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# A REVIEW OF 3D PRINTING TECHNOLOGY IN PHARMACY: TECHNOLOGY AND APPLICATIONS, NOW AND FUTURE

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**Abstract**

Three-dimensional (3D) printing, also known as additive manufacturing, enables the fabrication of personalized pharmaceutical dosage forms through computer-aided design and layer-by-layer construction. In recent years, the use of 3D printing in the pharmaceutical field has advanced rapidly. Since the first FDA-approved 3D-printed drug Spritam® in 2015, multiple investigational new drug (IND) applications-particularly from Triastek-have demonstrated the growing feasibility of commercial-scale 3D-printed medicines. Compared with conventional manufacturing, 3D printing offers unique advantages in tailoring drug dose, geometry, and release characteristics, enabling the production of complex structures and small-batch personalized medicines. This review summarizes the principles of widely used 3D printing technologies, their advantages, limitations, and pharmaceutical applications. It further analyzes the global commercialization landscape, identifies regulatory and technical challenges, and outlines future trends to guide ongoing research and development in 3D-printed drug production.



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## Introduction to Migraine

Three-dimensional (3D) printing technology has emerged as a transformative tool in modern pharmacy, providing unprecedented flexibility in the design, manufacturing, and delivery of pharmaceutical products. As an additive manufacturing method, 3D printing constructs objects layer by layer based on digital models, in contrast to traditional subtractive or molding-based techniques [1]. This has opened new possibilities for precise, customizable drug dosage forms and medical devices, greatly enhancing precision medicine and patient-centered therapy.

The American Society for Testing and Materials (ASTM) classifies 3D printing technologies into seven major categories based on their technical principles: material extrusion, binder jetting, powder bed fusion, vat photopolymerization, material jetting, directed energy deposition, and sheet lamination [2]. Each category differs in materials used, deposition mechanisms, and final product characteristics, enabling diverse pharmaceutical applications.

Interest in 3D printing within the pharmaceutical sector has grown substantially due to its ability to produce structurally complex dosage forms, rapidly prototype formulations, and enable personalized dosing [3]. These innovations support precise control over drug release kinetics, improved therapeutic outcomes, and reduced development timelines.

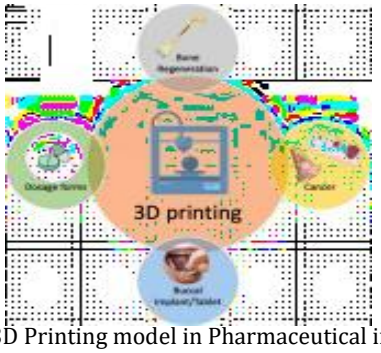


Fig 01: 3D Printing model in Pharmaceutical industry

Table 01. Extrusion-Based 3D Printing Systems: Techniques, Concepts, Advantages, and Limitations

| Category | Technique | Concept / Rationale | Advantages | Limitations |
|---|---|---|---|---|
| Extrusion-Based Systems | Material Extrusion – Fused Deposition Modeling (FDM) | Drug-loaded filaments are heated to a critical temperature, softened into a semi-fluid state, and extruded through a printer nozzle according to the model parameters. | 1. High equipment diversity (multiple nozzles available)<br>2. Low equipment cost<br>3. Good mechanical properties of printed dosage forms | • Difficult to scale up • Low drug-loading capacity |
| Extrusion-Based Systems | Semi-Solid Extrusion (SSE) | A semi-solid paste or gel containing the drug is extruded at room or slightly elevated temperature to build the dosage form layer by layer. | 1. Suitable for thermolabile drugs<br>2. Allows high drug loading<br>3. Flexibility in formulation composition | • Lower mechanical strength than FDM • Requires careful rheological control |

**Table 02: Comparison of SSE and MED® 3D Printing Techniques**

| Technique | Working Principle | Advantages | Disadvantages |
|---|---|---|---|
| Extrusion (SSE) | Extrudes the paste evenly via a syringe-based print head under pressure or screw-gear rotation and deposits layer-by-layer on the platform for printing. | 1. High drug loading<br>2. Mild printing process/conditions<br>3. Broad range of excipients | • Post-processing required • Low resolution • Low efficiency |
| Melt Extrusion Deposition (MED®) | Converts powder feedstocks into softened/molten states followed by precise layer-by-layer deposition to produce objects with desired structures. | • No post-processing<br>• Easy to scale up<br>• High equipment diversity (multiple nozzles) | • Low drug loading |

**Table 03: Comparison of Powder-Based and Liquid-Based 3D Printing Systems**

| System Type | Technique | Method | Working Principle | Advantages | Disadvantages |
|---|---|---|---|---|---|
| Powder-Based Systems | Binder Jetting (BJ) | Ink-Jet 3D Printing | BJ assembles 3D objects by preparing a 2D powder layer and ejecting a binder solution to pattern and solidify specific regions in the powder bed. | • Easy to scale up • High volume • High drug loading | • Post-processing required • Inefficient powder usage |
| Powder-Based Systems | Powder Bed Fusion (PBF) | Selective Laser Sintering (SLS) | PBF uses a focused power source (laser or electron beam) to selectively consolidate powder particles into solid objects. | • High resolution • No need for support materials | • Risk of drug degradation • Post-processing required |
| Liquid-Based Systems | Vat Photopolymerization (VP) | Stereolithography (SLA), Digital Light Processing (DLP) | VP is based on the selective photopolymerization of liquid photosensitive resins. | • High resolution and accuracy | • Post-processing required • Potential material limitations |

## Development of 3D Printing in Pharmaceuticals

The pharmaceutical application of 3D printing was first reported in the mid-1990s [4]. Over the past three decades, research has expanded to include immediate-release, controlled-release, and multi-layered tablets, as well as transdermal systems, implants, microneedles, and dispersible films [5]. A milestone was reached in 2015, when the U.S. Food and Drug Administration approved Spritam® (levetiracetam)-the world's first 3D-printed drug manufactured using ZipDose® technology [6]. This approval demonstrated the scalability and regulatory acceptability of additive manufacturing for pharmaceuticals. More recently, several 3D-printed medicines developed by Triastek using the Melt-Extrusion Deposition (MED™) technology have received IND approvals, signaling continued progress toward commercial adoption [7].

Pharmaceutical 3D printing techniques are broadly categorized as extrusion-based, powder-based, liquid-based, and sheet-lamination systems [8]. Among these, commonly used technologies include:

- Binder Jet 3D Printing (BJ-3DP)
- Fused Deposition Modeling (FDM) / Fused Filament Fabrication (FFF)
- Semi-Solid Extrusion (SSE)
- Melt-Extrusion Deposition (MED)
- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- PolyJet printing
- Digital Light Processing (DLP)

Each technique offers unique advantages related to dosage customization, resolution, scalability, and material compatibility.

## Applications of 3D Technology in Pharmacy

### 1. Personalized Medicine

3D printing enables the fabrication of drug products tailored to the patient's age, weight, pharmacogenomics, and disease state [9]. Personalized tablets can incorporate variable doses, flavors, shapes, and release profiles to improve efficacy and adherence, especially in pediatric and geriatric populations.

### 2. Polypills and Multi-Drug Combinations

3D printing allows multiple active pharmaceutical ingredients (APIs) with distinct release profiles to be combined into a single tablet. This simplifies regimens for patients with chronic conditions such as cardiovascular disease, improving compliance [10].

### 3. Controlled and Targeted Drug Release

Complex internal geometries-such as honeycomb structures, channel networks, or multilayered constructs-can be printed to achieve immediate, sustained, delayed, or pulsatile release [11]. This capability is crucial for therapies requiring precise plasma concentration control.

### 4. Pediatric and Geriatric Formulations

Dose flexibility and the ability to produce chewable, flavored, or easy-to-swallow formulations make 3D printing particularly valuable for populations with swallowing difficulties or special dosing needs [12]. An example is the production of personalized chewable printlets for children with maple syrup urine disease [13].

### 4. Rapid Prototyping in Drug Development

3D printing significantly accelerates formulation screening by enabling rapid production of prototype tablets with different geometries, drug loads, and excipient ratios, reducing R&D costs and timelines [14].

### 6. On-Demand and Point-of-Care Manufacturing

Hospitals and pharmacies can print medications on-site, reducing storage needs and enabling immediate access to personalized treatments-a major advantage in emergency care, remote locations, and military environments [15].

### 7. Implants and Drug-Delivery Devices

Biodegradable implants, microneedles, and localized delivery systems can be printed with precise drug content and release characteristics, supporting cancer therapy, antimicrobial treatment, and regenerative medicine [16].

### 8. Educational and Training Tools

3D models of organs, anatomical structures, and molecular interactions enhance pharmacy education, aiding the training of healthcare professionals [17].

### 9. Medical Devices and Prosthetics

Custom inhalers, pill organizers, prosthetics, and orthotic devices can be produced to improve patient comfort and adherence [18].

## Challenges in Pharmaceutical 3D Printing

### 1. Regulatory Frameworks

Current regulations are still evolving. Clear guidance is required for quality standards, batch consistency, validation protocols, and supply-chain oversight specific to additive manufacturing [19].

### 2. Quality Control and Standardization

Ensuring uniformity in dose, mechanical properties, and drug release remains challenging due to variability in printing parameters, material properties, and environmental conditions [20].

### 3. Scalability and Manufacturing Efficiency

While 3D printing excels in personalization, scaling up production to industrial levels while maintaining efficiency and cost-effectiveness remains a major limitation [21].

## Future Directions

### 1. Integration with Artificial Intelligence (AI)

AI can optimize printing parameters, predict material behavior, and accelerate formulation development, enabling fully automated, intelligent manufacturing systems [22].

### 2. Bioprinting and Regenerative Medicine

Advances in bioprinting-printing living cells and tissues-may revolutionize the creation of tissue grafts, organoids, and disease models for personalized therapy and drug testing [23].

### 3. Point-of-Care Manufacturing

Future hospitals and pharmacies may routinely use 3D printers to produce patient-specific medications on demand, especially for rare diseases or personalized dosing programs [24].

## Summary

3D printing is reshaping pharmaceutical manufacturing by enabling precise control over dosage form design, drug release, and patient-specific therapy. Extrusion-based systems such as FDM, SSE, and MED® support flexible formulation strategies, while powder-based and liquid-based techniques expand the range of achievable geometries, material properties, and applications. The technology has enabled innovations such as polypills, complex release structures, pediatric-friendly formulations, and customizable implants, marking significant progress toward personalized medicine. However, challenges remain in scaling up production, establishing regulatory standards, and ensuring consistent product quality. Continued research into advanced materials, automated optimization, and clinical validation is essential for widespread pharmaceutical adoption.

## Future Perspective

As pharmaceutical 3D printing continues to advance, its integration with emerging technologies is expected to accelerate innovation across drug development and personalized therapy. Artificial intelligence will play a pivotal role in automating formulation design, optimizing printing parameters, predicting printability, and ensuring real-time quality control. Bioprinting holds promise for developing patient-specific implants, tissue constructs, and regenerative therapies, potentially bridging the gap between pharmaceutical and biomedical engineering. Point-of-care manufacturing-where hospitals, clinics, and pharmacies produce customized medicines on demand-may become a standard practice, particularly for rare diseases, pediatric populations, and precision dosing applications. To fully harness these opportunities, future efforts must focus on establishing comprehensive regulatory frameworks, improving scalability, and developing standardized, biocompatible printing materials. Through sustained innovation and cross-disciplinary collaboration, 3D printing is positioned to become a cornerstone of next-generation pharmaceutical manufacturing and personalized healthcare.

## Conclusion

Three-dimensional (3D) printing has rapidly evolved from a novel manufacturing concept to a transformative technology with significant implications for modern pharmacy. Its capacity to fabricate complex, customizable, and patient-specific dosage forms marks a paradigm shift from traditional mass-production models toward personalized medicine. As demonstrated across extrusion-based, powder-based, and liquid-based systems, each 3D printing technique offers distinct advantages in terms of flexibility, structural complexity, and formulation precision, enabling tailored drug release profiles, multi-drug polypills, pediatric-friendly formulations, and advanced drug-delivery devices. The introduction of FDA-approved products such as Spritam® and the continued progress of technologies like Melt-Extrusion Deposition (MED®) further validate the clinical and regulatory potential of additive manufacturing.

Despite its promise, widespread adoption of 3D printing in the pharmaceutical industry faces notable challenges. Regulatory frameworks must be strengthened to ensure quality, safety, and consistency. Scalability, material standardization, and real-time quality control remain critical barriers to industrial implementation. Nevertheless, ongoing advancements-including the integration of artificial intelligence, bioprinting innovations, and the development of point-of-care manufacturing systems-are poised to overcome many of these obstacles.

Overall, 3D printing stands at the forefront of a new era in pharmaceutical science, offering unprecedented opportunities to enhance therapeutic outcomes, streamline drug development, and deliver truly personalized healthcare. Continued interdisciplinary research, regulatory engagement, and technological refinement will be essential to fully realizing its potential and establishing 3D printing as a cornerstone of future pharmaceutical practice.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Author Contribution

Both contribute equally

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## Ethical Considerations and Informed Consent

Not Applicable

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