



INNOVATIVE TECHNOLOGY FOR FORMULATION DESIGN BY 3D PRINTING IN PHARMACEUTICAL INDUSTRY

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Abstract

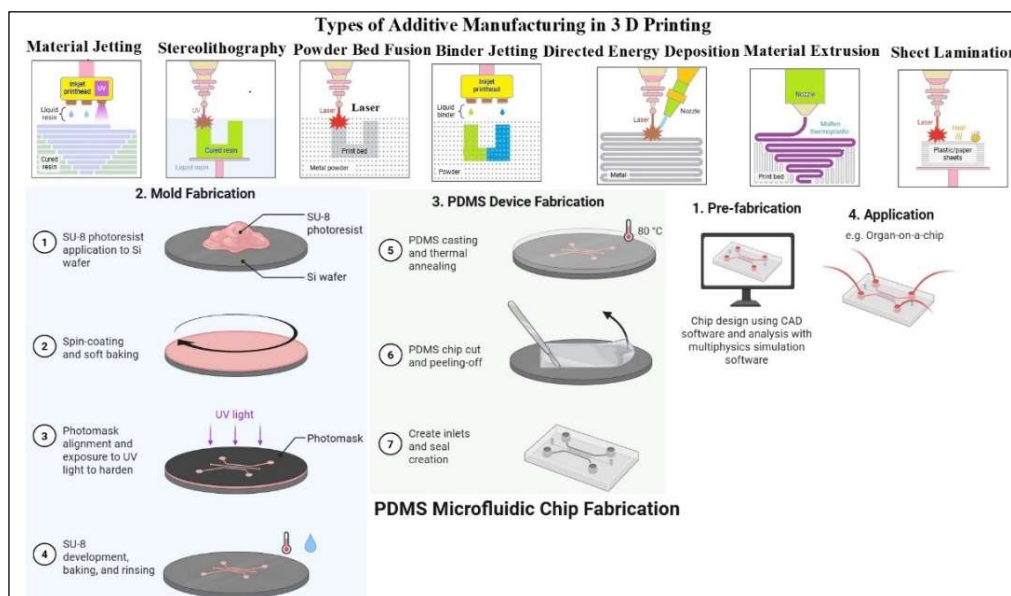
Using computer-aided design models, additive manufacturing, also referred to as three-dimensional (3D) printing, allows for the production of personalized drugs. Compared to traditional drug production techniques, 3D printing has clear advantages in the field of personalized medicine. It makes it easier to create dosage forms with complex geometries or customized drug release profiles, and it makes small-scale batch production more effective. The most popular 3D printing methods are described in this article along with their special characteristics, advantages, disadvantages and applications in the pharmaceutical industry. In order to assist scientists and professionals in this developing sector, it also looks at the current condition of the global commercialization of 3D-printed pharmaceuticals, highlighting current and upcoming issues and providing insights into emerging market trends. 3D printing has attracted much attention recently as a disruptive technology in pharmaceutical development and manufacturing due to numerous advantages over conventional manufacturing such as the ability for dose personalization, high-precision manufacturing of complex solid dosage forms, on-demand manufacturing and cost-effectiveness.

Keywords: Additive manufacturing, computer-aided design models, 3D printing techniques, high-precision production, transformative approach.

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Graphical Abstract



1. INTRODUCTION

The pharmaceutical industry is witnessing a major shift driven by the emergence of three-dimensional (3D) printing, a technology that enables more personalized and efficient methods of drug delivery (1). By leveraging 3D printing, dosage forms can be precisely tailored to individual patient characteristics such as age, body weight and specific health conditions, thereby enhancing both the safety and effectiveness of treatments. This innovation allows for the production of tablets and capsules containing multiple active pharmaceutical ingredients, customized in shape, size and structure to meet unique patient needs (2). Furthermore, the technology facilitates the development of advanced drug formulations with intricate geometries and controlled release mechanisms, leading to improved therapeutic outcomes and a reduction in side effects. Despite these promising advancements, several challenges remain, particularly in the areas of material compatibility, adherence to regulatory standards, and maintaining consistent product quality (3). Comprehensive research is essential to establish standardized protocols and regulatory frameworks that ensure the reliability and performance of 3D-printed medications. The high precision, reproducibility and uniformity offered by 3D printing are revolutionizing pharmaceutical manufacturing, contributing to greater efficiency and innovation across the sector. While healthcare is one of the most prominent fields impacted by this technology, 3D printing has also made significant inroads into industries such as aerospace, automotive, construction and medicine (4). 3D printing builds physical objects layer by layer from digital models, enabling the creation of highly

complex and customized structures. In pharmacy, this capability allows for the design of sophisticated drug delivery systems that can be adapted to specific clinical requirements (5). The technology holds the potential to improve patient adherence, optimize treatment efficacy, and transform traditional pharmaceutical practices. However, widespread adoption faces hurdles including technical limitations, regulatory complexities, and economic considerations (6).

This review aims to provide a comprehensive examination of 3D printing in pharmacy, covering its historical development, current applications, future prospects and existing challenges. Globally, research in pharmaceutical 3D printing is expanding rapidly, offering significant advantages over conventional manufacturing techniques. These include design flexibility for complex internal drug architectures, on-demand dose customization, rapid prototyping, and accelerated development cycles (7). Such capabilities support precise modulation of drug release profiles, cater to diverse clinical demands and foster innovation in personalized medicine. As a result, 3D printing is paving the way for a new era in drug production, redefining how medications are formulated, manufactured and administered (8). Various pharmaceutical products have already been developed using this technology, including immediate-release and sustained-release tablets, oral dissolvable films, microneedle arrays, implants and transdermal delivery systems (9). The primary 3D printing methods employed in the pharmaceutical field include binder jetting (BJ-3DP), fused deposition modelling (FDM), semi-solid extrusion (SSE), material extrusion-based

manufacturing (MED), and stereolithography (SLA), each offering distinct advantages for specific drug formulation needs (10).

2. PURPOSE OF 3D PRINTING

In pharmacy, 3D printing provides innovative solutions to advance tissue engineering, medical devices, and systems for drug delivery. Its applications span personalized dosing, novel delivery mechanisms, implant fabrication, regenerative medicine, educational tools, quality assurance, rapid prototyping, intellectual property development and customized drug formulations (11). This technology transforms digital models into physical three-dimensional objects, enabling the creation of highly complex structures that surpass the limitations of traditional manufacturing. Used across professional and personal domains, 3D printing is becoming more widely available as local providers increasingly offer outsourced industrial printing services (12). Key benefits include the ability to produce unique, cost-effective designs on demand, significantly shorten development timelines, reduce prototyping expenses and fabricate intricate geometries using less material compared to conventional methods (13).

Beyond healthcare, 3D printing supports automotive enthusiasts in customizing vehicles or reviving vintage models by reproducing obsolete components. However, the technology is not without limitations. Since objects are built in successive layers, there is a risk of layer separation under stress,

and inaccuracies may arise if the design software is improperly configured (14).

3. 3D PRINTING IN MEDICINE TECHNOLOGY OVERVIEW

Additive manufacturing, commonly known as 3D printing, involves building three-dimensional objects by depositing material layer by layer onto a base surface, guided by digital models created through computer software (15). This process consists of two essential phases: the first is digital design, and the second is physical fabrication using a 3D printer. Designers can create 3D models using various software tools such as SolidWorks, Sketch Up, Fusion 360, Auto CAD and 3D Slash. Once the model is complete, it undergoes a slicing procedure using specialized programs like Slic 3r, Simplify 3D, Octo Print, KIS Slicer or Cura (16). These slicing applications convert the 3D model into G-code, a machine-readable language that the printer can interpret (**Figure 1**). During slicing, key printing parameters are defined, such as layer count, print speed, infill density, distance between the nozzle and build platform, layer height, and estimated print time (17). The resulting G-code file is then transferred to the 3D printer, which upon receiving the print command, begins fabricating the object according to the specified dimensions and settings. The actual method of material deposition varies depending on the type of 3D printer and its underlying technology (18).

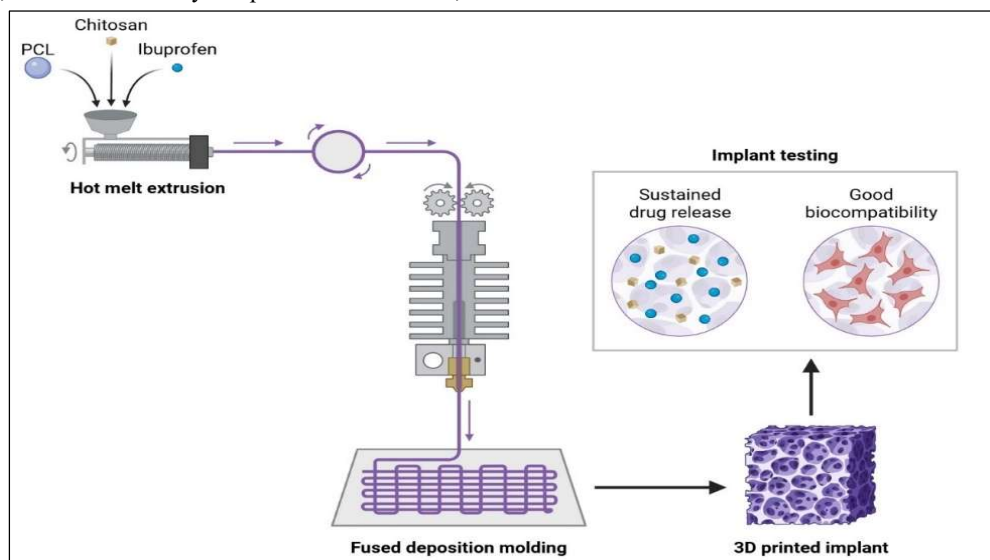


Figure 1: 3 D printing drug delivery implants

3.1. Drop-on-demand (DOD) printing

This method generates micro-droplets of ink with diameters ranging from 10 to 50 μm and volumes between 1 and 70 pL. DOD systems utilize two primary types of print heads: thermal and

piezoelectric. In thermal DOD printing, the ink is rapidly heated to temperatures as high as 300 $^{\circ}\text{C}$, forming vapor bubbles that propel the ink droplet out of the nozzle (19). However, this approach is limited to volatile inks and may pose risks to heat-

sensitive pharmaceuticals due to extreme thermal and vapor pressure conditions. Piezoelectric heads, in contrast, use electric pulses to deform crystals and eject ink, offering better compatibility with delicate compounds. DOD printing can be further categorized into drop-on-deposition and drop-on-solid techniques, depending on the target substrate (20).

3.2. Binder jet printing

This additive manufacturing process involves selectively depositing a liquid binding agent onto layers of powdered materials-such as metal, ceramic, foundry sand or composites-using an industrial-grade print head. The precise application of the binder fuses the powder particles locally, enabling the creation of complex, high-value components and machinery. A well-known pharmaceutical application is the production of Spritam®, an FDA-approved epilepsy medication manufactured using this method (21).

3.3. Selective laser sintering (SLS)

SLS employs a focused laser beam to heat and fuse powdered material at the particle surfaces, forming solid 3D structures layer by layer. Early systems used a 100-watt neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, but modern commercial SLS printers typically utilize

carbon dioxide (CO₂) lasers, which are more cost-effective and deliver higher power output (22). This advancement allows for the processing of a wide array of thermoplastic powders. SLS stands out among 3D printing technologies due to its high resolution, structural integrity and the ability to use printed dosage forms immediately without requiring additional treatments like drying or UV exposure (23).

3.4. Stereolithography (SLA)

The term SLA originates from the Greek "stereo" (meaning solid) and "lithography" (writing with light), reflecting its core principle of using light to solidify materials. As the earliest form of 3D printing, SLA remains highly effective for producing objects with smooth finishes and intricate designs, thanks to its exceptional resolution (24). It operates by using a UV laser to trigger photochemical reactions in liquid, photosensitive resins, curing them layer by layer into precise 3D forms (**Figure 2**). Advantages include high accuracy, fast printing speed and minimal thermal impact, making it particularly suitable for thermally sensitive drugs. Originally developed for creating nano- and micro-scale patterns in micro-electro-mechanical systems (MEMS), SLA's precision has expanded its use into advanced pharmaceutical and biomedical applications (25).

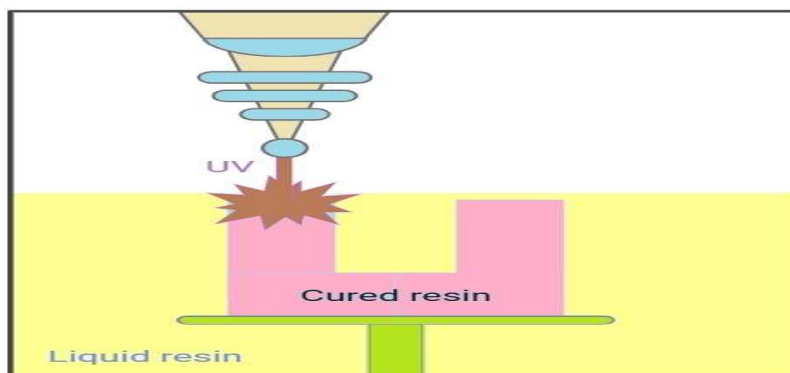


Figure 2: Stereolithography 3D printing

4. APPLICATIONS OF 3D PRINTING

4.1. Cardiovascular disease

The diagnosis and treatment of cardiovascular diseases (CVD) increasingly rely on minimally invasive imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI) and echocardiography (26). While these techniques are standard in clinical settings, converting two-dimensional (2D) cardiovascular images into accurate three-dimensional (3D) visualizations remains a complex task-especially

when dealing with intricate anatomical structures and conditions like congenital heart defects, which often involve multiple cardiac anomalies (27). Three-dimensional printing has emerged as a transformative solution, enabling the creation of highly realistic physical models that offer superior spatial understanding compared to traditional imaging. This technology provides substantial advantages in preoperative planning, medical education and patient communication. Key applications of 3D printing in cardiology include the development of antiplatelet tubular grafts, synthetic blood vessels, cardiovascular

stents and advanced nanocomposite materials designed for enhanced therapeutic outcomes (28).

4.2. Cancer

Cancer remains one of the leading causes of death globally, associated not only with high mortality rates but also with significant patient suffering due to treatment side effects. Additive Manufacturing offers transformative potential in the fight against malignant tumors by enabling more precise and personalized therapeutic approaches. These advanced models enhance clinicians' understanding of individual patient pathology and tumor behavior (29). Three-dimensional printing plays a crucial role in advancing cancer research, particularly in the development of realistic tumor models used for diagnostic testing and therapy planning. Customized 3D-printed models-such as physical replicas, bioprinted tissues, and tumor-on-a-chip systems-demonstrate superior accuracy in predicting outcomes in drug testing, metastasis studies and disease prognosis (30). Among the various applications in oncology, 3D printing technologies are being utilized to create cardiovascular implants, porous scaffolds, Fe-CaSiO₃ bioactive scaffolds and hydrogel-based structures embedded with nanoparticles for targeted delivery (31).

4.3. Dentistry

The integration of 3D printing into dentistry has revolutionized the field by enabling fast production, high precision, and patient-specific solutions, making full dentures and dental implants more accessible. This technology supports the provision of affordable, tailored dental care while streamlining traditionally complex processes involved in manufacturing dental prosthetics and instruments (32). Prior to the adoption of 3D printing, restorations were predominantly fabricated using milling techniques. However, recent advancements show that 3D-printed restorations offer distinct advantages, including improved fit and reduced marginal and internal gaps compared to milled counterparts (33). While dental crowns were traditionally crafted using plaster models, digitally printed crowns are now gaining widespread acceptance. Studies suggest that 3D-printed crowns exhibit a better fit than those derived from conventional methods, highlighting the technology's potential despite being relatively

underexplored. Key 3D printing applications in dentistry include chlorhexidine-infused mouthguards, monolithic zirconia crowns, occlusal splints, dental implants, and customized crown restorations (34).

4.4. Diabetes

Diabetes is a chronic metabolic disorder marked by elevated levels of blood glucose. Prediabetes refers to a condition where blood sugar levels are higher than normal but not yet at diabetic thresholds. Prolonged hyper glycemia primarily damages large blood vessels, leading to macrovascular complications and over time affects smaller vessels, causing microvascular issues (35). Elevated glucose levels can impair immune function, increasing susceptibility to infections in diabetic individuals compared to those without the condition. In recent years, 3D printing and 3D bioprinting have emerged as ground breaking tools in diabetes management, facilitating the development of innovative diagnostic devices and therapeutic delivery systems (36, 37). These include sensors for real-time glucose monitoring and advanced oral dosage forms. Notable 3D printing applications in diabetes care encompass microneedle-based biosensors, electro chemiluminescent detection devices and 3D-printed tablets formulated with self-nanoemulsifying drug delivery systems (38).

5. 3D PRINTING OF DRUG DELIVERY SYSTEMS

Microneedle technology represents an advanced approach to active transdermal drug delivery, offering a potential alternative to traditional hypodermic needle injections. This system employs an array of microscopic needles-ranging in height from 25 to 2000 μm -to breach the outermost layer of the skin, the stratum corneum, enabling minimally invasive drug administration (39). One of the key advantages of utilizing 3D printing in this context is its capacity to integrate pharmaceutical compounds with challenging solubility characteristics into microneedle designs tailored to individual patient needs (**Figure 3**). The resulting microneedles ensure accurate dosage control and enhanced structural integrity when compared to conventional fabrication methods. Moreover, microneedles engineered with nanoscale-sharp tips improve skin penetration efficiency and open possibilities for precise, targeted delivery at the cellular level (40).

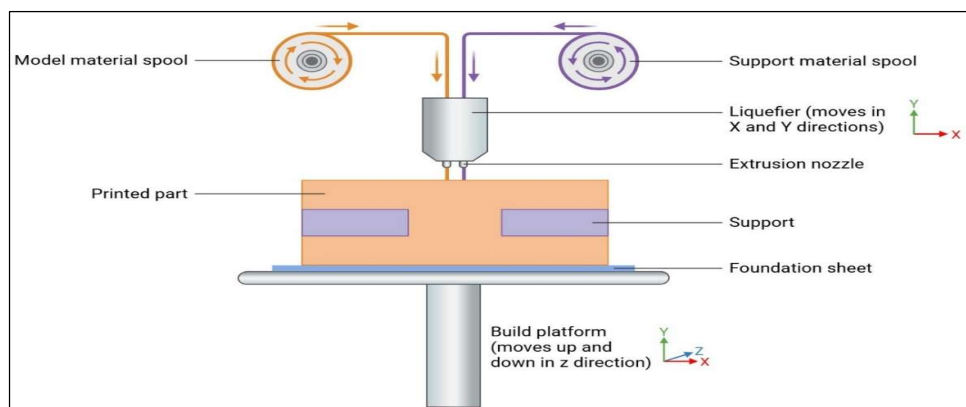


Figure 3: 3D printing modelling

5.1. Evolution in 3d printing technology

5.1.1. Multi-Material 3D Printing

One of the most significant innovations in additive manufacturing is the ability to print with multiple materials simultaneously. This advancement allows for the production of objects that incorporate diverse colors, textures, and material properties within a single print run. It holds substantial promise in advanced engineering applications and the development of customized prosthetic devices (41).

5.1.2. 4D printing

An emerging evolution beyond 3D printing, 4D printing involves creating structures that can transform their shape or function over time. These dynamic changes are triggered by external stimuli such as temperature or humidity, enabled by the use of responsive "smart" materials that adapt autonomously after printing (42).

5.1.3. Metal 3D printing

Once limited by cost and complexity, metal additive manufacturing has become increasingly accessible and efficient. Recent improvements in precision, speed and output quality have expanded its use in critical sectors such as aerospace, automotive engineering and medical implant development, where complex, high-performance metal components are essential (43).

5.1.4. Continuous 3D printing

This method enables the uninterrupted fabrication of large-scale structures, significantly reducing production time and the need for assembly or post-processing. It opens the door to printing full-sized constructions like houses, bridges, and marine vessels directly from digital models, revolutionizing construction and industrial manufacturing (44).

5.1.5. Bioprinting

Bioprinting leverages 3D printing techniques to layer living cells and biomaterials, aiming to

construct functional human tissues and organs. This frontier in regenerative medicine could one day eliminate transplant waiting lists by enabling the creation of patient-specific, biologically compatible organs (45).

5.1.6. Light-activated 3D printing

Scientists at the University of California, San Diego have pioneered a technique that uses light to initiate and control the printing process across different materials. This approach enhances precision and enables the fabrication of highly complex geometries that were previously difficult or impossible to achieve (46).

5.1.7. 3D printing with living cells

Researchers at the University of California, Berkeley have developed a method to print with living cells, producing biologically active tissues. This innovation paves the way for patients to grow personalized replacement tissues or organs, marking a major step toward regenerative therapies (47).

6. CONTINUOUS 3D PRINTING OF CARBON FIBER COMPOSITES

A team at the Massachusetts Institute of Technology has introduced a continuous printing process for carbon fiber-reinforced composites. This breakthrough allows for the creation of durable, lightweight components ideal for high-performance applications in aviation, automotive design, and advanced engineering.

6.1. 3D Printed drugs

Drugs can be made in specialised forms and dosages addressing a patient's needs with 3-D printers. The first and only 3D-printed medicine approved by the FDA is Spritam (levetiracetam) from Aprelia Pharmaceuticals. The first 3-D printer for personalised drug manufacturing has been released by Merck KGaA and FabRx recently announced a 3-D printed medicine development and manufacturing alliance with AMCM (48).

With Aprecia's ZipDose Technology, 3DP for Pharma technology is at the forefront of personalised medicine, redefining quick melt and creating new possibilities for drug administration. This technology may potentially make it easier to create deadly medications, although this raises questions about safety (49).

7. PERSONALIZED MEDICINE

Personalized medicine is an emerging and rapidly evolving field focused on customizing healthcare strategies to suit individual patients based on their distinct genetic profiles, lifestyle choices and other personal characteristics. One of the most promising innovations within this domain is the application of 3D printing technology to fabricate patient-specific medical devices, implants and prosthetics (50). This advancement holds immense potential to revolutionize personalized care by enabling the creation of medical solutions precisely aligned with a patient's unique anatomical structure and clinical needs. This technology is particularly transformative in the development of prosthetics, where conventional options often suffer from ill-fitting designs, discomfort, and restricted functionality. With 3D printing, prosthetic limbs can be engineered to match the patient's body precisely, resulting in improved comfort, usability, and overall performance (51).

Beyond prosthetics, 3D printing also opens new frontiers in pharmaceutical customization. It enables the fabrication of polypills-single dosage forms that incorporate multiple medications-allowing for simplified treatment regimens (52). Additionally, the technology supports the design of personalized drug delivery systems and precise dosing strategies, which can enhance treatment efficacy and patient adherence. By streamlining drug development and reducing production costs, 3D printing may also contribute to more affordable and accessible therapies (53). An emerging evolution of this technology, known as 4D printing, builds upon 3D printing by introducing time as a dynamic fourth dimension, allowing printed materials to change shape or function over time in response to environmental stimuli (54). While still in its early stages, this innovation could further expand the possibilities for adaptive medical devices. Looking ahead, experts anticipate that within the next 15 years, 3D and 4D printing will play a central role in advancing personalized medicine, paving the way for more targeted treatments, improved clinical outcomes, and a more patient-centered approach to healthcare (55,56).

7.1. 3D PRINTING IN THE PHARMACEUTICAL SECTOR

Innovative delivery mechanisms

3D printing facilitates the development of advanced drug delivery platforms that overcome constraints

inherent in traditional methods. A notable example is the creation of 3D-printed microneedle arrays, which allow transdermal drug administration. These devices offer a less invasive alternative to hypodermic needles, improving patient experience and adherence (57).

7.2. Custom implants

y leveraging patient-specific anatomical data, 3D printing can generate bespoke medical implants that precisely match a recipient's physiology. This customization enhances integration, functionality and safety. For example, patient-tailored spinal implants have been successfully manufactured using 3D printing techniques, leading to improved surgical outcomes (58).

7.3. Regenerative medicine and scaffolding

The technology supports the fabrication of intricate 3D scaffolds that promote tissue regeneration. These structures serve as frameworks for growing new biological tissues, with applications in repairing damaged skin, bone, or cartilage. Researchers have already engineered biocompatible scaffolds via 3D printing to support bone tissue reconstruction (59).

7.4. Pharmaceutical testing and screening

3D printing can produce biologically relevant, three-dimensional tissue models ideal for evaluating drug responses. These models offer a more accurate representation of human physiology than traditional 2D cultures, reducing reliance on animal experimentation. For example, 3D-printed liver tissue constructs have been utilized to assess drug toxicity and metabolism (60).

7.5. Training and educational tools

The creation of detailed physical models of molecules, organs, or medical devices through 3D printing enhances learning and professional training. These tangible representations help students and healthcare practitioners grasp complex pharmaceutical and anatomical concepts more effectively. Educational institutions have adopted 3D-printed molecular models to improve science instruction (61).

7.6. Quality assurance applications

3D printing allows the production of precise replicas of pharmaceutical components or medical devices for inspection and validation. These models assist in identifying manufacturing defects or design inconsistencies early in development. For instance, 3D-printed capsule models have been used to verify product specifications and ensure consistency (62).

7.7. Accelerated development through prototyping

The ability to quickly produce prototypes of new drugs, delivery devices, or equipment accelerates research and development timelines. This rapid iteration reduces costs and supports innovation. Inhalers, for example, have been prototyped using 3D printing to test design variations efficiently (63).

7.8. Intellectual property protection

3D printing enables the creation of detailed physical models of pharmaceutical inventions or medical devices for patent submissions. These models provide clear, tangible evidence of novel designs, aiding in the protection of intellectual property and deterring unauthorized replication. Companies have used such models in patent applications for new medical technologies (64).

7.9. Advanced drug formulation

3D printing allows for the design of formulations with improved characteristics such as enhanced solubility, stability, and bioavailability. By precisely controlling the internal architecture of dosage forms, this technology enables the development of complex release profiles and combination therapies, paving the way for next-generation medicines (65).

8. INKJET PRINTING (IJP)

A technique known as mask-less or tool-free fabrication, inkjet printing enables accurate and reproducible structural formation by leveraging the motion of either the print nozzle or the substrate. This method operates by ejecting fine ink droplets onto a non-powder surface, where they solidify after deposition (66). When combined with a powdered foundation, it allows for the controlled delivery of precise amounts of active pharmaceutical ingredients. Inkjet-based 3D printing (3DP) is versatile, supporting a broad range of materials such as resins, ceramics and food-safe inks. The process builds up the final object layer by layer (LbL), with the print head meticulously placing material in a pre-programmed arrangement (67).

Inkjet printing (IJP) is a form of additive manufacturing that enables the precise, layer-by-layer deposition of ink-based materials to fabricate either three-dimensional structures or two-dimensional designs, with fine control over both architecture and composition. This method has

gained significant attention as a flexible and innovative solution to meet the growing need for customization in modern healthcare and personalized medicine (68). While initially designed for non-medical purposes, IJP has evolved through the development of pharma-inks-specially engineered formulations that incorporate active pharmaceutical ingredients along with suitable excipients. A close examination of these pharma-inks, including their composition and design principles, reveals the foundation behind IJP's ability to deliver accurate and customizable material placement (69, 70).

Continuous inkjet printing (CIJP) operates by employing a high-pressure pump to push ink through a nozzle, generating a constant liquid jet. Surface tension causes this jet to fragment into individual droplets, with the droplet generation rate being adjustable via frequency modulation (71). For pattern creation, selected droplets are electrically charged by electrodes and then steered by electrostatic deflection plates. The charged droplets are directed onto the target surface, while those left uncharged continue on a non-deflected path and are collected for reuse. Although the mechanics of droplet generation and deflection in CIJP are well-documented in existing literature, they fall outside the scope of this review (72).

Conversely, drop-on-demand (DoD) printing relies on electrical signals to dispense minute quantities of liquid only when needed. DoD systems utilize two primary printhead types: thermal and piezoelectric (**Figure 4**). In thermal inkjet printing, an electric pulse heats a resistive element within the printhead, rapidly raising the ink's temperature-often to 200-300 °C-forming vapor bubbles that expand and force a droplet out of the nozzle (73). In piezoelectric inkjet printing (PIJP), the printhead contains a piezoelectric material that changes shape in response to an applied voltage, mechanically pushing a droplet out through the nozzle (74).

Table 1: 3D printing technology in pharmaceutical industry

Technology	Working Principle	Ingredients	Applications	References
Inkjet	Droplet deposition	API solutions	Buccal Films	66,67
SLS	Laser sinters powders	Polymer blends	Sustained Release products	68
SSE	Semi-solid extrusion	Hydrogels	Patches	69
Binder Jetting	Binder fuses powder	Lactose	Fast Dissolving Tablets	70,71
SLA	UV-curing resin layers	Photopolymers	Implants	72,73
FDM	Extrusion of heated filaments	Polyvinyl alcohol	Chewable tablets	74

DoD technology is widely favoured in pharmaceutical contexts due to its exceptional precision and compatibility with automated processes, enabling controlled and reproducible deposition of functional inks. Both thermal and piezoelectric approaches offer distinct pros and

cons. Thermal printheads are generally more cost-effective to produce, though concerns exist about their suitability for heat-sensitive compounds (75). However, this concern remains largely theoretical, as the interaction time between the heating element and the ink is extremely brief-approximately 2

microseconds-which may prevent significant thermal degradation, even for delicate biomolecules like deoxyribonucleic acid (DNA). In comparison, PIJP offers greater versatility in handling diverse

pharma-inks, including those with higher viscosities or temperature sensitivity, making it a preferred choice for many advanced pharmaceutical formulations (**Table 1**) (76).

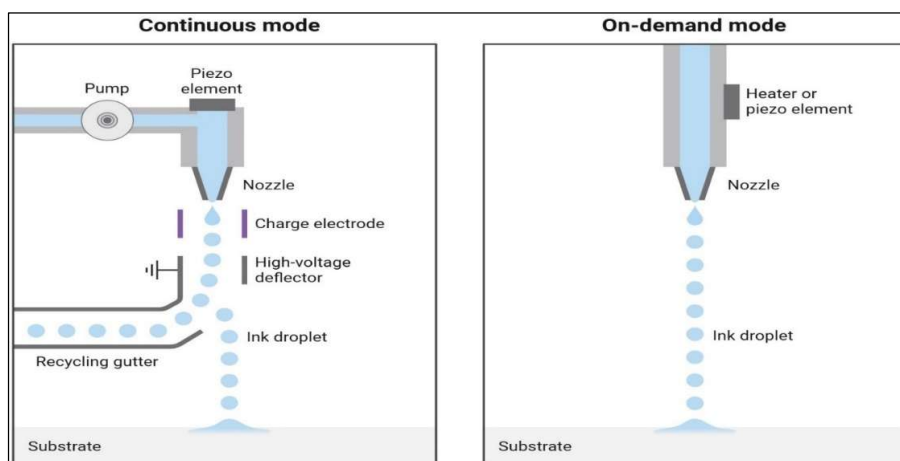


Figure 4: Inkjet modes of 3D printing

9. ADVANCEMENT OF SUSTAINED RELEASE DESIGN BY 3D PRINTING

The advancement of sustained medication by 3D printing has significantly enhanced the precision, efficacy and safety of medication therapy. By leveraging additive manufacturing, it is now possible to engineer customized drug delivery platforms with highly accurate temporal and spatial control over medication release (77). One approach involves the design of porous architectures using 3D printing, where interconnected pores serve as reservoirs for drug payloads. These porous matrices facilitate sustained release through diffusion. For example, researchers have fabricated 3D-printed scaffolds loaded with ciprofloxacin, an antibiotic, which exhibited a consistent and prolonged release profile over several days, ideal for localized infection control (78). Another innovative strategy integrates drug-loaded microspheres into 3D-printed devices. These microspheres act as miniature depots that release their contents gradually as they degrade or dissolve. A notable application includes a 3D-printed implant designed for the extended delivery of dexamethasone, an anti-inflammatory agent. By adjusting the concentration and distribution of microspheres within the device, researchers achieved a controlled release spanning multiple weeks, offering potential for chronic inflammatory conditions (79).

Additionally, multi-material 3D printing enables the fabrication of composite structures with distinct release kinetics. In one study, a dual-material device was developed to deliver doxorubicin, a chemotherapy agent. One component provided

immediate drug release, while the other ensured a slow, sustained delivery. This dual-phase release mechanism allows for targeted treatment of tumour cells with improved therapeutic outcomes and reduced systemic toxicity (80).

Beyond these strategies, 3D printing supports the creation of personalized dosage forms tailored to individual patient requirements. The technology allows for intricate geometries that modulate drug release rates and enables the production of multi-layered tablets, each layer engineered for a specific release profile such as immediate, delayed, or extended release. This level of customization enhances patient compliance and therapeutic performance (81). Overall, 3D printing is revolutionizing drug delivery by enabling precise control over release dynamics, structural complexity and material composition. These capabilities are particularly beneficial for managing chronic diseases requiring long-term, consistent medication levels, ultimately improving treatment efficacy, minimizing side effects and advancing personalized medicine (82).

10. PROSTHETICS AND MEDICAL IMPLANTS IN 3D PRINTING

3D printing has revolutionized the development of prosthetics and medical implants, enabling the rapid and precise fabrication of patient-specific devices tailored to individual anatomical structures. This technology has opened new possibilities in healthcare, offering customized solutions that enhance both functionality and comfort.

10.1. Paediatrics

In the field of prosthetics, 3D printing has made a significant impact, particularly for children born with limb differences or those who have undergone amputations. A notable example is the work of the e-NABLE community-a worldwide collective of volunteers who design and produce affordable, customizable 3D-printed prosthetic hands for children. These low-cost devices have dramatically improved mobility and quality of life for many young patients who might otherwise lack access to traditional prosthetics (83).

10.2. Dentistry

Dentistry has also embraced 3D printing to create personalized dental implants. By using CT scan data from individual patients, clinicians can fabricate implants with exceptional accuracy. These are typically printed using biocompatible materials such as titanium, ensuring both safety and durability. The resulting implants offer a superior fit, enhancing patient comfort and long-term performance (84).

10.3. Orthopaedic

Orthopaedic medicine has similarly benefited, with 3D printing being used to produce joint replacements such as hips and knees. These custom implants are designed to mirror the patient's unique bone structure, leading to better alignment, reduced recovery times, and improved surgical outcomes (**Figure 5**). For instance, a titanium hip implant was successfully created using 3D printing for a patient suffering from osteonecrosis. The precise anatomical match contributed to a successful procedure and faster rehabilitation (85).

Beyond these applications, 3D printing is being used to manufacture a wide range of implantable devices, including vascular stents, artificial heart valves, spinal implants and custom joint replacements. Innovative developments even include carbon-based 3D-printed artificial retinas, which are being explored to restore partial vision in individuals with certain types of blindness (86). Additionally, facial reconstruction has advanced through the use of 3D-printed jaw implants following tumour removal, while personalized clavicle implants have been successfully implanted in surgical patients. A major advantage of 3D printing lies in its ability to produce complex geometries with high precision, minimal material waste and reduced production time (87). This makes it ideal for creating bespoke medical solutions at a lower cost compared to conventional manufacturing methods. As a result, access to personalized prosthetics and implants is expanding, especially in underserved regions (88).

11. CUSTOMIZATION OF PROSTHETICS AND IMPLANTS IN 3D PRINTING

One of the most significant benefits of 3D printing in the field of prosthetics and medical implants is its capacity for personalization. Below are several examples illustrating how this technology enables tailored solutions in healthcare:

11.1. Cranial implants

3D printing has been used to fabricate patient-specific implants for individuals who have undergone cranial surgery. By leveraging CT scan data from the patient, these implants are digitally designed to match the unique contours of the skull and then printed using biocompatible materials such as titanium. This precise fit enhances surgical outcomes and promotes faster recovery (89).

11.2. Maxillofacial reconstruction

For patients requiring facial or jaw surgery, 3D printing allows the production of customized implants based on individual anatomical data. Using CT imaging, surgeons can design implants in titanium or other compatible materials that align perfectly with the patient's facial structure, leading to improved functional and aesthetic results (90).

11.3. Prosthetic limbs

3D printing enables the creation of personalized prosthetic limbs that conform exactly to the residual limb of the patient. These prosthetics can be printed using various materials-including ABS, PLA and nylon-offering flexibility in strength, weight, and durability. Design adjustments can be made to enhance both comfort and functionality, meeting the specific lifestyle demands of the user (91).

These applications demonstrate the transformative role of 3D printing in enabling highly customized medical devices. By producing implants and prostheses that mirror a patient's unique anatomy, the technology contributes to superior clinical outcomes and enhanced quality of life (**Figure 5**). Beyond implants, 3D printing is also used to develop patient-tailored surgical tools, such as guides for tibial osteotomies and implants for complex bone defects, such as those resulting from pelvic tumour resection. Additionally, the technology supports the fabrication of lightweight, intricately designed prosthetics that improve usability, comfort and appearance. A further advantage is the ability of prosthetists to thermally adjust 3D-printed components using a heat gun, allowing on-the-spot modifications for optimal fit and patient satisfaction (92).

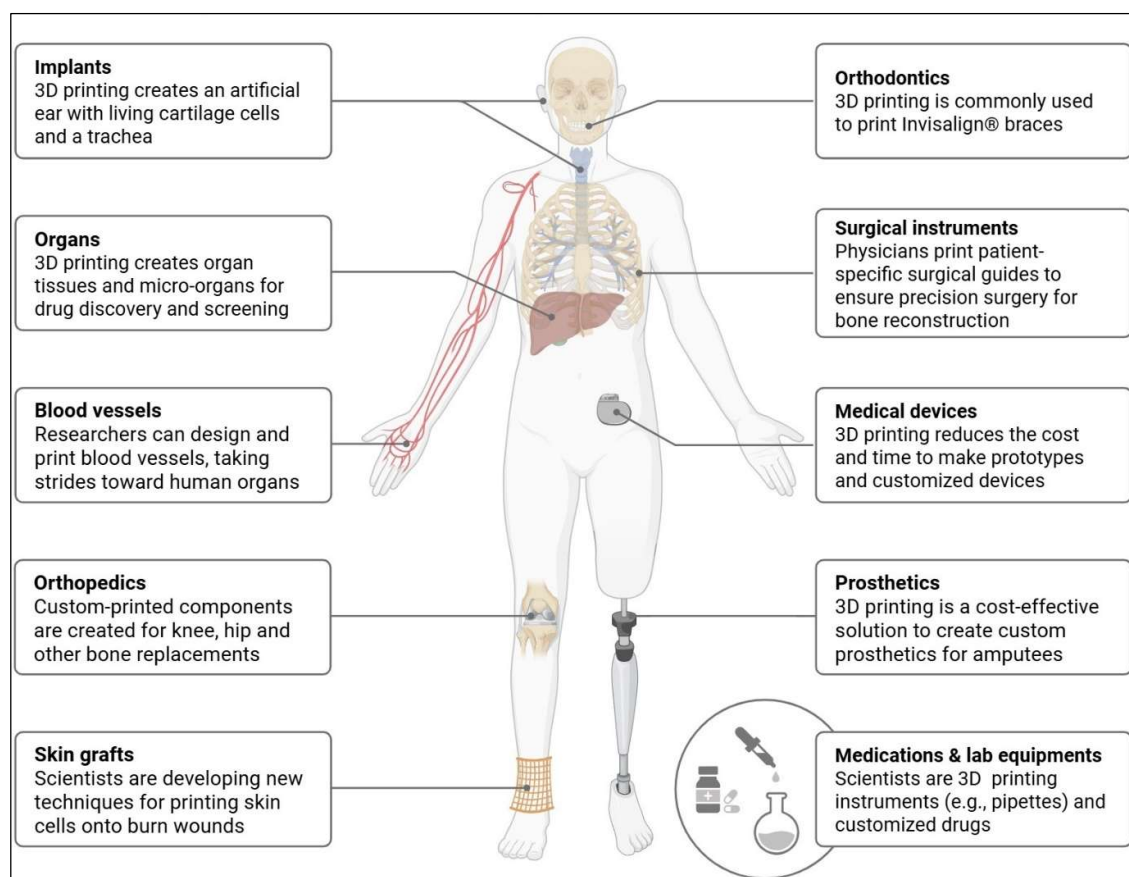


Figure 5: Application of 3D printing technology in medicine

12. CONCLUSIONS

The advent of 3D printing is revolutionizing the pharmaceutical industry by enabling the creation of bespoke dosage forms tailored to unique patient profiles. By facilitating the production of customized medications-such as multi drug “polypills”-this technology serves as a cornerstone for personalized medicine. It is especially transformative for vulnerable groups like children and elderly, where modifying physical attributes like form, texture, or flavour can substantially boost medication compliance.

Beyond oral doses, 3D printing is expanding its reach into regenerative medicine through the development of biocompatible scaffolds and drug-eluting implants, often integrated with stem cell research. Breakthroughs in specialized materials-such as hydrogels, responsive polymers, and sophisticated bio-inks-are driving rapid improvements in both tissue engineering and

controlled drug delivery, even as the field navigates ongoing technical and regulatory challenges.

The long-term outlook for 3D printed therapeutics is exceptionally bright. As material science matures and precision manufacturing techniques become more refined, we can expect a shift toward highly site-specific therapies and individualized medical hardware. Achieving this vision will require ongoing interdisciplinary collaboration and a commitment to rigorous research to ensure these advancements translate into improved patient outcomes.

This article provides a comprehensive overview of current industry trends, technological milestones and ongoing development arc of 3D-printed drugs. As these frameworks mature and technology evolves, 3d printing is poised to become a foundational element of a more intelligent, precise and patient-centered pharmaceutical manufacturing ecosystem.

13. FUTURE SCOPE

The field of additive manufacturing is evolving at a breakneck pace. As industries demand increasingly specialized materials to meet precise performance standards, the variety of available options is set to expand significantly. For high-end industrial

printers, the key to the next generation of hardware lies in versatility-specifically the capacity to process a boarder spectrum of sophisticated materials. The shift is enabling companies to apply 3D printing to sectors that were once out of reach.

Author's Contribution

The all authors played an important role for the conceptualisation and design of the study, data collection, writing, editing, data interpretation, drafting and sketching of diagram for build up the good quality of manuscript and gave the final approval for the manuscript to be published.

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