computer software has been employed for developing this design. After that, the software creates a particular file type that is sent to the printer. Upon interpreting this file, the 3D printer manufactures the product by layering one layer on top of the other. Nearly all 3DP processes rely on layering to build a part. The printer reads each part as a series of individual two-dimensional layers rather than as a single, complete object.

As illustrated in Fig.1. 3D printers are designed to read and process files in Standard Tessellation Language (STL) format.

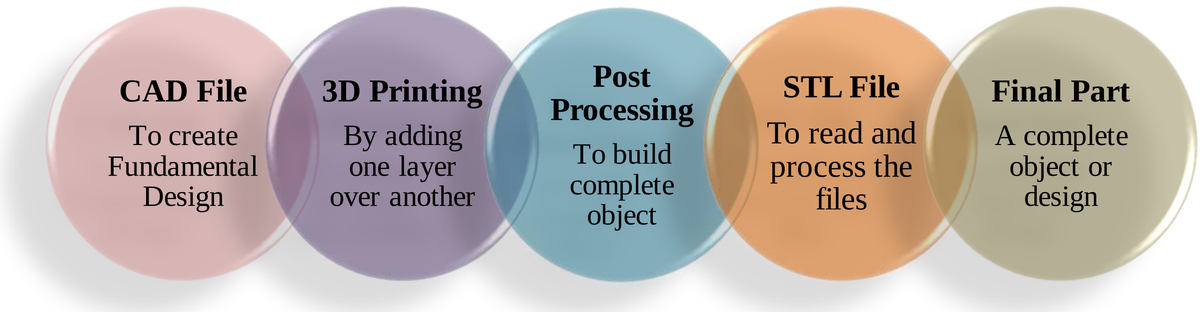

Fig.1 Basic Process of 3D Printing

3DP has been identified as a technology of the future due to its sustainable features, including affordable pricing even for manufacturing complex parts, minimal post-processing, along with reduced material waste. Sustainability has been further enhanced by 3DP's capacity to recycle, reuse plastics, & minimize emissions. Lightweight components with better strength-to-weight ratios could be developed, attributable to the technology's ability to create designs with intricate, optimized geometries. Thus, 3DP contributes substantially to the development of sustainable designs.

There have been several 3DP technologies established, each with unique purpose. ASTM Standard F2792 divides 3DP technologies into 7 groups: vat photopolymerization, powder bed fusion, material extrusion, binder jetting, directed energy deposition, as well as sheet lamination. Since every machine & technology is made for specific purpose, there is no argument over which one operates best. These days, 3DP technologies are being employed more and more to manufacture a variety of products, extending beyond basic prototyping. Advancement of contemporary technology is 3DP. In this paper, we will explore additive manufacturing, commonly known as 3DP. We will begin by defining the term and highlighting what makes it so revolutionary. Next, we will briefly explore its history. The 3DP procedure & materials employed for manufacturing 3D-printed objects will then be discussed. We will additionally examine many current 3DP utilization, as well as its benefits & drawbacks. Finally, we will outline the future potential of this technology. [4,5]

1.1 History

A digital design file employed for manufacturing solid objects with three dimensions utilizing additive manufacturing frequently referred to as 3D printing. Layer by layer, material is incorporated in this process for developing object. Until entire object has been manufactured, each layer of material is layered on top of previous one until it during additive manufacturing (AM). These layers represent thin, horizontal cross-sections of the final object, gradually constructing it in precise detail.

In the history of manufacturing, subtractive techniques have traditionally taken precedence. Precision machining, which involves shaping materials with accuracy, was largely a subtractive process involving methods like filing, turning, milling, & grinding. The 1980s witnessed the emergence of AM materials and technologies. Chuck Hull of 3D Systems Corporation developed stereolithography in 1984. It is a technique that employs UV lasers for

curing photopolymers to generate layers. Hull referred to this as a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed." In addition to digital slicing as well as infill techniques that are currently prevalent, he additionally established STL file format, that is frequently employed in 3DP software.
Initially, the acronym "3D printing" had been utilized for describing procedures that employed conventional & customized inkjet print heads. But as technology has developed, AM techniques became more prevalent in manufacturing process' production stage. Previously made only with subtractive techniques, some parts are capable of being produced more effectively with additives techniques.
Despite these advances, newer additive technologies are not fully replacing subtractive methods. Instead, they complement them. The future of commercial manufacturing is expected to require firms to be adaptable, leveraging both subtractive and additive technologies to remain competitive in an ever-evolving industry. [1,6]

2. Types of 3DP Processes

Different processes are shown in Fig.2

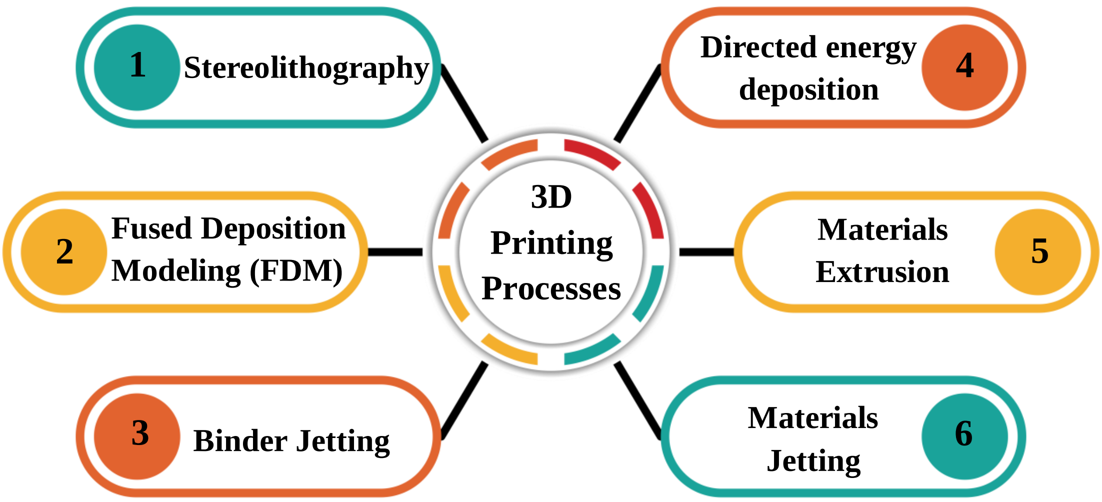

Fig. 2 Different Processes of 3D Printing

2.1. Stereolithography

Stereolithography (SLA) is among earliest & most prevalent 3DP technologies, as illustrated in Fig. 3. 3DP era commenced in late 1980s, with SLA as inaugural 3D printing process launched into market. SLA machines initially 3D printers primarily utilized for production of 3D models, components, patterns, & prototypes. Research in domain of 3DP commenced in 1970s; however, Charles Hull pioneered SLA technique patented in 1984. It functions based on vat photopolymerization principle, wherein liquid photopolymer resin is polymerized then solidified through exposure to laser or UV rays. Procedure commences with a computer-generated three-dimensional model that is segmented into thin layers. SLA printer employs a laser to outline each layer of model on surface of a vat containing liquid resin, selectively solidifying material. Upon curing each layer, build platform descends progressively, then procedure reiterates, adding layers until final object formed.
SLA is recognized for generating high-resolution components with smooth surface finishes as well as intricate details, providing techniques suitable for precision-demanding applications,

including prototyping, dental with medical models, as well as jewellery design. However, the materials used in SLA printing are generally more expensive than those used in other 3DP methods; the printed parts might demand post-processing, encompassing curing & cleaning, for achieving desired properties. Despite these considerations, SLA remains a popular choice for producing high-quality, detailed prototypes and small-scale production parts. [7-9]

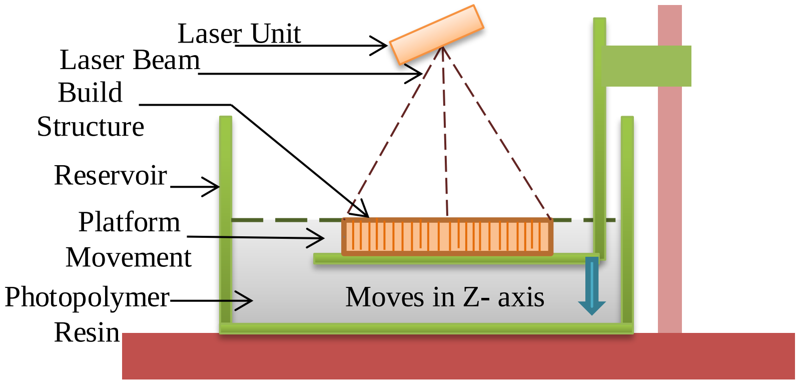

Fig. 3 Stereolithography Process for 3D printing

2.2. Fused Deposition Modeling (FDM)

Stratasys, headquartered in Eden Prairie, Minnesota, invented FDM. This method involves extruding a plastic or wax substance layer by layer through nozzle that follows part's cross-sectional geometry. After SLA, FDM is second most prevalent rapid prototyping technique. It is among most frequently available as well extensively employed 3DP technologies. Layer by layer, material is deposited on build platform by extruding thermoplastic filament through heated nozzle. Initial stage involves printer's software cutting CAD model into thin layers. Immediately following that, FDM printer adheres to software's suggested course, applying material in layers until object is completely formed. [17]

Support base of 3D printers employed in FDM has some degree of freedom, enabling vertical movement. Filament is attached to an extruder that's in charge of heating it to its melting point, in addition to base. For manufacturing of desired object, extruder subsequently applies the material layer by layer through a nozzle. There are 3 directions in which extruder is able to rotate: x, y, & z. As extruder deposits adjacent layers, they fuse together, enabling 3D printer to model object. [10-12] This process is known as FDM. Depending on the desired surface finish, the final product may be dipped in resin, similar to the stereolithography process. The FDM is shown in Fig.4

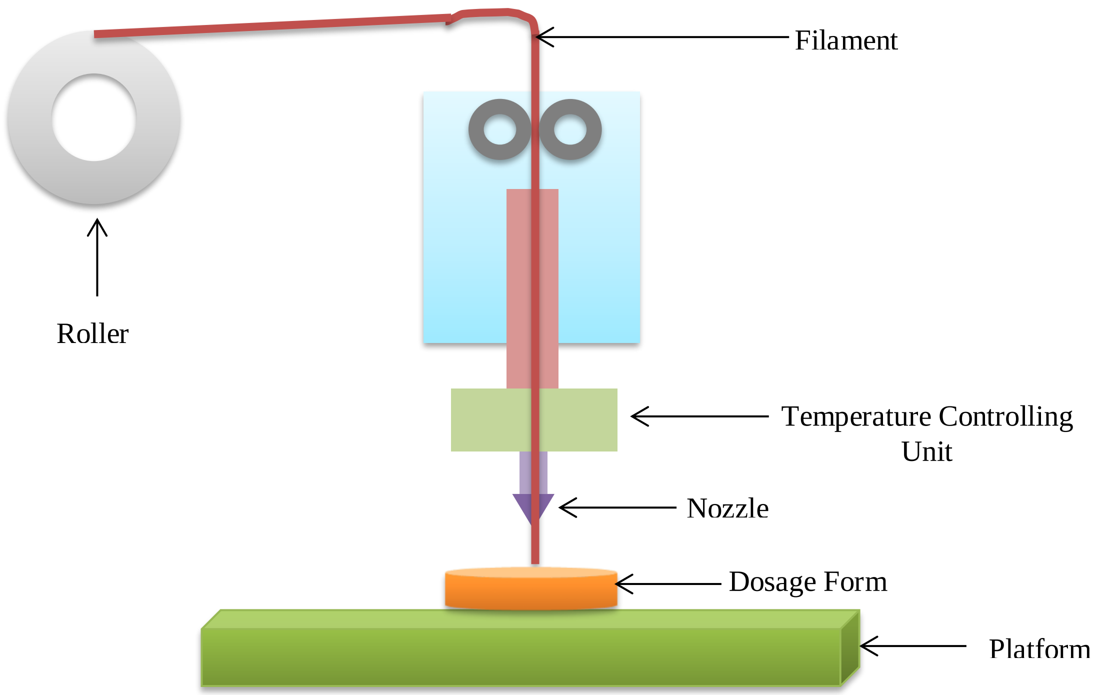

Fig.4 FDM Process for 3D printing

2.3. Binder Jetting

Binder jetting is quick manufacturing & 3DP technology that selectively applies liquid binding agents to adhere to powder particles. Binder jetting technique utilizes chemical binder to consolidate dispersed powder into layer. Binder jetting is employed for developing raw sintered products, analogous large-volume items from sand, & casting patterns, as illustrated in Fig. 5. Binder jetting is capable of printing diverse array of materials, encompassing sand, metals, hybrids, polymers, & ceramics. Certain materials, including sand, might not necessitate further processing. Moreover, binder jetting is efficient, rapid, & cost-effective as powder particles are cohesively bonded. [13,2] Ultimately, binder jetting possesses capability to produce exceptionally large objects.

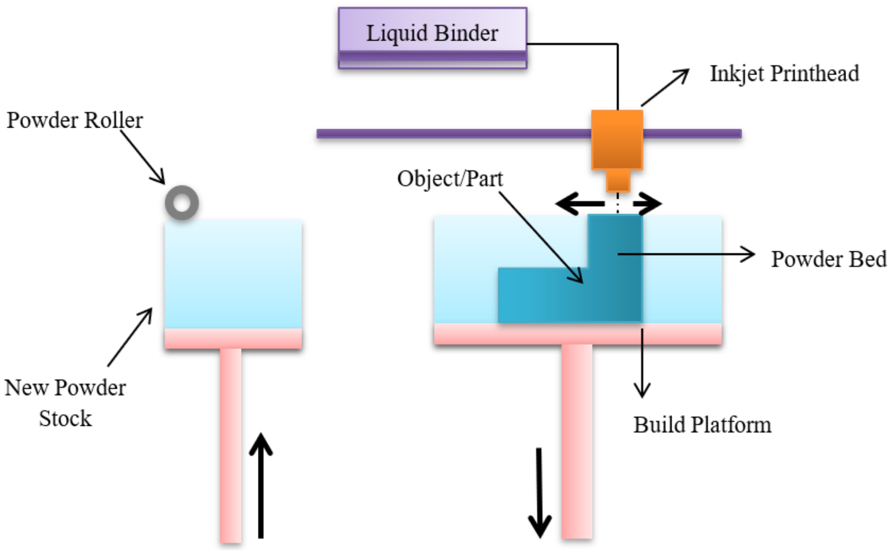

Fig. 5 Binder Jetting Process for 3D printing

2.4. Directed energy deposition

As demonstrated in Fig. 6, Directed energy deposition (DED) is an advanced printing method frequently employed to repair or expand existing components. This process provides substantial control over the grain structure, yielding superior output. Despite its resemblance to material extrusion, DED is distinct in that its nozzle possesses multi-directional mobility, as opposed to being constrained to the singular axis. Although applicable to ceramics & polymers, DED is predominantly utilized with metals & metal-based hybrids that are available in wire or powder formats. Instances of this technology encompass laser deposition as well as Laser Engineered Net Shaping (LENS). Laser deposition, an emerging technology, may generate or repair components ranging from millimetres to meters in size. This technology is becoming more prevalent in sectors including tooling, transportation, aerospace, as well as natural gas and oil, attributable to its scalability & versatility. [14-16] LENS specifically employs thermal energy for melting during the casting process, resulting in the subsequent production of parts.

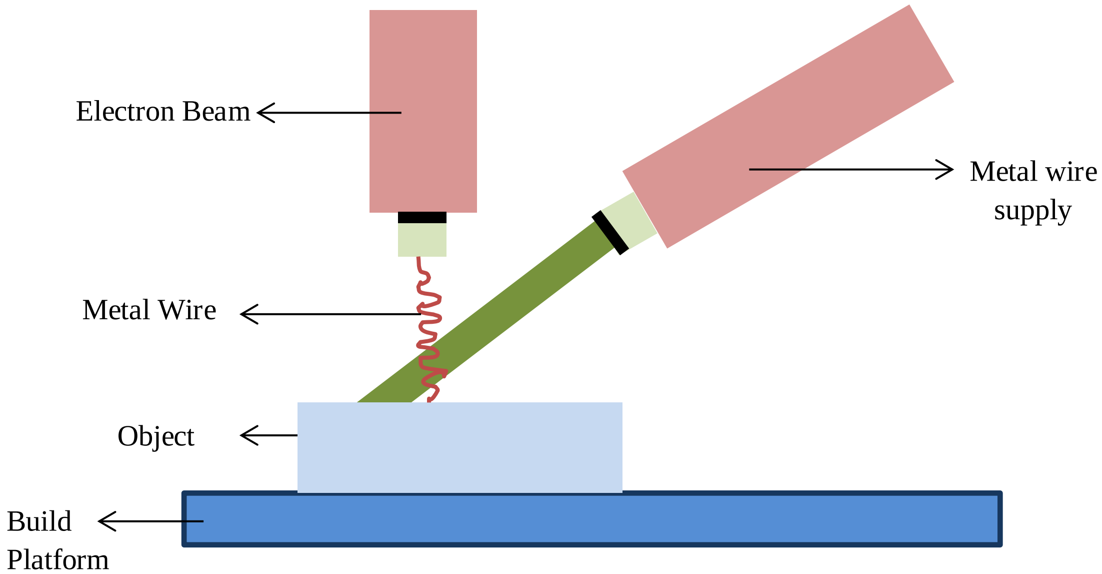

Fig. 6 Directed Energy Deposition Process for 3D printing

2.5. Materials Extrusion

A prominent 3DP technique is material extrusion, in which an object is constructed layer by layer by selectively dispensed material via nozzle or orifice. The process is also referred as FFF (fused filament fabrication) or FDM. Thermoplastic filament heated to its melting point prior to being extruded via a nozzle in material extrusion. Nozzle deposits melted material on build platform by rotating along predetermined paths. Substance solidifies then forms a layer of object as it cools. The build platform or nozzle moves vertically once a layer has been completed, depositing the subsequent layer on top of the one preceding it. This procedure is repeated until the completed item is manufactured. [17,3]

2.6. Materials Jetting

An advanced 3DP technique termed material jetting produces objects layer by layer, employing droplets of photopolymer or other materials on top of the ink. In industries where accuracy along with surface quality are crucial, this process is frequently employed for manufacturing parts with smooth surfaces that are exceptionally precise & accurate. Versatile

3DP technology, material jetting excels at manufacturing detailed, high-quality parts; however, considering precision & material costs required, it is usually more expensive than other techniques, FDM or SLA. Material jetting generates parts with excellent dimensional accuracy along with remarkably smooth surface finish. With wide range of materials, comprising hybrids, polymers, biological materials, composites, as well as ceramics, this technology also facilitates multi-material printing. The working of this process is shown in Fig.7 [18-20]

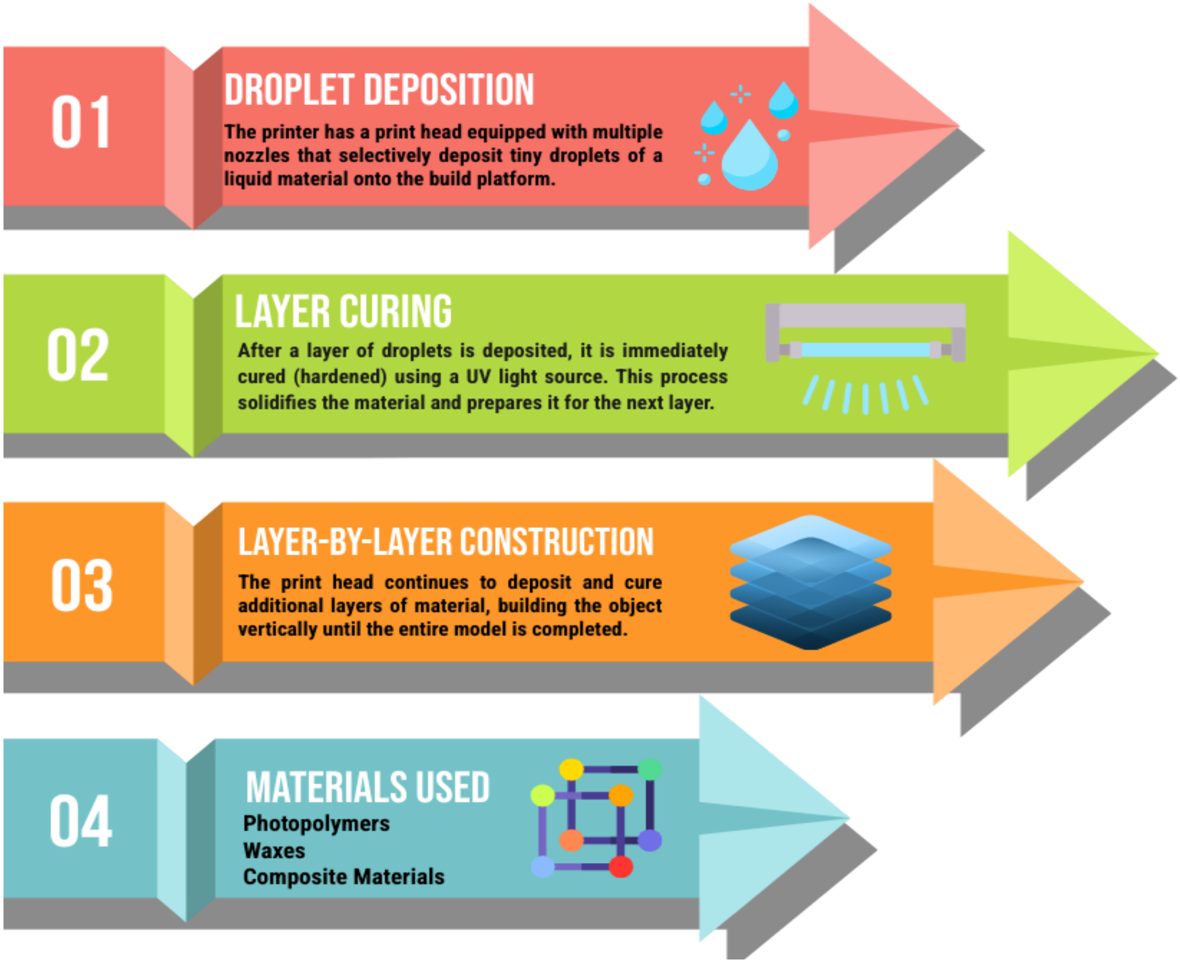

Fig.7 Material Jetting Process

2.6.1 Sheet lamination

For generating 3D object, sheet lamination is 3DP technique that entails stacking & bonding layers of material, usually in sheet form. **LOM (Laminated Object Manufacturing) as well as UAM (Ultrasonic Additive Manufacturing)** are 2 primary forms of sheet lamination. It is a viable option for specific use cases where speed, cost, and material waste are important considerations, and the limitations in resolution and material choice are acceptable. [21,4]

2.6.2 Vat Photopolymerization

Vat of liquid photopolymer resin is employed in 3DP process of vat photopolymerization. Resin is selectively cured (hardened) layer by layer with the assistance of a light source, usually laser or a digital light projector. Prevalent methods for vat photopolymerization are **DLP (Digital Light Processing)** & **SLA(Stereolithography)**. It is a preferred technology for applications demanding accuracy as well as visual appeal since it has its unique capacity for generating detailed, high-resolution parts with excellent surface finishes. [22-25]

Table1 outlines advantages & disadvantages of several processes.

Table1. Advantages and Disadvantages of Different 3DP Processes [26-29]

S.no	3DP Process	Advantages	Disadvantages
1.	**Material Extrusion (FDM/FFF)**	• Cost-effective and widely accessible.	• Lower resolution and surface finish compared to other methods.
		• Suitable for a variety of thermoplastics.	• Issues with layer adhesion and warping.
		• Simple and easy to use.	• Limited to relatively simple geometries.
		• Ideal for prototyping and functional parts.	• Slower print speeds for complex designs
2.	**Stereolithography (SLA)**	• High resolution and detailed features.	• More expensive materials and equipment.
		• Smooth surface finish.	• Post-processing required (e.g., UV curing, washing)
		• Ideal for small, intricate parts	• Limited material options (primarily photopolymers)
3.	**Binder Jetting**	• Capable of producing large parts quickly.	• Parts typically require infiltration or post-processing for strength.
		• Wide range of material options encompassing ceramics, sand, & Metals.	• Lower mechanical properties compared to other methods.
		• No thermal stresses during printing	• Rough surface finish and porosity issues
4.	**Directed Energy Deposition (DED)**	• High degree of material properties & control over grain structure	• Complex and expensive equipment
		• Could repair and add material to existing parts	• Limited to metals & metal-based hybrids

		• Capable of producing large metal parts	• Requires significant post-processing.
5.	**Sheet Lamination**	• Uses inexpensive materials like paper, metal, or plastic sheets.	• Less precise than other 3DP methods, leading to rougher surface finishes.
		• Can produce parts relatively quickly compared to other methods.	• Material options are generally limited to paper, polymers, and metals, depending on the process.
		• Capable of producing larger parts since the sheets are pre-formed.	• Parts often need additional post-processing, such as cutting or finishing, achieving the final desired shape and quality.
		• Suitable for producing large, simple prototypes or concept models.	• If bonding is not strong, layers may separate over time, especially in functional parts.
6.	**Vat Photopolymerization**	• Capable of producing parts with very fine details and smooth surfaces.	• Photopolymers can be costly compared to other 3DP materials.
		• Parts have a naturally smooth finish, often requiring minimal post-processing.	• Parts need to be washed in a solvent and cured under UV light after printing.
		• Excellent for creating intricate designs and small, detailed parts.	• Primarily restricted to photopolymer resins, which may not be suitable for all applications.
		• DLP can produce entire layers at once, making it faster than laser-based methods.	• The build size is often limited compared to other 3DP processes.

3. Materials Used In 3DP Manufacturing

3DP utilizes variety of materials, each chosen on basis of specific printed object requirements, such as strength, flexibility, thermal resistance, and aesthetics. Each material brings specific benefits & trade-offs, influencing choice based on intended usage, required properties, as well as 3DP technology employed. An outline of standard components included within various 3DP technologies:

3.1. Thermoplastics

Different kinds of thermoplastics and photopolymers are described in Table 2. [30,26,28]

Table 2. Various materials employed in 3D printing

S. No	Material	Properties	Applications
THERMOPLASTICS			
1.	**Polylactic Acid (PLA)**	Biodegradable, easy to print, Low warping.	Prototyping, educational models, consumer products.
2.	**Acrylonitrile Butadiene Styrene (ABS)**	Strong, impact-resistant, can be post-processed (e.g., acetone smoothing).	Functional prototypes, automotive parts, toys.
3.	**Polyethylene Terephthalate Glycol-Modified (PETG)**	Strong, impact-resistant, chemically resistant, easy to print.	Bottles, food containers, mechanical parts.
4.	**Nylon (Polyamide)**	Flexible, strong, wear-resistant.	Gears, bearings, functional prototypes.
PHOTOPOLYMERS			
1.	**Standard Resins**	High detail, smooth surface finish, brittle	Jewellery, prototypes, dental models
2.	**Tough Resins**	Greater strength and durability compared to standard resins	Functional prototypes, engineering parts.
3.	**Flexible Resins**	Elastic, rubber-like	Wearable devices, grips, seals
4.	**Biocompatible Resins**	Safe for medical use, sterilizable	Dental models, surgical guides, medical devices
5.	**Castable Resins**	Burn out cleanly without ash	Jewellery casting, dental casting
METALS			
1.	**Stainless Steel**	Strong, corrosion-resistant, biocompatible	Medical implants, tools, automotive and aerospace parts
2.	**Titanium**	Lightweight, strong, corrosion-resistant, biocompatible	Aerospace, medical implants, high-performance engineering parts.
3.	**Aluminium**	Lightweight, strong, good thermal conductivity	Automotive parts, aerospace components, heat exchangers

4.	**Cobalt-Chrome**	Very hard, wear-resistant, corrosion-resistant	Medical implants, dental prostheses, aerospace components
5.	**Gold and Silver**	Precious, excellent for fine details	Jewellery, luxury items
6.	**Ceramics**	High heat resistance, biocompatible, brittle	Dental crowns, bone implants, art and decorative objects
COMPOSITES			
1.	**Carbon Fiber-Reinforced Plastics**	High strength-to-weight ratio, stiff, lightweight.	Aerospace, automotive, sports equipment
2.	**Glass Fiber-Reinforced Plastics**	Strong, less brittle than carbon fiber.	Automotive parts, structural components.
3.	**Metal Matrix Composites (MMC)**	Combines metal with ceramic or other materials for enhanced properties.	High-performance engineering applications, aerospace.
OTHER MATERIALS			
1.	**Paper** (for Sheet Lamination)	Inexpensive, recyclable, easy to process.	Architectural models, conceptual prototypes.
2.	**Wax**(for Investment Casting)	Easy to mould and burn out.	Jewellery, Precision casting patterns.
3.	**Sand** (for Binder Jetting)	Used to create molds and cores for metal casting.	Foundry molds, sand casting.
BIOPRINTING MATERIALS			
1.	**Bioinks**	Composed of living cells and biomaterials.	Tissue engineering, regenerative medicine, organ printing research.

4. 3DP Market Size

With a compound annual growth rate (CAGR)23.6%, global 3DP market projected to increase from its 2023 valuation of USD 22.39billion to USD 150.20billion by 2032, from USD 27.52billion in 2024. By 2032, U.S. market alone is expected to grow to value of about USD 33.78billion, driven by large investments from governments along with prominent tech firms.

Online 3DP requirement in simulation applications driven by quick development of digitization as well as accelerating uptake of cutting-edge technologies comprising Industry 4.0, machine learning, smart factories, & robotics. Fig. 8 illustrates various 3DP technology applications, including production, prototyping, along with proof of concept. [31-34]

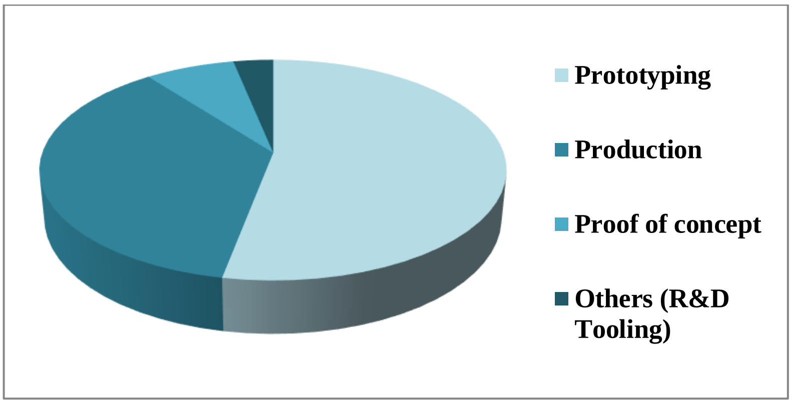

Fig. 8 Global 3D Printing Market Share by Applications

Market Trends which play important role in 3DP are given below in Fig.9:

Fig. 9 Key market trends of 3D printing

When choosing a material for 3D printing, there is a wide range of options, and ongoing research is focused on creating new 3D-printable materials. Selecting the appropriate material is equally as crucial as choosing the right printing technology for the specific application. As 3DP technologies evolve, new materials and increasingly advanced machines with enhanced capabilities are continually being introduced. By 2024, it is anticipated that global market for 3D-printed goods & services will have expanded to over 40 billion dollars attributable to current growth of additive manufacturing. From 2020-24, industry is expected to expand at compound annual rate 29%. The U.S. 3D printer market size and Growth is described in Fig.10. [35-37]

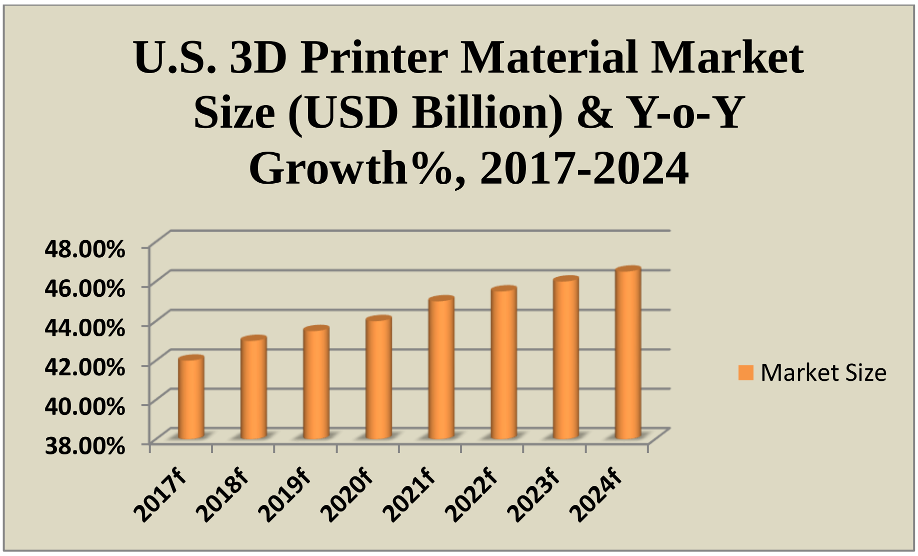

Fig. 10 U.S. 3D Printer Market Size

5. Applications of 3DP Technology in Pharmaceutical Industries [32-34, 37]

Various pharmaceutical & 3DP medical applications is given in Fig.11

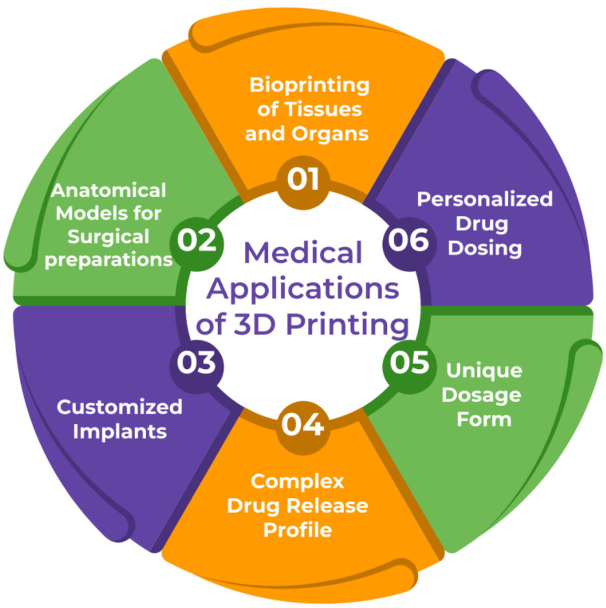

Fig. 11 3D Printing Medical Applications

5.1. Bioprinting of Tissues and Organs

A major medical challenge comprises organ & tissues failure caused by congenital defects, ageing, accidents, & other factors, with the current solution being organ transplants from deceased or living donors. Unfortunately, only a limited number of patients receive transplants, while many others die due to a shortage of donors. Additionally, organ transplant procedures are prohibitively expensive for most people, and finding a donor with a compatible tissue match is difficult.

Employing patient's own cells to generate essential tissue or organ-viable solution would greatly lower risk of rejection along with reducing requirement for immunosuppressants. Tissue engineering typically involves collecting a small sample of tissue, isolating stem cells, combining them with growth factors, then expanding them in a lab. Following that, the cells are seeded onto scaffolds that direct their development and enable them to differentiate into functional tissues.

5.2. Anatomical models for surgical preparations

3DP application in anatomical models created for surgical preparations has revolutionized medical field. These models offer surgeons a highly accurate, patient-specific representation of anatomy, which allows for better preoperative planning and improved outcomes. [38-40] Some key benefits are included in Table 3:

Table 3. Key Benefits of Anatomical Models for surgical preparations

S. No	Benefits	Key Outcomes
1.	**Enhanced Visualization**	3D-printed models provide a precise, tangible representation of complex anatomical structures, making it easier for surgeons to visualize the affected area before surgery.
2.	**Customization and Personalization**	This customization helps in planning and practicing procedures, ensuring a more targeted and effective surgical approach.
3.	**Preoperative Simulation**	Surgeons can use 3D models to simulate and rehearse complex procedures, reducing the likelihood of errors during surgery. This practice allows for better decision-making and can shorten surgery times, which in turn reduces the risks associated with lengthy procedures.
4.	**Improved Communication**	Anatomical models serve as excellent tools for explaining surgical plans to patients improving patient understanding and consent. They also facilitate better communication within the surgical team and can be used in medical training to teach students complex procedures.
5.	**Reduction in Surgery Time and Costs**	By enabling precise planning, 3D models can help surgeons anticipate potential challenges, leading to quicker and more efficient surgeries. This reduces operating room time, costs, and patient recovery time.

5.3. Customized Implants

Customized 3D implants are transforming the medical field by providing patient-specific solutions for a wide range of conditions. The ability to tailor implants to the unique anatomy of each individual offers numerous benefits in terms of fit, function, and recovery. Here are the key advantages of customized 3D implants shown in Fig.12

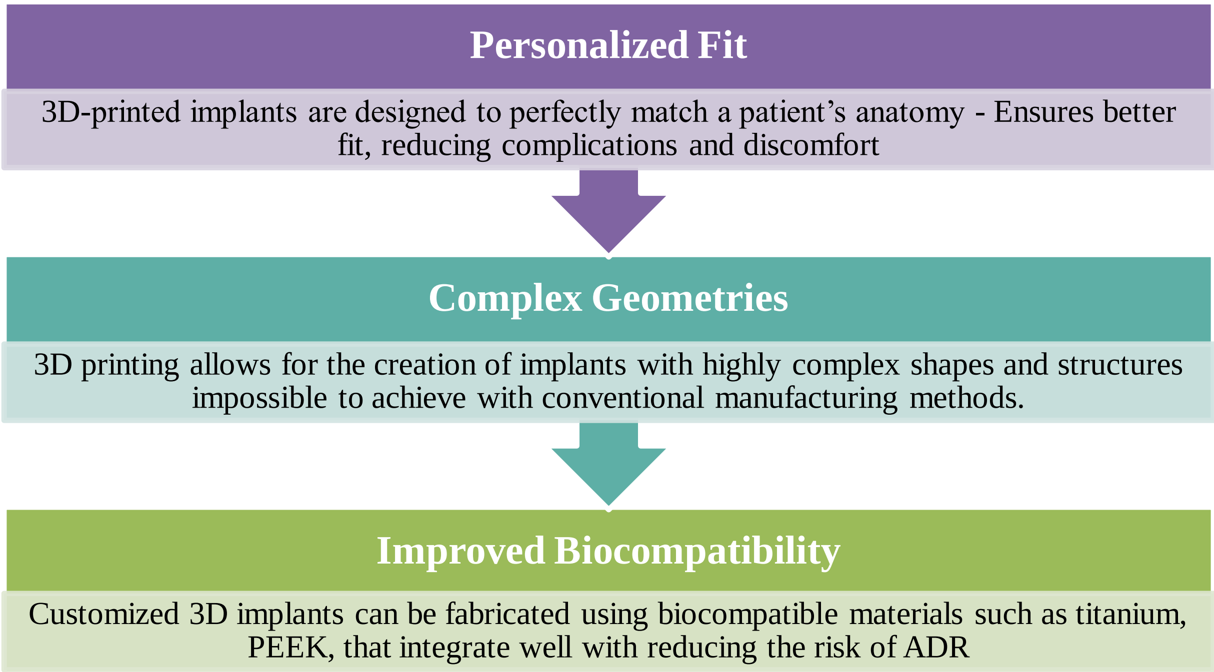

Fig. 12 Advantages of customized 3D implants

5.4. Complex Drug Release Profile

With consistent blend of active ingredients, drug release in conventional compressed dosage forms usually follows simple profile. By allowing creation of complex geometries with porous structures & multiple drug layers often encircled by barrier layers that regulate release rate, 3D-printed dosage forms, on contrary, provide more complex drug release profile. For instance, pulsed release mechanism is achieved by 3DP multi-layered bone implant with alternate drug layers of isoniazid & rifampicin. Furthermore, antibiotic micropatterns that act as drug implants to target then eradicate *Staphylococcus epidermidis* have been made on paper utilizing 3DP. [30-32]

5.5. Unique Dosage Form

Unique 3D dosage forms represent an innovative approach to drug delivery, offering advantages over traditional dosage forms through their customized and complex structures. Here are some notable examples of unique 3D dosage forms are given in Fig.13.

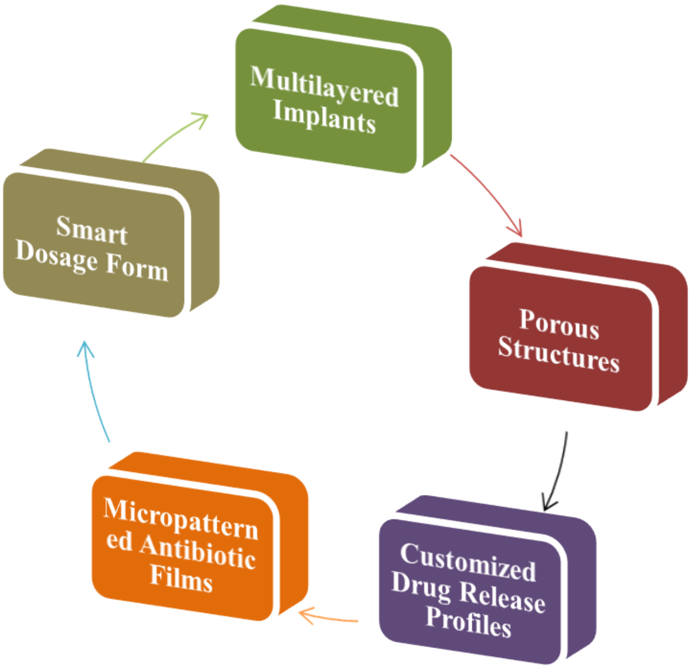

Fig. 13 Some Examples of Unique 3D Dosage

5.6. Personalized Drug Dosing

Personalized drug dosing through 3DP represents a significant advancement in tailoring medical treatments to individual patient needs. This approach leverages 3DP technology to create dosage forms that are customized based on specific patient characteristics, such as genetic profiles, medical conditions, and anatomical differences. Since 3DP technology enables precise formulation according to patient's pharmacogenetic profile along with characteristics including race & age, it could be utilized for managing drugs with narrow therapeutic index. This ensures that the optimal dosage is administered to each patient. Furthermore, 3DP provides the possibility of developing completely novel drug formulations, including multi-reservoir tablets or pills that incorporate several active pharmaceutical ingredients. [41,42,26]

6. Conclusion

3DP technology is a vital & promising asset in pharmaceutical sector, facilitating transition towards personalized medicine customized to individual patient requirements. It provides several benefits, including enhanced cost efficiency and faster manufacturing processes. By transforming traditional manufacturing methods, 3DP improves design and production while also reducing lead times and tooling costs for new products. This chapter highlights various fabrication techniques & notable 3DP applications within healthcare sector, with particular focus on pharmaceutical sciences. This review examines 3DP comprehensive scope in the manufacturing sector. Presently, 3DP technology is proliferating across multiple manufacturing industries, providing substantial advantages to individuals, corporations, along with governmental entities. Enhancing 3DP adoption necessitates additional information & research to refine while broadening its infrastructure. Current paper presents an overview of various 3DP technologies, materials utilized in production, as well as 3DP applications.

Prospective research should concentrate on examining different types of 3DP machines & determining appropriate materials for each machine type to enhance technology's efficacy along with integration.

Abbreviations

3DP: Three-dimensional Printing

CAD: Computer-Aided Design

STL: Standard Tessellation Language

ASTM: American Society for Testing and Materials

AM: Additive Manufacturing

SLA: Stereolithography

FDM: Fused Deposition Modeling

LENS: Laser Engineered Net Shaping

LOM: Laminated Object Manufacturing

UAM: Ultrasonic Additive Manufacturing

DLP: Digital Light Processing

DLD: Directed Energy Deposition

PLA: Polylactic Acid

ABS: Acrylonitrile Butadiene Styrene

PETG: Polyethylene Terephthalate Glycol-Modified

MMC: Metal Matrix Composites

CAGR: Compound Annual Growth Rate

ADR: Adverse Drug Reaction

PEEK: Polyetheretherketone

Declaration of competing interest

The authors declare no conflict of interest.

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References

1. Arya RK, Bisht D, Dhondiyal K, Kausar M, Lalhlenmawia H, Bhutia PL, Kumar D. Role of 3D printing in pharmaceutical industry. In New Horizons for Industry 4.0 in Modern Business 2023 Feb 10 pp. 273-294.
2. Amin R, Marashi SM, Noori SM, Alavi Z, Dehghani E, Maleki R, Safdarian M, Rocky A, Berizi E, Alemohammad SM, Zamanpour S. Medical, pharmaceutical, and nutritional applications of 3D-printing technology in diabetes. Diabetes & Metabolic Syndrome: Clinical Research & Reviews. 2024 Apr 10:103002.
3. Adimulapu AK, Jesudasan RE, Arya RK, Thathapudi D, Namballa M, Sonowal K, Matta A. 3D Printing Coatings for Pharmaceutical Applications. Functional Coatings for Biomedical, Energy, and Environmental Applications. 2024 Oct 4:123-43.
4. Beer N, Kaae S, Genina N, Sporrong SK, Alves TL, Hoebert J, De Bruin ML, Hegger I. Magistral compounding with 3D printing: a promising way to achieve personalized medicine. Therapeutic Innovation & Regulatory Science. 2023 Jan;57(1):26-36.
5. Seoane-Viaño I, Otero-Espinar FJ, Goyanes Á. 3D printing of pharmaceutical products. In Additive Manufacturing 2021 Jan 1: 569-597.
6. Li H, Alkahtani ME, Basit AW, Elbadawi M, Gaisford S. Optimizing environmental sustainability in pharmaceutical 3D printing through machine learning. International Journal of Pharmaceutics. 2023 Dec 15; 648:123561
7. Lamichhane S, Bashyal S, Keum T, Noh G, Seo JE, Bastola R, Choi J, Sohn DH, Lee S. Complex formulations, simple techniques: Can 3D printing technology be the Midas touch in pharmaceutical industry. Asian journal of pharmaceutical sciences. 2019 Sep 1;14(5):465-79.
8. Crișan AG, Porfire A, Iurian S, Rus LM, Lucăcel Ciceo R, Turza A, Tomuță I. Development of a bilayer tablet by fused deposition modeling as a sustained-release drug delivery system. Pharmaceuticals. 2023 Sep 19;16(9):1321.
9. Mishra J, Hardenia S, Jain DK. 3D Printing in Pharmacy: A Burgeoning Field in Development of Drug Delivery System. International Journal of Newgen Research in Pharmacy & Healthcare. 2023 Jun 30:28-38.
10. Milliken RL, Quinten T, Andersen SK, Lamprou DA. Application of 3D printing in early phase development of pharmaceutical solid dosage forms. International Journal of Pharmaceutics. 2024 Feb 14:123902.
11. W. Yu-Cheng, C. Toly, & Y. Yung-Lan, “Advanced 3D printing technologies for the aircraft industry: a fuzzy systematic approach for assessing the critical factors,” The International Journal of Advanced Manufacturing Technology, 2018; 3(3): 1-10.
12. A. Vanderploeg, Seung-Eun, Lee, & M. Mamp, “The application of 3D printing technology in the fashion industry,” Journal International Journal of Fashion Design, Technology and Education, 2017; 10 (2): pp. 170-179.
13. L. Lili, M. Yuanyuan, C. Ke, & Z. Yang, “3D Printing Complex Egg White Protein Objects: Properties and Optimization,” Food and Bioprocess Technology, 2018; (1):1-11.

14. Wadher K, Trivedi R, Wankhede N, Kale M, Umekar M. 3D printing in pharmaceuticals: an emerging technology full of challenges. In Annales Pharmaceutiques Françaises 2021 Mar 1 Vol. 79, No. 2: 107-118.
15. Sen K, Mehta T, Sansare S, Sharifi L, Ma AW, Chaudhuri B. Pharmaceutical applications of powder-based binder jet 3D printing process–a review. Advanced drug delivery reviews. 2021 Oct 1; 177:113943.
16. Azad MA, Olawuni D, Kimbell G, Badruddoza AZ, Hossain MS, Sultana T. Polymers for extrusion-based 3D printing of pharmaceuticals: A holistic material–process perspective. Pharmaceutics. 2020 Feb 3;12(2):124.
17. Parulski C, Jennotte O, Lechanteur A, Evrard B. Challenges of fused deposition modeling 3D printing in pharmaceutical applications: where are we now. Advanced drug delivery reviews. 2021 Aug 1; 175:113810.
18. Awad A, Trenfield SJ, Gaisford S, Basit AW. 3D printed medicines: A new branch of digital healthcare. International journal of pharmaceutics. 2018 Sep 5;548(1):586-96. Pandey M, Choudhury H, Fern JL, Kee AT, Kou J, Jing JL, Her HC, Yong HS, Ming HC, Bhattamisra SK, Gorain B. 3D printing for oral drug delivery: a new tool to customize drug delivery. Drug delivery and translational research. 2020 Aug; 10:986-1001
19. Than YM, Titapiwatanakun V. Tailoring immediate release FDM 3D printed tablets using a quality by design (QbD) approach. International Journal of Pharmaceutics. 2021 Apr 15; 599:120402.
20. Jamróz W, Szafraniec J, Kurek M, Jachowicz R. 3D printing in pharmaceutical and medical applications–recent achievements and challenges. Pharmaceutical research. 2018 Sep; 35:1-22.
21. Huanbutta K, Burapapadh K, Sriamornsak P, Sangnim T. Practical application of 3D printing for pharmaceuticals in hospitals and pharmacies. Pharmaceutics. 2023 Jul 4;15(7):1877.
22. Kulkarni VR, Saha T, Giri BR, Lu A, Das SC, Maniruzzaman M. Recent Advancements in Pharmaceutical 3D Printing Industry. Journal of drug delivery science and technology. 2024 Aug 15:106072.
23. Jamróz W, Szafraniec J, Kurek M, Jachowicz R. 3D printing in pharmaceutical and medical applications–recent achievements and challenges. Pharmaceutical research. 2018 Sep; 35:1-22.
24. Bhusnure OG, Gholve SV, Sugave BK, Dongre RC, Gore SA, Giram PS. 3D printing & pharmaceutical manufacturing: opportunities and challenges. Int. J. Bioassays. 2016;5(1):4723-38.
25. Sultana N, Ali A, Waheed A, Aqil M. 3D Printing in pharmaceutical manufacturing: Current status and future prospects. Materials Today Communications. 2023 Dec 28:107987.
26. Tan DK, Maniruzzaman M, Nokhodchi A. Advanced pharmaceutical applications of hot-melt extrusion coupled with fused deposition modelling (FDM) 3D printing for personalised drug delivery. Pharmaceutics. 2018 Oct 24;10(4):203.

27. Samiei N. 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. 2020 Dec; 9:1-2.
28. Awad A, Fina F, Goyanes A, Gaisford S, Basit AW. 3D printing: Principles and pharmaceutical applications of selective laser sintering. International Journal of Pharmaceutics. 2020 Aug 30; 586:119594.
29. Milliken RL, Quinten T, Andersen SK, Lamprou DA. Application of 3D printing in early phase development of pharmaceutical solid dosage forms. International Journal of Pharmaceutics. 2024 Feb 14:123902.
30. Seoane-Viaño I, Trenfield SJ, Basit AW, Goyanes A. Translating 3D printed pharmaceuticals: From hype to real-world clinical applications. Advanced Drug Delivery Reviews. 2021 Jul 1; 174:553-75.
31. Kotta S, Nair A, Alsabeelah N. 3D printing technology in drug delivery: recent progress and application. Current pharmaceutical design. 2018 Nov 1;24(42):5039-48.
32. Douroumis D. 3D printing of pharmaceutical and medical applications: a new era. Pharmaceutical Research. 2019 Mar;36(3):42.
33. Chen G, Xu Y, Kwok PC, Kang L. Pharmaceutical applications of 3D printing. Additive Manufacturing. 2020 Aug 1; 34:101209.
34. Tracy T, Wu L, Liu X, Cheng S, Li X. 3D printing: Innovative solutions for patients and pharmaceutical industry. International Journal of Pharmaceutics. 2023 Jan 25; 631:122480.
35. Capel AJ, Rimington RP, Lewis MP, Christie SD. 3D printing for chemical, pharmaceutical and biological applications. Nature Reviews Chemistry. 2018 Dec;2(12):422-36.
36. Nasereddin JM, Wellner N, Alhijjaj M, Belton P, Qi S. Development of a simple mechanical screening method for predicting the findability of a pharmaceutical FDM 3D printing filament. Pharmaceutical research. 2018 Aug; 35:1-3.
37. Park BJ, Choi HJ, Moon SJ, Kim SJ, Bajracharya R, Min JY, Han HK. Pharmaceutical applications of 3D printing technology: current understanding and future perspectives. Journal of Pharmaceutical Investigation. 2019 Nov; 49:575-85.
38. Seoane-Viaño I, Otero-Espinar FJ, Goyanes Á. 3D printing of pharmaceutical products. InAdditive Manufacturing 2021 Jan 1 (pp. 569-597). Elsevier.
39. Bhusnure OG, Gholve SV, Sugave BK, Dongre RC, Gore SA, Giram PS. 3D printing & pharmaceutical manufacturing: opportunities and challenges. Int. J. Bioassays. 2016;5(1):4723
40. Ponni RT, Swami Velmanickam M, Sivakrishnan S. 3D printing in pharmaceutical technology–a review. Int J Pharm Invest. 2020 Mar 12; 10: 8-12.
41. Beg S, Almalki WH, Malik A, Farhan M, Aatif M, Rahman Z, Alruwaili NK, Alrobaian M, Tarique M, Rahman M. 3D printing for drug delivery and biomedical applications. Drug Discovery Today. 2020 Sep 1;25(9):1668-81.
42. Andreadis II, Gioumouxouzis CI, Eleftheriadis GK, Fatouros DG. The advent of a new era in digital healthcare: a role for 3D printing technologies in drug manufacturing Pharmaceutics. 2022 Mar 10;14(3):609.