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REVIEW ARTICLE

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3D printing in drug delivery: A review of emerging technologies and applications

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ABSTRACT

Background: Three-dimensional (3D) printing is emerging as a versatile pharmaceutical manufacturing technology capable of producing personalized dosage forms with tailored drug loading, geometry, and release characteristics.

Scope: This review summarizes recent advances in pharmaceutical 3D-printing technologies, including fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography (SLA), and hybrid approaches, with particular emphasis on personalized dosage forms, controlled drug release, and multi-drug polypills.

Key Findings: Recent studies demonstrate the ability of 3D printing to achieve programmable drug-release profiles and individualized dosing. Notably, hybrid SLS–FDM tablets have demonstrated approximately 12 h of controlled drug release with near-zero-order kinetics, highlighting the potential for precise modulation of drug liberation. Clinical application in maple syrup urine disease (MSUD) has also demonstrated improved control of blood leucine concentrations using individualized 3D-printed dosage forms. Furthermore, 3D-printed polypills have demonstrated the feasibility of incorporating multiple drugs into a single dosage form with tailored release characteristics.

Main Challenges: Despite these advances, translation into routine pharmaceutical manufacturing remains constrained by relatively low production throughput compared with conventional tablet compression, formulation and material limitations, dose uniformity, process reproducibility, scalability, quality control, regulatory requirements, and limited commercial adoption.

Outlook: Future research should focus on increasing printing speed and manufacturing scalability, establishing robust process-validation and regulatory frameworks, and generating stronger clinical evidence. Integration of digital manufacturing with personalized dosing and advanced drug-release design could position 3D printing as a valuable platform for patient-specific pharmaceutical therapy.

KEYWORDS

Lithography; Polymers; Microsyringes; Drug delivery; Microneedles; 3D printing

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Introduction

Numerous methods have been studied for usage in pharmaceutical applications, ink-jet printing, stereolithography (SLA), pressure-assisted microsyringe (PAM), and multi-material 3D printing [1]. This additive manufacturing technology, which creates objects layer by layer using computerized patterns, allows for hitherto unheard-of flexibility and precision in drug composition and delivery. In the 1980s, Charles Hull originally put out the concept of additive manufacturing, now known as 3D printing. The technology, which was first applied in industries like aerospace and automotive, has now spread to the pharmaceutical and medical fields, opening the door for cutting-edge drug delivery systems and creative approaches to personalized care [2].

3D printing offers a number of advantages in the pharmaceutical industry. It makes it possible to create complex shapes, precisely control medication release patterns, and create dose forms that are tailored to the needs of individual patients. In an era where precision medicine is growing in importance, this level of personalization is particularly essential since it enables medical practitioners to increase medication efficacy while lowering side effects. FDM, SLA, and powder bed fusion (PBF) are the three primary 3D printing techniques utilized in pharmaceutical applications. Each of these approaches has unique benefits and limitations, making them suitable for certain aspects of drug development and delivery. For instance, SLA offers superior resolution and is perfect for creating intricate designs, whereas FDM is more often used because of its price and ease of usage [3].

Making customized dosage forms is a very potential use of 3D printing in the pharmaceutical industry. Because traditional tablet manufacturing techniques are limited in their ability to provide a wide range of dosages, pill-splitting or liquid versions are sometimes required for precise dosing. This limitation is overcome by 3D printing, which makes it possible to precisely position active pharmaceutical ingredients (APIs) in various sizes and forms, allowing for the on-demand production of customized dosages for patients [4].

History

When Pierre A. L. Giraud described the procedure of depositing powdered material and hardening each layer with a high-intensity beam in the early 1970s, the concept of three-dimensional printing, or 3DP, was born. In this instance, the product might be made by melting materials like metal or plastic. In a patent titled "A molding process for forming a three-dimensional article in lavers." Ross Householder

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around the beginning of the 1980s. Carl Deckard, however, created a technique called selective laser sintering (SLS) that uses laser beams to harden powdered layers. The first technique that Chuck Hull created and pushed was stereolithography (SLA). This process depended on the UV light-induced photo-polymerization of liquid resin. In the late 1980s, Scott Crump submitted a patent application for fused deposition modeling (FDM), a method of producing objects using thermoplastic materials. In the 1990s, MIT scientist Emanuel Sachs developed "three-dimensional printing methods" by combining specific powder regions with a binding agent [5].

The benefits of 3D printing technology in the pharmaceutical industry

Tailored medicine for unique groups

Medication safety and health for particular populations, such as children and the elderly, have long been major concerns. Children go through a lot of growth and development, which makes them especially sensitive to drugs and reactive. The elderly usually struggle with several health concerns and overlapping drugs, and they frequently have reduced absorption and metabolic skills. Children's prescriptions are sometimes administered by manually splitting tablets, which can be both inaccurate and damaging to the preparation's structure, perhaps leading to adverse effects, even if contemporary pharmaceutical dosages are consistent and there are few specialty drugs for particular groups. By altering model attributes like size, shape, or density, three-dimensional printing technology is incredibly flexible and may produce particular drugs. 3D printing technology makes it possible to create low-dose, kid-specific pharmaceuticals for pediatric patients while also improving the taste and look of the drugs to increase young patients' adherence. 3D printing can create loose and porous formulations that help older people who have trouble swallowing take their prescriptions. To improve medication safety and efficacy for patients taking numerous prescriptions at once, different medications can be separated and blended into a single tablet to avoid errors or missed doses. Additionally, to help patients who are blind or visually challenged, special symbols can be printed on the surface of the medication or specially shaped formulations can be produced. Some 3D printed pharmaceutical companies are moving closer to personalized treatment thanks to the advantages of 3D printing technology for tailored drug administration. Such as Fab Rx in the UK, which develops customized drugs for kids with maple syrup urine disease and has set up SSE printers in a pharmacy at a hospital in Spain, doing out clinical research on the subject [6].

The other Benefits such as

Accurate management of drug release

Quick integration of manufacturing [7].

Summary of 3D printing

The idea behind 3D printing is building things layer by layer. The process begins by creating a computer-aided design (CAD) file that outlines the medication's dimensions, shape, and release properties, along with any required supporting elements. For sustainable manufacturing practices, this technology's capacity to produce customized parts and minimize material waste is essential. Recent advancements in 3D printing have allowed for total control over the translation, rotation, and scaling of individual layers during the fabrication process, converting the printing process from a static approach to a dynamic assembly technique. This facilitates the easy integration of different materials and the development of patient-specific structures, such as vascular scaffolds based on MRI data, increasing performance and versatility. An overview of workflow for fabricating 3D bioprinting illustrated in Figure 1 [8].

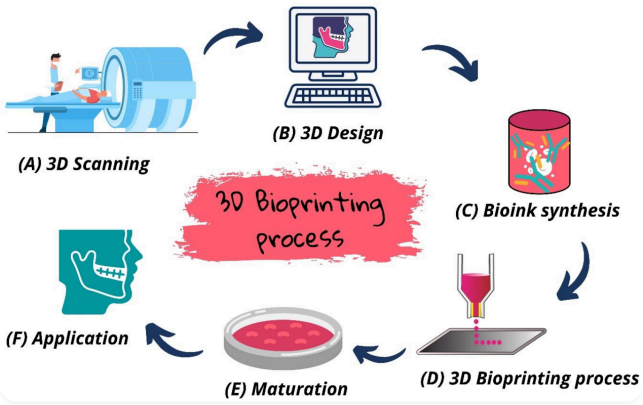


Figure 1. A summary of the 3D bioprinting workflow.

Approaches to 3D printing in drug delivery

Several 3D printing techniques have been adapted for application in the pharmaceutical industry. Each with its own strengths depending on how they print, what materials they work with, and the results they're meant to deliver.

Fused Deposition Modelling (FDM)

It involves extruding thermoplastic polymers or drug-loaded filaments through a heated nozzle, building up solid objects layer by layer. Figure 2 shows how thermoplastic filament containing drugs is heated and extruded through a nozzle, under CAD control, to build solid dosage forms layer by layer.

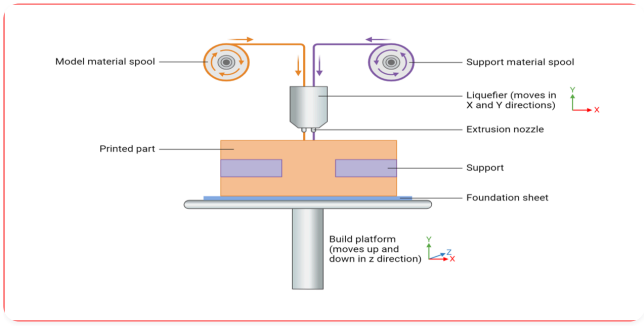


Figure 2. A fused deposition modeling system.

Inkjet printing

Using thermal or piezoelectric nozzles, inkjet printing is a non-contact method that applies tiny droplets of ink or medication solution to a substrate. It allows for exact control over droplet size and location when operating in either continuous or drop-on-demand modes. Dispersible films, quickly disintegrating tablets, and multi-drug dosage forms are all made possible by inkjet printing, which is particularly useful for low-viscosity, aqueous, or solvent-based formulations. Contrasts on-demand mode, which uses thermal or piezoelectric actuation to assure precise drug delivery, with continuous mode, which uses electrostatic forces to regulate drug droplets (Figure 3).

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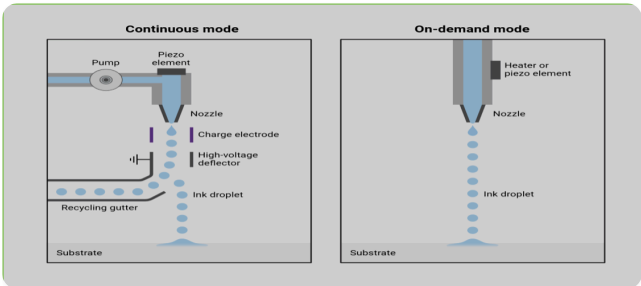


Figure 3. Inkjet printing.

Stereolithography

Stereolithography, which includes digital light processing (DLP), selectively cures layers of photosensitive resin into solid three-dimensional objects using ultraviolet (UV) lasers or projected light. SLA is ideal for producing intricate drug delivery systems like microneedles, transdermal patches, and biodegradable implants because of its remarkable accuracy and precise surface detail. It makes precise control over drug delivery and device form possible. However, when applying SLA in the pharmaceutical industry, the necessity of polymerization additives and the possibility of photodegradation in delicate drugs are important considerations. Figure 4 shows how layers of photosensitive resin containing medication are cured by a UV laser to create precise structures utilized in the production of implants and microneedles.

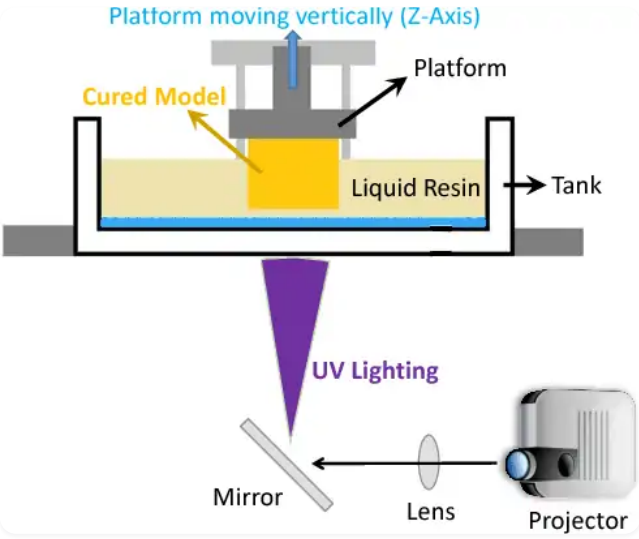


Figure 4. Stereolithography.

Selective Laser Sintering (SLS)

It is a powder-bed fusion-based additive manufacturing technique that fabricates three-dimensional structures by selectively fusing successive layers of powdered material using a focused laser beam. Unlike solvent-based manufacturing approaches, SLS can process polymeric powders and polymer–drug blends without the need for conventional liquid binders. During fabrication, a thin layer of powder is deposited onto the build platform, followed by selective laser irradiation of the regions corresponding to the desired geometry. The laser energy promotes localized sintering or partial melting of the particles, and repeated powder deposition and laser scanning progressively build the final three-dimensional structure. SLS has been investigated for the fabrication of porous drug-delivery systems, implantable scaffolds for tissue regeneration, and customized dosage forms. The process enables modulation of the internal porosity, geometry, and mechanical properties of the fabricated structure and can be particularly advantageous for thermally stable drug substances.

Figure 5 illustrates the SLS process, showing powder-bed deposition, selective laser scanning/sintering, layer-by-layer fabrication, and the resulting three-dimensional structure.

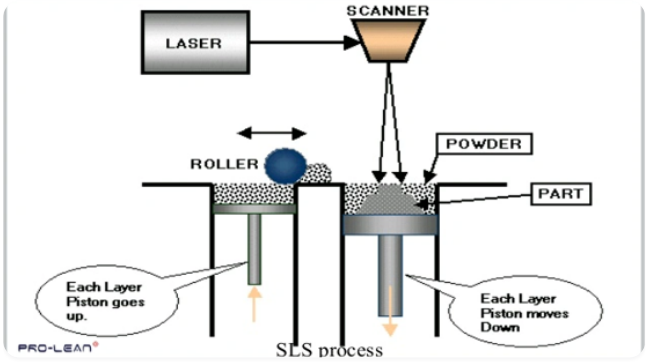


Figure 5. Selective laser sintering.

Multi-material 3D printing

Multi-Material 3D printing deposits various polymers, APIs, or excipients simultaneously in a single construct by combining two or more printing techniques or using multiple print heads. This method enables the creation of complex drug delivery systems, such as segmented structures with adjustable release profiles, multilayer tablets, and polypills. However, sophisticated software, material compatibility testing, and stringent quality control measures are needed to manage various materials and printing settings. Created a unique hybrid printing method that blends FDM and SLS (Figure 6) [9].

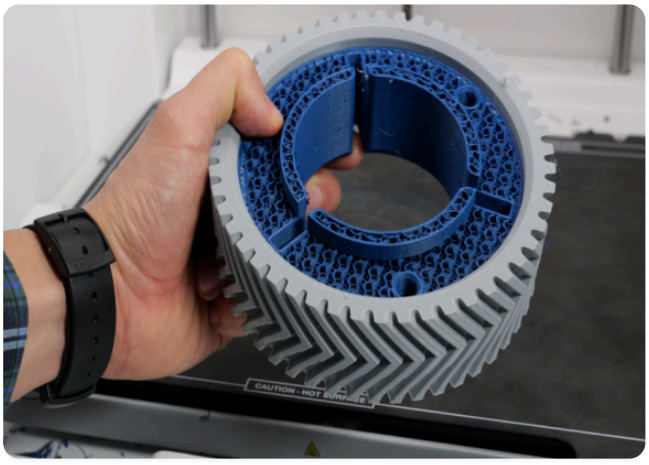


Figure 6. Multi-material 3D printer.

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Table 1. Comparative overview of major 3D-printing techniques for pharmaceutical applications.

3D-printing technique	Printing principle	Typical materials/formulations	Major advantages	Major limitations	Pharmaceutical applications
Fused Deposition Modeling (FDM)	Drug-loaded thermoplastic filament is heated, melted and extruded through a nozzle layer-by-layer	PVA, PVP, HPMC, HPC, PEO, Eudragit® and other thermoplastic polymers	High dimensional control; solvent-free printing; suitable for complex geometries; relatively accessible technology	Requires elevated temperature; limited to thermally stable APIs/excipients; filament preparation required; relatively slow compared with conventional tablet compression	Immediate- and modified-release tablets, implants, polypills, controlled-release systems
Semi-Solid Extrusion (SSE)	A viscous/semi-solid formulation is deposited through a nozzle under pneumatic or mechanical pressure	Hydrogels, polymer pastes, HPMC, poloxamers, lipids, starch-based formulations	Low processing temperature; suitable for thermolabile drugs; flexible formulation composition	Requires appropriate rheological properties; drying may be required; lower mechanical strength in some products	Pediatric formulations, orally disintegrating tablets, buccal systems, films, personalized dosage forms
Selective Laser Sintering (SLS)	A laser selectively fuses/sinters successive layers of drug-containing powder	Thermoplastic polymers, pharmaceutical powders, drug–excipient blends	Nozzle-free; complex geometries; high porosity can be achieved; useful for modified drug release	Thermal/laser exposure may degrade sensitive APIs; powder characteristics strongly affect printing; process optimization is critical	Immediate- and modified-release tablets, polypills, porous dosage forms
Stereolithography (SLA)	UV/visible light selectively photopolymerizes a liquid resin layer-by-layer	Photocurable polymers/resins, photoinitiators and compatible APIs	High resolution and dimensional accuracy; complex structures can be produced; relatively fine features	Limited pharmaceutical-grade photopolymers; potential photochemical/API degradation; post-print washing and curing may be required	Drug-loaded implants, microneedles, complex oral dosage forms and drug-delivery devices
Digital Light Processing (DLP)	A projected light pattern simultaneously cures an entire layer of photosensitive formulation	Photocurable polymers/resins and drug-containing formulations	High resolution; rapid layer curing; complex geometries; potentially faster than point-by-point photopolymerization	Limited printable materials; photoinitiator and light compatibility issues; residual monomer/post-processing concerns	Personalized tablets, implants, microneedles and complex drug-delivery systems
Inkjet Printing (IJP)	Microliter/nanoliter-scale droplets of drug-containing ink are deposited accurately onto a substrate or successive layers	Drug solutions, nanosuspensions, polymer solutions and solvent-based formulations	High printing precision; suitable for low-dose drugs and microdosing; relatively high printing speed	Requires low-viscosity printable inks; nozzle clogging; solvent evaporation/drying required; drug solubility limitations	Personalized dosing, oral films, polypills, microdosing and drug-loaded coatings
Binder Jetting (BJ)	Binder droplets are selectively deposited onto successive powder layers to bind particles into the desired structure	Drug–excipient powders with aqueous or organic binder solutions	Can produce highly porous dosage forms; does not require melting of the entire formulation; high drug loading possible	Post-processing/drying required; friability can be an issue; powder recovery and binder distribution must be controlled	Orodispersible tablets, porous tablets, high-dose formulations and personalized medicines

Drug Delivery Methods Using 3D Printing [10]

Pressure-Assisted Micro syringe (PAM)

PAM method utilizing polysaccharides

The scaffold is made of alginate hydrogel fibers that have been ionically crosslinked, coated with chitosan, and combined with bone cells and diclofenac. The scaffolds were grown with activated macrophages that released proinflammatory modulatore [10,11].

The findings showed that, in comparison to the control, the chitosan coating tripled the amount of diclofenac loaded in the scaffold. Additionally, because of the creation of a cross-linked network between the two polymers—the positive groups (NH+) of chitosan molecules creating ionic interactions with the negative groups (COO−) of alginate molecules—the coated sample displayed a delayed release profile. They showed greater mineralization and up regulated expression of genes encoding proteins that contribute to extracellular matrix remodeling, rendering it appropriate for use in bone regeneration.

Inks with higher concentrations were considered more appropriate for fabricating calcium phosphate-based scaffolds, effectively tackling both infection and bone regeneration at the same time [12].

A total of 1% w/w of genipin (calculated from the chitosan mass) was incorporated into the mixture as a crosslinking agent, and then subjected to homogenization. A total of 2% w/w of levofloxacin (calculated from the mass of inorganic component) was incorporated into the 3% w/w chitosan solution prior to combining it with BCP powder to create levofloxacin-loaded scaffolds, facilitated by the absence of a sintering step [12].

Chitosan and pectin are frequently used in crosslinked forms to produce polyelectrolyte films or networks, useful for the development of colon targeted drug delivery systems [13].

The artificial scaffolds showed great printability, robust physical strength, and were flexible and capable of adhering to the skin on their own. Thus making more useful for wound dressings.

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The PAM 3D printing technique has also been utilized to employ other polysaccharides, such as those from Astragalus root and Snake gourd root, which are rarely used in drug delivery systems but are derived from traditional Chinese medicine.

It has been shown that 3D printing technology may be used to produce hydrogels in a variety of shapes that can be tailored to match the complex and different forms of diabetic ulcers of particular individuals, demonstrating the enormous promise this technology offers in personalized treatment. These formulations' biocompatibility is improved by the addition of natural ingredients, indicating significant potential for use in the future.

PAM method utilizing proteins

Because of its low viscosity behavior during extrusion and its capacity to create a shape-stable gel after ink application, a 10% w/v gelatin colloidal solution was chosen. Consequently, the gelatin solution's viscosity was sufficient to create a continuous filament and regulate the printed scaffolds' shape [14]. The medication was added to the formulation at a concentration of 4 mg/mL, and 20% w/w lactose was used as a plasticizer and cross-linking agent. Gelatin scaffolds can transport dexamethasone, which is crucial for reducing the harmful side effects associated with long-term or widespread usage of glucocorticosteroids, Thus, the development of biomaterials for precise medication distribution is made possible by integrating gelatin with 3D printing technology, which lowers the possibility of systemic side effects.

PAM method utilizing a combination of polysaccharides and proteins

For use in bone tissue engineering, PAM-based 3D-printed composite scaffolds coated by layer-by-layer (LBL) deposition have been created using a variety of natural materials. Specifically, porous hydroxyapatite (HAP) scaffolds made via PAM bio-printing were coated with sodium hyaluronate and chitosan utilizing the layer-by-layer (LBL) approach.

Sodium hyaluronate is used to treat osteoarthritis in the knee and to reduce arthritis-related discomfort. Additionally, it makes it easier and longer to obtain and use eye drugs. It can be utilized to bond biomaterials in tissue engineering because of its capacity to suppress immunological responses.

MC-3T3E1 cells exhibited great biocompatibility with scaffolds coated with LBL, creating the perfect environment for cell adhesion and growth. It suggests that printed hydroxyapatite composite scaffolds have a great deal of promise as bone regeneration solutions and as medication and growth factor transporters [10].

PAM method utilizing lipids

Despite studies showing its efficacy, safety, and acceptability in children when employing lipids, no commercially accessible oral formulations based on chocolate have been commercialized to far. Theobroma oil, which has a melting point between 31 and 34 degrees Celsius, is the primary ingredient in chocolate and has historically been used as a foundation for suppositories Chocolate has previously been tested for its ability to cover up the bitter taste of oral formulations, increasing children's willingness to take their medications.

Recently, 3D printing technology was used to create a chocolate-based formula for kids. 3D printing using PAM Melting dark chocolate and combining it with corn syrup that contained dissolved paracetamol or melted ibuprofen resulted in drug-laden chocolate inks with final concentrations of 22.9 mg/g and 19.6 mg/g, respectively [15].

In simulated saliva, the chewable chocolate-based dose forms demonstrated rapid and significant drug breakdown. Therefore, a formulation that is especially enticing to kids is created by combining the personalization potential of 3D printing with the allure of real chocolate [16].

3D Printing Applications

This enables the production of drug-delivery systems customized in size, shape, dosage, architecture, porosity, and release profiles. This makes it particularly beneficial for customized and individualized medication delivery.

Personalized drug delivery

3D printing enables patient-specific dosage forms by adjusting the dose, size, shape and drug-release characteristics according to individual therapeutic requirements. This is especially helpful for pediatric, geriatric, and patients needing customized dosages.

Controlled and modified drug release

The internal geometry, porosity, infill density and polymer composition of a printed dosage form can be modified to achieve immediate, sustained, delayed or pulsatile drug release.

Polypill technology

Several APIs can be integrated into one 3D-printed dosage unit. Different compartments or layers can provide independent drug-release profiles, thereby reduce pill burden and potentially improve patient compliance.

Complex oral dosage forms

3D printing can manufacture tablets, capsules, films, pellets and other geometrically complex dosage forms that may be difficult to produce using conventional manufacturing techniques.

Implantable drug-delivery systems

Customized implants and drug-loaded devices can be fabricated with controlled drug release and patient-specific dimensions, providing localized and prolonged drug delivery.

Transdermal and microneedle delivery

3D printing can be used to fabricate customized microneedles and other cutaneous delivery systems, providing minimally invasive drug administration and potentially improving localized or systemic delivery.

Targeted and localized drug delivery

Designs for complex structures and multi-material printing can be engineered to regulate the timing and manner of drug release. They enables the localized treatment and sophisticated targeted delivery methods.

Patient-friendly dosage forms

Dosage forms can be tailored regarding their shape, size, and drug potency. They could enhance acceptability and adherence, especially among pediatric and geriatric groups.

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On-demand manufacturing

3D printing could enable the on-demand production of medicines, bringing manufacturing closer to where care is delivered. This could be beneficial for personalized treatment and distributed pharmaceutical production.

Advanced and regenerative drug-delivery systems

3D bioprinting can be integrated with hydrogels, bioinks, and other biomaterials to support localized drug delivery, tissue engineering, and regenerative medicine [17].

Quality control and evaluation

The important evaluation parameters include:

Appearance and dimensions

The printed dosage form is examined for shape, surface defects, dimensions, and consistency.

Weight variation – Individual units are weighed to determine uniformity of the printed dosage forms.

Drug content and content uniformity – The amount and distribution of drug in individual print lets are determined to ensure accurate dosing.

Mechanical properties

Hardness, friability, tensile strength, and structural integrity may be evaluated depending on the dosage form.

Surface morphology- SEM and other imaging techniques can be used to examine surface characteristics, pores, and printing defects.

Solid state characterization

DSC, FTIR, and XRD can be used to investigate drug–polymer interactions, thermal behavior, and crystallinity.

In-vitro drug release

Dissolution studies are performed to determine whether the printed formulation provides the intended immediate, sustained, or controlled drug release.

Stability studies – Stability testing assesses alterations in drug composition, physical characteristics, and drug-release performance over time in storage. Non-destructive testing – NIR, Raman spectroscopy, terahertz spectroscopy, optical imaging, and machine vision are emerging approaches for rapid and potentially real-time quality assessment of 3D-printed medicines [18–20].

Current Limitations and Translational Challenges of 3D-printed Pharmaceuticals

Despite the considerable advantages of three-dimensional (3D) printing for personalized and patient-specific drug delivery, several technological and translational limitations continue to restrict its widespread pharmaceutical application. One of the most important challenges is manufacturing throughput. Conventional high-speed rotary tablet presses can produce several hundred thousand to more than one million tablets per hour, depending on the equipment configuration, tablet size, compression parameters, and number of tooling stations. In contrast, the production rate of pharmaceutical 3D-printing technologies is generally substantially lower and is highly dependent on the printing technique, formulation viscosity, layer height, infill pattern, nozzle diameter, and printing speed. Consequently, although

3D printing is highly attractive for small-batch, personalized, and geometrically complex dosage forms, it remains less competitive than conventional compression technologies for large-scale production of standardized tablets. This productivity gap represents an important consideration for industrial translation and commercial-scale manufacturing.

The clinical and commercial translation of 3D-printed medicines also remains relatively limited. The approval of Spritam® (levetiracetam), manufactured using ZipDose® 3D-printing technology, represented a major milestone as the first FDA-approved 3D-printed pharmaceutical product. However, the number of commercially established 3D-printed medicines remains very small compared with the extensive range of conventionally manufactured oral dosage forms. This limited commercial adoption highlights the continuing challenges associated with process validation, reproducibility, raw-material consistency, quality control, regulatory standardization, scalability, and economic feasibility. Therefore, the current evidence suggests that the principal value of pharmaceutical 3D printing may lie initially in personalized medicines, low-volume production, pediatric and geriatric formulations, and complex drug-release systems rather than in replacing conventional high-throughput tablet manufacturing.

Another important limitation is the need to establish robust quality-control strategies specific to printed dosage forms. Variations in printing temperature, deposition rate, layer adhesion, infill density, nozzle performance, and environmental conditions can influence drug content uniformity, mechanical properties, dissolution behavior, and dose accuracy. Furthermore, the absence of universally harmonized regulatory guidelines specifically addressing pharmaceutical 3D-printing processes creates additional challenges for technology transfer and large-scale commercialization. Future research should therefore focus not only on improving printing technologies but also on establishing validated manufacturing platforms, standardized critical process parameters, scalable production strategies, and regulatory frameworks that can facilitate the transition from laboratory-scale proof-of-concept studies to clinically and commercially viable products [21].

Table 2. Structured comparison of various parameters for conventional tablet compression 3D printing.

Parameter	Conventional tablet compression	Pharmaceutical 3D printing	Implication
Production throughput	Typically hundreds of thousands to >1 million tablets/h depending on press configuration	Generally much lower; often suitable for small-batch production	Major disadvantage for mass production
Production approach	Continuous/high-throughput manufacturing	Layer-by-layer additive manufacturing	3D printing provides greater geometric flexibility

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Table 2 (continued)

Parameter	Conventional tablet compression	Pharmaceutical 3D printing	Implication
Dose customization	Limited once tooling is established	Highly adaptable through digital design/formulation changes	Major advantage for personalized medicine
Tooling requirement	Punches and dies required	No conventional tablet tooling required	Reduces tooling requirements for individualized designs
Complex geometries	Relatively difficult	Highly feasible	Advantage of 3D printing
Small-batch production	Economically less attractive	Particularly suitable	Potential niche application
Personalized dosage	Limited	Potentially high	Important for precision medicine
Commercially approved 3D-printed medicine	Conventional tablets are extensively commercialized	Spritam® represents the landmark FDA-approved example	Demonstrates the current translational gap
Scale-up	Well established	Still challenging for many technologies	Important industrial limitation

Conclusion

A new era of tailored, intelligent treatments is anticipated as 3D printing in medication delivery advances in conjunction with cutting-edge technology like artificial intelligence, digital health platforms, and smart materials. To enhance design parameters and forecast the printability of drug-polymer mixtures, 3D printing can incorporate AI and machine learning models. As a result, pharmacists may create personalized tablets with precise geometric features that fit each patient's pharmacokinetic profile on demand. A revolutionary development, 4D printing allows printed structures to alter over time or in reaction to environmental stimuli like pH, temperature, light, or magnetic fields. Stimuli-responsive dosage forms, such as shape-memory polymer-based floating systems and electro-responsive printed devices, are highlighted in recent 4D printing research. This shows how intelligent printed platforms can offer dynamic, on-demand medication distribution that surpasses the capabilities of static 3D structures by simultaneously changing their geometry or release profiles in response to pH, temperature, or electrical signals. By using machine-learning tools like M3DISEEN and conditional generative adversarial networks to forecast printability, processing parameters, drug-release profiles, and to create novel FDM-compatible formulations, AI-driven techniques are now enhancing 3D-printed formulations and structures. Thus suggesting a move toward designing future personalized dosage forms based on data.

Data Availability Statement

This manuscript is a review article. No new experimental data were created or examined in this study. All the data mentioned can be found in the references that are cited in the manuscript.

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Conflict of Interest StatementConceptualization

The Authors declare no conflict of Interests.

Authors Contribution Statement

Raghavendra Kumar Gunda: Conceptualization, writing (original draft), writing (review and editing), project administration, and corresponding author.

J.N. Suresh Kumar : Writing (review and editing), Supervision.

Modi Bharathi: Literature collection.

Pari Naga Venkata Sai Manikanta: Literature collection.

Pasumarthi Rama Krishna: Literature collection.

Pilli Vanitha: Literature collection.

Pogarthi seshu: Literature collection.

All authors have read and approved the final version of the manuscript.

Ethics Declaration

This article provides an overview of existing literature. It does not include data from human participants, animal studies, clinical trials, or any materials that would require ethical review by an institutional committee. There was no need for ethics committee approval for this work.

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