



# Three-Dimensional Printing in Pharmaceuticals: The Future of Personalized and On-Demand Pharmaceutical Manufacturing

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## Mini Review

Volume 8 Issue 1

Received Date: July 02, 2025

Published Date: July 16, 2025

## Abstract

Three-dimensional (3D) printing is emerging as an innovative pharmaceutical manufacturing technology capable of producing dosage forms with customized geometry, composition, dose, and release characteristics. Unlike conventional large-scale manufacturing, additive manufacturing can support small-batch and patient-specific production. Technologies including fused deposition modeling, stereolithography, selective laser sintering, inkjet printing, and semi-solid extrusion have been investigated for pharmaceutical applications. The technology may be particularly valuable for personalized dosage forms, multidrug polypills, pediatric and geriatric formulations, and on-demand manufacturing. However, material compatibility, process reproducibility, scalability, quality control, stability, and regulatory requirements remain important challenges. This mini review summarizes the pharmaceutical significance of 3D printing and considers its future role in personalized and flexible pharmaceutical manufacturing.

**Keywords:** 3D Printing; Pharmaceuticals; Additive Manufacturing; Personalized Pharmaceutical Manufacturing; Dosage Forms; Pharmaceutical Technology

## Introduction

Conventional pharmaceutical manufacturing is optimized for large-scale production of standardized dosage forms. This model provides important economic and quality advantages, but it has limited flexibility when individual patients require different doses, release profiles, or combinations of pharmaceutical ingredients. Three-dimensional printing offers an alternative approach. The technology constructs objects layer by layer using computer-controlled manufacturing processes. In pharmaceuticals, this allows the physical characteristics of a dosage form to be modified through digital design.

Recent literature identifies 3D printing as an important emerging technology for personalized pharmaceutical

manufacturing [1–3].

- Pharmaceutical 3D-Printing Technologies
- Several printing technologies have been investigated in pharmaceuticals.
- **Fused Deposition Modeling (FDM)** uses thermoplastic materials that are deposited layer by layer.
- **Stereolithography (SLA)** uses light to selectively polymerize photoreactive materials.
- **Selective Laser Sintering (SLS)** uses laser energy to fuse powdered materials.
- **Inkjet printing** deposits small quantities of material in controlled patterns.
- **Semi-solid extrusion** can process pastes and gels and may be particularly useful for formulations that cannot tolerate high temperatures.

The choice of technology depends on the formulation,

material properties, desired dosage form, and target manufacturing characteristics.

### Personalized Dosage Forms

One of the most attractive pharmaceutical applications is personalized dosage manufacturing. Patients can differ in age, body size, swallowing ability, disease status, and required dosage. A digitally controlled manufacturing system could theoretically produce dosage forms with patient-specific characteristics rather than relying exclusively on standardized strengths. This approach may be particularly relevant to pediatric and geriatric pharmaceutical care.

### 3D-Printed Polypills

Polypills are another promising application. A conventional medication regimen may require several pharmaceutical products taken at different times. 3D printing can potentially create a single dosage form containing multiple pharmaceutical components in different compartments or layers. The geometry and composition of the printed structure can be adjusted to influence release behavior. A recent 2026 review highlights the potential of 3D-printed polypills for personalized oral pharmaceutical practice while also identifying challenges related to manufacturing consistency, regulation, scalability, and stability [2].

### Control of Pharmaceutical Release

An important advantage of 3D printing is the ability to modify dosage-form geometry.

Different structures can produce different surface-area-to-volume relationships and potentially influence dissolution and release. Porosity, internal architecture, layer thickness, and material distribution may therefore become formulation variables. This expands pharmaceutical formulation beyond conventional parameters such as powder composition and compression force.

### On-Demand Manufacturing

3D printing may also support on-demand pharmaceutical manufacturing. Instead of storing every possible dosage strength, a decentralized facility could potentially manufacture selected dosage forms when required. This concept may be relevant to hospitals, specialized pharmacies, clinical trials, and patient populations requiring uncommon dosage strengths. The development of pharmacy-on-demand systems and flexible pharmaceutical manufacturing is increasingly being investigated alongside 3D printing and

continuous manufacturing [3].

### Quality Control Challenges

The flexibility of 3D printing also creates pharmaceutical quality challenges. Traditional manufacturing relies on established batch procedures and validated production systems. In 3D printing, changes in printing speed, temperature, material properties, layer thickness, nozzle characteristics, or other parameters can influence the final product. Therefore, robust process control is essential. Process Analytical Technology and digital monitoring may become important tools for ensuring reproducibility.

### Regulatory Challenges

Regulatory pathways remain an important barrier. A conventional pharmaceutical product is manufactured using established processes, whereas a 3D-printed product may be generated through a digitally controlled, potentially decentralized process. Questions therefore arise concerning process validation, digital file control, material specifications, product traceability, quality assurance, and manufacturing-site oversight. Recent work specifically identifies the need for more harmonized regulatory frameworks for pharmaceutical 3D printing [4].

### Future Directions

Future research should focus on pharmaceutical-grade printable materials, improved printing speed, process monitoring, automated quality control, digital manufacturing standards, and scalable production. Integration with AI may further improve process optimization and quality prediction. The combination of 3D printing, digital manufacturing, PAT, and QbD could ultimately create highly flexible pharmaceutical production systems.

### Conclusion

Three-dimensional printing represents a significant technological opportunity for pharmaceuticals. Its greatest contribution may be the ability to move pharmaceutical manufacturing from a predominantly standardized model toward more flexible, personalized, and on-demand production. However, successful implementation will require more than technological innovation. Material science, formulation development, manufacturing engineering, quality assurance, regulatory science, and digital technologies must develop together. If these challenges are addressed, 3D printing could become an important component of the next generation of pharmaceutical manufacturing.

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