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Personalized pharmaceuticals through 3D printing: Innovations in drug delivery and dosage forms

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Abstract

Three-dimensional (3D) printing has emerged as a transformative technology in pharmaceutical manufacturing, offering unprecedented opportunities for the development of personalized drug delivery systems and customized dosage forms. Conventional pharmaceutical production relies on standardized, large-scale manufacturing approaches that often fail to address interindividual variability in patient characteristics, disease progression, and therapeutic response. In contrast, additive manufacturing enables precise, layer-by-layer fabrication of drug products based on digital designs, allowing modulation of dose, geometry, internal architecture, and drug release behavior at an individual patient level.

This review provides a comprehensive overview of the evolution, principles, and technological foundations of 3D printing in pharmaceutical sciences, with particular emphasis on its role in enabling personalized pharmaceuticals. Key 3D printing technologies applied in drug delivery, along with advances in printable materials and innovative dosage form designs, are critically discussed. The review further highlights rational design strategies for personalized drug delivery, quality control and characterization requirements, and emerging clinical applications across diverse patient populations. Regulatory considerations, manufacturing challenges, and ethical implications associated with individualized and decentralized drug production are also examined. Finally, future perspectives focusing on digital pharmacies, smart materials, and the integration of artificial intelligence and data-driven approaches are presented. Collectively, this review underscores the potential of 3D printing to redefine pharmaceutical manufacturing and advance precision medicine through patient-centric drug therapy.

Keywords: 3D Printing; Personalized Pharmaceuticals; Additive Manufacturing; Drug Delivery Systems; Customized Dosage Forms; Precision Medicine; Pharmaceutical Manufacturing

1. Introduction

The paradigm of pharmaceutical manufacturing has traditionally relied on mass production of standardized dosage forms, designed under the assumption that a single formulation can adequately address the therapeutic needs of a broad patient population. While this approach has ensured scalability and regulatory compliance, it has increasingly been recognized as insufficient to accommodate interindividual variability in age, body weight, genetics, disease state, comorbidities, and patient adherence. Contemporary advances in personalized medicine have highlighted the need for patient-centric drug products that can deliver optimized therapeutic outcomes through tailored dosing, release profiles, and dosage form design. In this context, three-dimensional (3D) printing, also referred to as additive manufacturing, has emerged as a disruptive and transformative technology within pharmaceutical sciences.

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Over the past decade, 3D printing has evolved from a rapid prototyping tool into a viable manufacturing platform capable of producing drug products with unprecedented design flexibility. Unlike conventional unit operations such as compression, granulation, or encapsulation, 3D printing enables layer-by-layer fabrication of dosage forms directly from digital designs. This digital-to-physical workflow allows precise control over dosage strength, geometry, internal microstructure, and spatial drug distribution, thereby facilitating true personalization of pharmaceutical products. The approval of the first 3D printed tablet marked a pivotal milestone, catalyzing extensive academic and industrial research into the applicability of additive manufacturing for drug delivery.

Recent literature has increasingly emphasized the role of 3D printing in addressing unmet clinical needs, particularly in populations where dose flexibility is critical, such as pediatrics, geriatrics, and patients with rare or chronic diseases. Studies published in the last few years demonstrate that 3D printing can be used to fabricate individualized tablets with adjustable doses, polypills combining multiple active pharmaceutical ingredients, and dosage forms with programmable release kinetics. Moreover, advances in printing technologies, including fused deposition modeling, semi-solid extrusion, selective laser sintering, and stereolithography, have expanded the range of drug substances and excipients compatible with pharmaceutical 3D printing.

In parallel, material science innovations have led to the development of pharmaceutical-grade printable polymers, drug-loaded filaments, and bioinks that meet safety, stability, and performance requirements. Recent research has also explored the integration of computational modeling, artificial intelligence, and digital health data to support rational design and optimization of personalized dosage forms. These developments align closely with the broader movement toward precision medicine and digital healthcare ecosystems, where on-demand and decentralized manufacturing are envisioned as future standards of care.

Despite these promising advancements, the translation of 3D printed pharmaceuticals from laboratory-scale demonstrations to routine clinical and commercial practice remains complex. Challenges related to process reproducibility, quality assurance, regulatory acceptance, and cost-effectiveness continue to be actively discussed in contemporary literature. Nevertheless, the growing body of recent publications underscores that 3D printing holds significant potential to redefine how drug products are designed, manufactured, and administered.

Against this backdrop, the present review aims to critically examine recent innovations in 3D printing technologies for personalized pharmaceuticals, with a particular focus on drug delivery systems and dosage form design. By synthesizing findings from the latest scientific literature, this article highlights technological progress, formulation strategies, clinical relevance, and future directions, thereby providing a comprehensive perspective on the role of 3D printing in advancing personalized drug therapy.1–7

2. Evolution of 3D Printing in Pharmaceutical Sciences

Three-dimensional (3D) printing, originally developed as a rapid prototyping technology for industrial and engineering applications, has undergone a remarkable evolution to become a promising manufacturing approach in pharmaceutical sciences. The early stages of 3D printing were primarily focused on producing physical models and design prototypes, with limited consideration for material biocompatibility or regulatory compliance. However, as the principles of additive manufacturing matured, researchers began to recognize its potential beyond prototyping, particularly for fabricating complex, customizable structures that could not be easily achieved using conventional manufacturing techniques.

The initial exploration of 3D printing in pharmaceutics emerged in the late 1990s and early 2000s, when binder jet printing was investigated for the fabrication of oral dosage forms. These early studies demonstrated that layer-by-layer deposition of drug-containing powders could generate tablets with highly porous structures, offering rapid disintegration and enhanced dissolution characteristics. Although these investigations were largely experimental, they laid the foundation for considering 3D printing as a functional drug manufacturing platform rather than merely a visualization tool.

A significant turning point in the evolution of pharmaceutical 3D printing occurred with the growing emphasis on personalized medicine and patient-centric drug development. Advances in printing hardware, coupled with improved control over processing parameters, enabled researchers to precisely manipulate dosage form geometry, internal architecture, and drug distribution. This shift coincided with increased interest in tailoring drug products to individual patient needs, which traditional mass-production methods struggled to address efficiently. As a result, 3D printing began to be viewed as a strategic solution for producing customized dosage forms with adjustable doses and release profiles.

The regulatory approval of the first 3D printed oral tablet represented a landmark achievement that validated the feasibility of additive manufacturing in pharmaceutical production. This milestone accelerated academic and industrial research, leading to a rapid expansion of printing technologies adapted for pharmaceutical use. Techniques such as fused deposition modeling, semi-solid extrusion, selective laser sintering, and stereolithography were progressively refined to accommodate drug substances and pharmaceutical excipients. Each technological advancement addressed specific limitations of earlier approaches, such as thermal degradation, poor mechanical strength, or limited material compatibility.

Parallel to technological progress, material science played a critical role in the evolution of pharmaceutical 3D printing. Early formulations were constrained by the availability of printable materials suitable for drug incorporation. Over time, the development of pharmaceutical-grade polymers, plasticizers, and photo-curable resins enabled the production of drug-loaded filaments, inks, and pastes with acceptable stability and safety profiles. These innovations expanded the scope of printable drug delivery systems, facilitating the fabrication of immediate-release, modified-release, and multi-drug dosage forms.

In recent years, the evolution of 3D printing in pharmaceutical sciences has been further driven by digitalization and computational advances. The integration of computer-aided design, process modeling, and data-driven optimization has enhanced precision and reproducibility in dosage form fabrication. Additionally, emerging concepts such as decentralized manufacturing, hospital-based printing, and on-demand drug production reflect a shift toward more flexible and responsive healthcare models. Contemporary research increasingly emphasizes not only technical feasibility but also quality assurance, scalability, and regulatory alignment, signaling the gradual transition of 3D printing from experimental innovation to a clinically relevant manufacturing strategy.

Overall, the evolution of 3D printing in pharmaceutical sciences reflects a progression from exploratory experimentation to a sophisticated, multidisciplinary field. Continuous advancements in printing technologies, materials, and digital tools have positioned 3D printing as a key enabler of personalized pharmaceuticals, with the potential to fundamentally transform drug manufacturing and delivery in the years ahead.8,9

3. Principles of 3D Printing for Personalized Pharmaceuticals

Three-dimensional (3D) printing in pharmaceutical sciences is fundamentally based on the principle of additive manufacturing, wherein drug products are fabricated through the sequential deposition of materials according to a predefined digital design. Unlike conventional subtractive or batch-based manufacturing processes, 3D printing enables the construction of dosage forms layer by layer, allowing precise spatial control over formulation composition, geometry, and internal architecture. This intrinsic design flexibility forms the cornerstone of personalized pharmaceutical manufacturing, as it permits modulation of dose, drug release behavior, and dosage form characteristics at an individual patient level.

At the core of pharmaceutical 3D printing lies a digital workflow that integrates computer-aided design (CAD), material formulation, and automated fabrication. The process begins with the creation of a digital model of the dosage form, which defines its size, shape, internal porosity, and drug distribution pattern. These digital blueprints can be readily modified to accommodate patient-specific requirements, such as altered dose strengths or customized release profiles. Once finalized, the design is translated into machine-readable instructions that guide the printer during fabrication, ensuring high precision and reproducibility.

Material selection represents a critical principle governing the successful application of 3D printing for personalized pharmaceuticals. Printable materials must not only possess suitable rheological or thermal properties to enable smooth deposition but also meet pharmaceutical standards for safety, biocompatibility, and stability. Depending on the printing technique employed, materials may be processed as thermoplastic filaments, semi-solid pastes, liquid inks, or photo-curable resins. The compatibility between the active pharmaceutical ingredient and the selected excipients is particularly important, as drug–polymer interactions can influence drug stability, content uniformity, and release behavior. Careful optimization of formulation composition is therefore essential to maintain therapeutic efficacy while ensuring printability.

Another defining principle of 3D printing in personalized drug delivery is the ability to control dosage and drug release through structural design rather than solely through formulation composition. Parameters such as infill density, layer thickness, surface area-to-volume ratio, and internal channel architecture can be systematically altered to modulate drug release kinetics. This structural approach enables the production of immediate-release, sustained-release, or pulsatile-release dosage forms using the same formulation, simply by modifying the digital design. Such versatility is

particularly advantageous for personalized therapy, where dosing regimens may need frequent adjustment based on patient response.

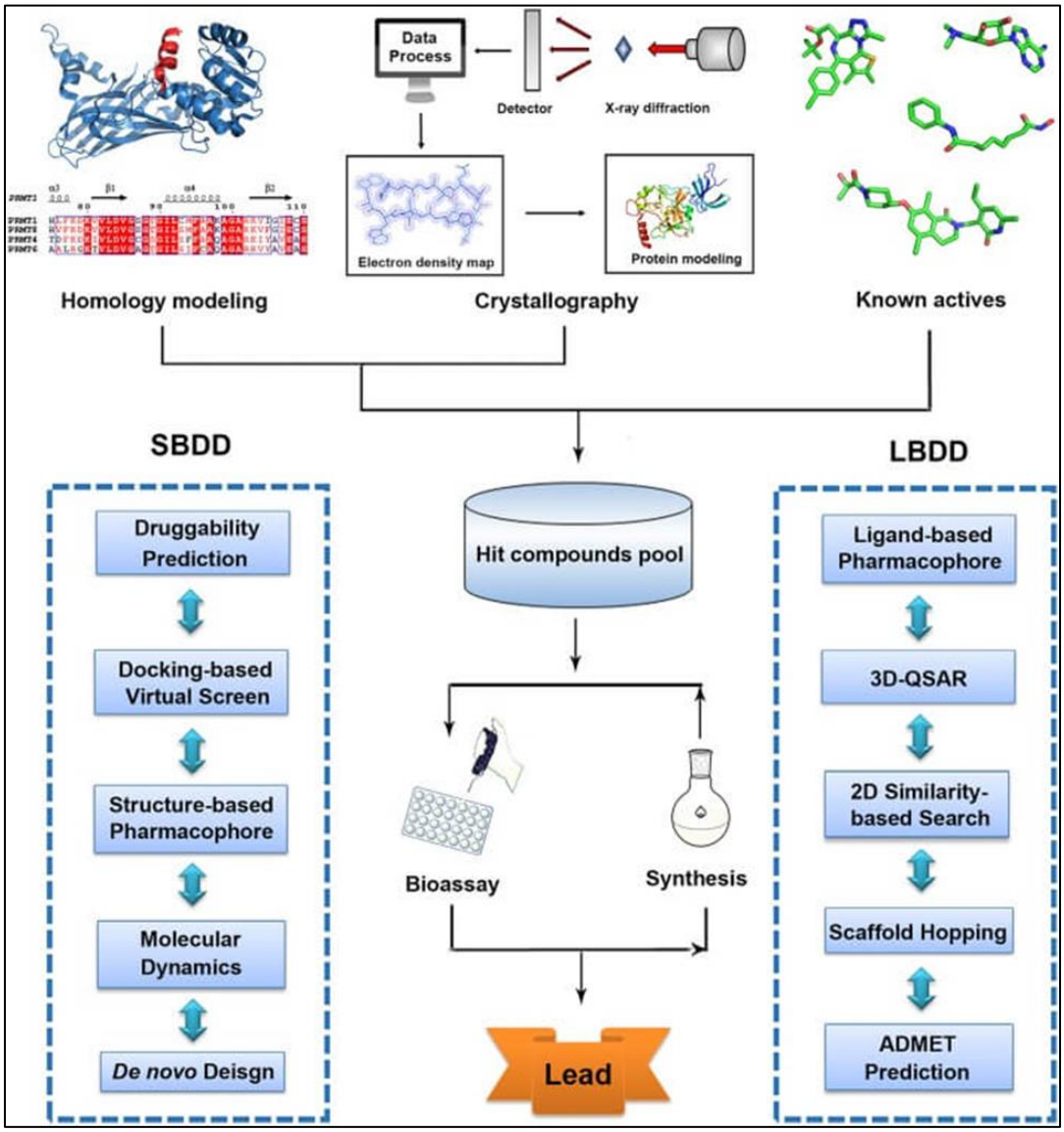

Figure 1 Computer-Aided Drug Design (CADD)

Process control and reproducibility are equally important principles underpinning pharmaceutical 3D printing. Printing parameters, including temperature, extrusion rate, printing speed, and layer resolution, directly influence the mechanical integrity and performance of the final dosage form. In personalized manufacturing settings, where small batch sizes or even single-unit production may be required, maintaining consistent quality becomes a significant consideration. Consequently, real-time monitoring, process validation, and standardized operating conditions are increasingly emphasized in recent research to ensure reliable and reproducible outcomes.

Finally, the principles of pharmaceutical 3D printing are closely aligned with the broader concepts of digitalization and patient-centric healthcare. The ability to integrate patient-specific clinical data, pharmacokinetic requirements, and therapeutic goals into the design process represents a major departure from traditional manufacturing paradigms. By linking digital prescription data with automated fabrication systems, 3D printing enables on-demand production of customized drug products, supporting a more responsive and adaptive approach to drug therapy.

In summary, the principles of 3D printing for personalized pharmaceuticals are founded on additive manufacturing, digital design flexibility, material–drug compatibility, structural control of drug release, and robust process management. Together, these principles establish a versatile framework that supports the development of

individualized drug delivery systems, positioning 3D printing as a key enabling technology in the advancement of personalized medicine.10,11

4. 3D Printing Technologies Applied in Drug Delivery

The application of three-dimensional (3D) printing technologies in drug delivery has expanded considerably over the past decade, driven by the need for flexible, patient-specific dosage forms and advanced drug release control. Different 3D printing techniques operate on distinct physical and material-processing principles, each offering unique advantages and limitations for pharmaceutical use. The selection of an appropriate printing technology is therefore closely linked to the physicochemical properties of the drug, the desired dosage form, and the targeted release profile. Collectively, these technologies have enabled the fabrication of innovative drug delivery systems that are difficult or impossible to achieve using conventional manufacturing approaches.

5. Fused Deposition Modeling (FDM)

Fused deposition modeling is one of the most widely explored 3D printing technologies in pharmaceutical research due to its simplicity, cost-effectiveness, and adaptability. In this technique, drug-loaded thermoplastic filaments are heated above their glass transition or melting temperature and extruded through a nozzle to form dosage forms layer by layer. FDM has been extensively investigated for the fabrication of oral solid dosage forms, particularly tablets with customized geometry and internal structure. By adjusting parameters such as infill density, shell thickness, and printing pattern, drug release kinetics can be finely tuned without altering the formulation composition. However, the relatively high processing temperatures involved in FDM may limit its applicability for thermolabile drugs, necessitating careful material selection and formulation optimization.

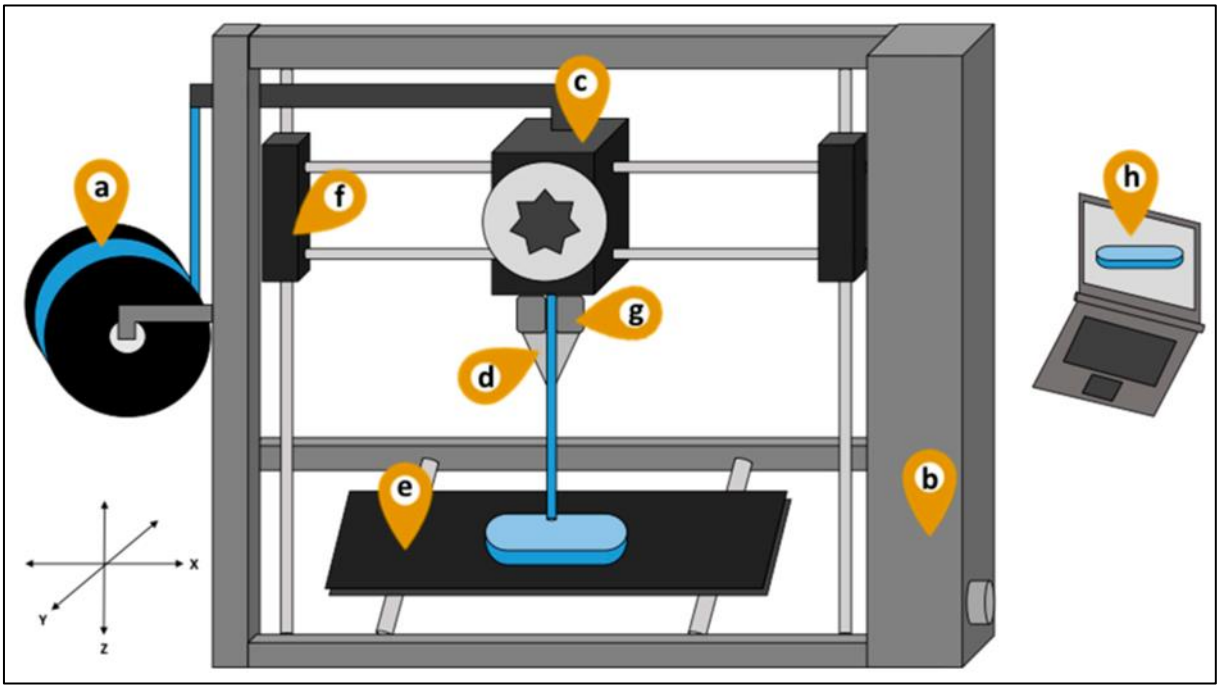

Figure 2 Schematic representation of a pharmaceutical fused deposition modeling 3D printer with indications of the specific points in which adaptations will be required for pharmaceutical production. (a) Spool, (b) printer enclosure, (c) extruder head, (d) nozzle, (e) build platform, (f) motor, (g) heater, (h) 3D design software

5.1. Semi-Solid Extrusion (SSE)

Semi-solid extrusion, also referred to as pressure-assisted microsyringe printing, employs the extrusion of pastes, gels, or semi-solid formulations through a nozzle at ambient or moderately elevated temperatures. This technology is particularly attractive for pharmaceutical applications because it minimizes thermal stress on active pharmaceutical ingredients, making it suitable for heat-sensitive compounds. SSE has been used to print a wide range of dosage forms, including immediate-release tablets, chewable formulations, orodispersible dosage forms, and personalized pediatric medicines. The rheological properties of the formulation play a critical role in ensuring printability and shape retention,

requiring precise control over viscosity and yield stress. Despite these challenges, SSE offers significant flexibility in formulation design and material selection.

5.2. Inkjet and Binder Jet Printing

Inkjet-based printing technologies involve the precise deposition of drug-containing liquid droplets onto a substrate, either directly forming the dosage form or binding layers of powder together in binder jet printing. These techniques allow highly accurate control over drug dose and spatial distribution, making them particularly suitable for low-dose drugs and complex release patterns. Binder jet printing has been historically important in pharmaceutical 3D printing, enabling the production of highly porous tablets with rapid disintegration properties. Inkjet printing also supports the fabrication of multi-layered or multi-drug systems, although challenges related to solvent compatibility, nozzle clogging, and formulation stability must be carefully addressed.

5.3. Selective Laser Sintering (SLS)

Selective laser sintering is a powder-based 3D printing technology that uses a laser to selectively fuse drug–polymer particles into a solid structure without the need for solvents or binders. This technique offers advantages in terms of producing mechanically robust dosage forms with controlled porosity and modified-release characteristics. SLS has been explored for the fabrication of oral tablets and implantable drug delivery systems, with drug release profiles governed by laser intensity, scanning speed, and powder composition. However, the high energy input associated with laser sintering raises concerns regarding potential drug degradation, necessitating thorough stability evaluation.

5.4. Stereolithography (SLA)

Stereolithography is a photopolymerization-based technique that utilizes light to cure liquid photo-reactive resins into solid structures with high spatial resolution. SLA enables the fabrication of dosage forms with intricate geometries and smooth surface finishes, offering precise control over drug distribution and release behavior. In pharmaceutical applications, this technology has been investigated for the development of modified-release tablets and implantable devices. Nevertheless, the limited availability of pharmaceutical-grade photo-curable materials and concerns regarding residual monomers and biocompatibility remain significant barriers to widespread adoption.

6. Comparative Considerations and Technological Selection

Each 3D printing technology presents distinct advantages and constraints when applied to drug delivery systems. While FDM and SSE are currently the most accessible and widely studied techniques, powder-based and photopolymerization methods offer superior resolution and structural complexity. The choice of technology depends on multiple factors, including drug stability, dose requirements, material compatibility, and intended clinical application. As research continues to address existing limitations, the convergence of these technologies with pharmaceutical manufacturing principles is expected to further expand the scope of personalized drug delivery.

In summary, the diverse range of 3D printing technologies applied in drug delivery underscores the versatility of additive manufacturing in pharmaceutical sciences. By enabling precise control over dosage form design, composition, and performance, these technologies collectively support the development of innovative, patient-centric drug delivery systems aligned with the goals of personalized medicine.12,13.

7. Printable Materials for Personalized Drug Products

The successful implementation of three-dimensional (3D) printing in personalized pharmaceuticals is critically dependent on the availability and performance of suitable printable materials. Unlike conventional pharmaceutical excipients, materials intended for 3D printing must simultaneously fulfill dual roles: they must possess physicochemical and mechanical properties that enable reliable printing while also meeting stringent pharmaceutical requirements related to safety, stability, and therapeutic performance. As a result, material selection and formulation design represent central challenges in the development of 3D printed drug products.

Pharmaceutical polymers constitute the most extensively investigated class of printable materials for personalized drug products. Thermoplastic polymers such as polyvinyl alcohol, polyvinylpyrrolidone, polylactic acid, polyethylene glycol derivatives, and cellulose-based materials have been widely employed due to their favorable mechanical strength and processability. These polymers can be formulated into drug-loaded filaments suitable for fused deposition modeling or into pastes and gels for semi-solid extrusion. Importantly, their molecular weight, crystallinity, and glass transition

temperature can be adjusted to modulate both printability and drug release characteristics, enabling the fabrication of immediate- or modified-release dosage forms.

In addition to solid polymers, semi-solid and hydrogel-based materials have gained increasing attention for their versatility and mild processing conditions. These materials are particularly suitable for printing thermosensitive drugs, peptides, and biologics that may degrade under elevated temperatures. Hydrogels based on gelatin, alginate, hydroxypropyl methylcellulose, and carbomers have been explored for orodispersible tablets, chewable formulations, and localized drug delivery systems. The rheological behavior of these materials is a key determinant of printability, requiring careful optimization of viscosity, yield stress, and shear-thinning properties to ensure consistent extrusion and structural integrity after deposition.

Powder-based materials used in technologies such as selective laser sintering and binder jet printing represent another important category of printable materials. These formulations typically consist of drug–polymer or drug–excipient blends with controlled particle size and flow characteristics. In selective laser sintering, polymers with suitable thermal and optical properties are required to enable efficient fusion without compromising drug stability. Binder jet printing, on the other hand, relies on liquid binders to consolidate powder layers, allowing the production of highly porous dosage forms with rapid disintegration. The choice of excipients in powder-based systems significantly influences mechanical strength, porosity, and drug release behavior.

Photo-curable resins employed in stereolithography offer exceptional spatial resolution and design precision, making them attractive for fabricating complex dosage forms and implantable devices. These materials typically consist of monomers or oligomers that polymerize upon exposure to light in the presence of photoinitiators. While stereolithography enables fine control over dosage form architecture, the pharmaceutical application of photo-curable resins remains limited due to concerns regarding biocompatibility, residual monomers, and the availability of regulatory-approved materials. Ongoing research efforts are focused on developing safer, biodegradable, and pharmaceutically acceptable photo-reactive materials to expand the applicability of this technology.

Beyond the choice of material class, drug–material compatibility is a critical consideration in personalized drug product design. Interactions between the active pharmaceutical ingredient and the printable matrix can influence drug stability, crystallinity, and dissolution behavior. Advanced characterization techniques, including thermal analysis and spectroscopic methods, are commonly employed to assess compatibility and guide formulation optimization. Furthermore, the incorporation of plasticizers, stabilizers, or release modifiers is often necessary to achieve the desired balance between printability and therapeutic performance.

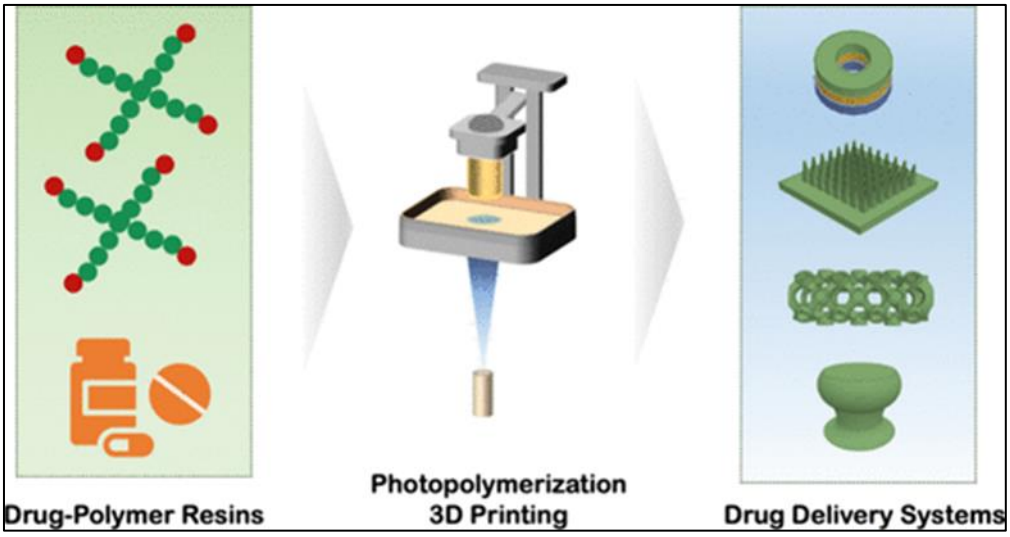

Figure 3 Schematic diagram of photopolymerization 3D printing for drug delivery

In recent years, material innovation has increasingly emphasized multifunctional and smart materials capable of responding to external stimuli such as pH, temperature, or enzymatic activity. These advanced materials open new possibilities for personalized drug delivery by enabling site-specific or on-demand drug release. Although such materials are still largely at the experimental stage, they represent a promising direction for future research in pharmaceutical 3D printing.

In summary, printable materials form the foundation of personalized drug products manufactured using 3D printing technologies. The continued development of pharmaceutical-grade polymers, semi-solid formulations, powder blends, and photo-curable materials is essential for advancing the field from experimental proof-of-concept studies to clinically and commercially viable personalized medicines.14,15

7.1. Innovations in 3D Printed Dosage Forms

Three-dimensional (3D) printing has catalyzed substantial innovation in the design and development of pharmaceutical dosage forms, enabling a shift from standardized products to highly customizable, patient-centric medicines. By decoupling dose and release characteristics from traditional formulation constraints, additive manufacturing allows drug performance to be governed by geometry, internal architecture, and spatial drug distribution. These capabilities have led to the emergence of novel dosage forms with enhanced therapeutic flexibility, improved patient adherence, and expanded clinical applicability.

7.2. Immediate-Release and Modified-Release Tablets

One of the earliest and most extensively studied innovations enabled by pharmaceutical 3D printing is the fabrication of immediate-release and modified-release tablets with precisely controlled dissolution behavior. Through manipulation of tablet geometry, infill density, layer thickness, and internal porosity, drug release can be accelerated or prolonged without altering the chemical composition of the formulation. Highly porous structures produced by certain printing techniques facilitate rapid disintegration and dissolution, whereas denser architectures enable sustained or delayed drug release. This design-driven control over release kinetics offers a powerful tool for tailoring therapy to individual patient needs.

7.3. Polypills and Multi-Drug Dosage Forms

The development of polypills represents a major advancement in 3D printed dosage forms, particularly for patients requiring complex medication regimens. Additive manufacturing allows the spatial separation of multiple active pharmaceutical ingredients within a single dosage unit, enabling independent control over dose and release profile for each drug. Such multi-compartment designs have demonstrated potential to reduce pill burden, simplify dosing schedules, and improve adherence, especially in chronic conditions such as cardiovascular disease and diabetes. The ability to customize polypills according to patient-specific therapeutic requirements highlights the transformative potential of 3D printing in personalized medicine.

7.4. Oro dispersible and Patient-Friendly Formulations

Innovations in 3D printing have also facilitated the development of patient-friendly dosage forms designed to address swallowing difficulties and adherence challenges. Oro dispersible tablets with tailored porosity and surface area can be fabricated to rapidly disintegrate in the oral cavity, making them particularly suitable for pediatric and geriatric populations. Additionally, chewable and visually customized dosage forms can be produced to enhance patient acceptability. The capacity to adjust dose strength without changing tablet size further supports individualized therapy while maintaining ease of administration.

7.5. Gastro-Retentive and Floating Dosage Forms

3D printing has enabled the rational design of gastro-retentive dosage forms with complex geometries that promote prolonged gastric residence. Floating tablets and expandable structures can be fabricated with low-density architectures that remain buoyant in gastric fluid, thereby extending drug release in the stomach. These systems are particularly advantageous for drugs with narrow absorption windows or those that exhibit enhanced solubility in acidic environments. The precise control over shape and internal voids afforded by 3D printing provides opportunities to optimize gastric retention beyond the capabilities of conventional manufacturing methods.

7.6. Implantable and Localized Drug Delivery Systems

Beyond oral dosage forms, 3D printing has facilitated innovation in implantable and localized drug delivery systems. Custom-shaped implants can be designed to match patient-specific anatomical requirements, enabling controlled and sustained drug release at targeted sites. Such systems have shown promise in areas including oncology, orthopedics, and post-surgical therapy. The ability to tailor implant geometry and drug loading offers significant advantages in achieving localized therapeutic concentrations while minimizing systemic exposure and adverse effects.

7.7. Emerging and Hybrid Dosage Form Concepts

Recent research has explored hybrid and multifunctional dosage forms that combine multiple delivery strategies within a single printed construct. Examples include tablets incorporating both immediate- and sustained-release regions, stimuli-responsive structures that alter release behavior in response to physiological conditions, and dosage forms integrated with digital features for tracking or identification. These emerging concepts underscore the versatility of 3D printing as a platform for innovation and highlight its potential to integrate drug delivery with broader digital health solutions.

In summary, innovations in 3D printed dosage forms extend well beyond incremental improvements to conventional products. By enabling unprecedented control over dosage form design and performance, 3D printing has opened new avenues for personalized drug delivery, positioning additive manufacturing as a key driver of next-generation pharmaceutical development.16,17.

8. Design Strategies for Personalized Drug Delivery

The design of personalized drug delivery systems represents one of the most transformative aspects of three-dimensional (3D) printing in pharmaceutical sciences. Unlike conventional formulation approaches that rely primarily on compositional modifications, 3D printing enables personalization through rational structural and digital design. By integrating patient-specific requirements with adaptable manufacturing processes, design strategies in 3D printed drug delivery focus on precise dose control, tailored release kinetics, and enhanced therapeutic performance. These strategies collectively support a shift toward individualized pharmacotherapy.

8.1. Dose Individualization Through Digital Design

One of the most fundamental design strategies in personalized drug delivery is dose individualization achieved through digital manipulation of dosage form dimensions and structure. In 3D printing, dose strength can be adjusted by modifying parameters such as tablet size, layer number, infill percentage, or drug-loaded region volume without altering the formulation composition. This approach is particularly valuable in clinical settings where frequent dose adjustments are required, such as in pediatric therapy, geriatric care, or drugs with narrow therapeutic indices. Digital dose customization enables rapid production of patient-specific medicines while maintaining formulation consistency.

8.2. Geometry-Driven Control of Drug Release

Control over dosage form geometry is a defining advantage of 3D printing-based design strategies. The shape of a dosage form, including surface area-to-volume ratio and external contours, has a direct influence on dissolution and drug release behavior. By designing complex geometries such as lattice structures, hollow cores, or multilayered architectures, drug release can be modulated from immediate to sustained or pulsatile profiles. This geometry-driven approach allows formulation scientists to fine-tune therapeutic outcomes through design rather than relying solely on chemical release modifiers.

8.3. Internal Architecture and Infill Design

Beyond external geometry, the internal architecture of 3D printed dosage forms plays a crucial role in personalized drug delivery. Infill patterns, porosity, and channel orientation can be precisely controlled to regulate fluid penetration and diffusion pathways. Lower infill densities and interconnected porous networks promote rapid drug release, whereas denser structures with limited porosity enable prolonged release. Such internal design strategies provide a robust and reproducible method for tailoring drug release kinetics, even when using the same formulation across different patient groups.

8.4. Multi-Compartment and Spatial Drug Distribution Strategies

3D printing enables spatial control over drug placement within a single dosage unit, supporting advanced design strategies such as multi-compartment systems. Different regions of a dosage form can be loaded with distinct drugs or varying concentrations of the same drug, allowing sequential or simultaneous release profiles. This strategy is particularly relevant for combination therapies, where individualized dosing and release timing are essential. Spatial drug distribution also facilitates the development of dosage forms with both immediate- and sustained-release components, improving therapeutic efficiency and patient compliance.

8.5. Patient-Centric and Disease-Specific Design

Personalized drug delivery design strategies increasingly emphasize patient-centric and disease-specific considerations. Anatomical factors, swallowing ability, lifestyle, and disease progression can be incorporated into dosage form design. For example, smaller or dispersible tablets may be designed for patients with dysphagia, while gastro-retentive structures can be tailored for drugs targeting gastric absorption. This level of customization supports improved adherence and aligns drug delivery with individual patient needs rather than generalized population averages.

8.6. Integration of Digital Health and Pharmacokinetic Data

Emerging design strategies involve the integration of digital health data and pharmacokinetic modeling into the 3D printing workflow. Patient-specific data, such as body weight, metabolic profile, or therapeutic response, can inform dosage form design and release characteristics. Computer-aided modeling and simulation tools are increasingly used to predict drug release and absorption, enabling rational design of personalized medicines. This data-driven approach represents a critical step toward precision medicine, where drug delivery systems are optimized based on real-time clinical insights.

In summary, design strategies for personalized drug delivery using 3D printing extend beyond traditional formulation approaches by leveraging digital design, structural control, and patient-specific data. Through dose customization, geometry-driven release modulation, and advanced internal architectures, these strategies enable the creation of individualized drug products that are better aligned with patient needs and therapeutic goals, reinforcing the role of 3D printing as a cornerstone technology in personalized medicine.18–22

9. Quality Control and Characterization of 3D Printed Pharmaceuticals

Quality control and comprehensive characterization are critical components in the development and clinical translation of three-dimensional (3D) printed pharmaceuticals. Unlike conventional batch manufacturing, 3D printing often involves small-batch or unit-level production, where variability in material properties, printing parameters, and digital design can directly influence product quality. Consequently, robust and adaptable quality control strategies are essential to ensure safety, efficacy, and reproducibility of personalized drug products manufactured using additive manufacturing technologies.

Physicochemical characterization forms the foundation of quality evaluation for 3D printed pharmaceuticals. Key attributes such as appearance, dimensional accuracy, weight variation, and drug content uniformity must be carefully assessed to confirm dose precision and consistency with the digital design. Given that dose individualization is often achieved through geometric modification, dimensional measurements and mass uniformity become particularly important indicators of dosage accuracy. Analytical techniques such as high-performance liquid chromatography and ultraviolet spectroscopy are commonly employed to quantify drug content and verify uniform distribution within the printed construct.

Mechanical characterization is another essential aspect of quality control, as the mechanical integrity of 3D printed dosage forms influences handling, packaging, and patient use. Parameters such as hardness, tensile strength, friability, and flexibility are evaluated depending on the dosage form and printing technology employed. For example, tablets produced using fused deposition modeling or selective laser sintering must exhibit sufficient strength to withstand mechanical stress, while semi-solid extrusion products require adequate shape retention. Mechanical properties are closely linked to printing parameters, infill density, and material composition, underscoring the need for systematic process optimization.

In vitro drug release and dissolution testing play a pivotal role in characterizing the performance of 3D printed drug delivery systems. One of the unique advantages of additive manufacturing is the ability to modulate drug release through structural design; therefore, dissolution behavior must be carefully correlated with geometry, porosity, and internal architecture. Standard pharmacopeial dissolution methods are widely applied, although adaptations may be required to account for unconventional shapes and multi-compartment designs. Establishing reliable in vitro–in vivo correlations remain an important focus in recent research to support clinical relevance.

Solid-state characterization is particularly important for understanding drug stability and performance in 3D printed pharmaceuticals. Thermal analysis and spectroscopic techniques are routinely used to evaluate drug crystallinity, polymorphic transitions, and potential drug–excipient interactions induced during the printing process. High processing temperatures, laser exposure, or photopolymerization may alter the solid-state properties of active

pharmaceutical ingredients, making thorough characterization essential to ensure long-term stability and consistent therapeutic outcomes.

Microstructural and morphological analysis provides critical insights into the internal architecture of 3D printed dosage forms. Imaging techniques such as scanning electron microscopy and micro-computed tomography are increasingly employed to visualize layer adhesion, pore distribution, and internal channels. These analyses are particularly valuable for correlating structural features with drug release behavior and mechanical performance. Microstructural consistency also serves as an indicator of process reliability and print quality.

Process monitoring and reproducibility are emerging priorities in the quality control of 3D printed pharmaceuticals. Variations in printing temperature, extrusion rate, laser intensity, or material viscosity can significantly impact product quality. As a result, recent studies emphasize the integration of process analytical technologies and real-time monitoring tools to enhance control over critical process parameters. Such approaches are aligned with quality-by-design principles and support regulatory acceptance of additive manufacturing processes.

In summary, quality control and characterization of 3D printed pharmaceuticals require a multidimensional approach encompassing physicochemical, mechanical, structural, and performance-related evaluations. The unique features of additive manufacturing demand both adaptation of conventional pharmaceutical tests and the development of new characterization strategies. Establishing robust quality frameworks is essential for ensuring that personalized 3D printed drug products meet regulatory standards and deliver consistent, safe, and effective therapy.23–27

10. Clinical Applications and Therapeutic Potential

The clinical translation of three-dimensional (3D) printing in pharmaceutical sciences has opened new avenues for delivering patient-centric therapies across diverse therapeutic areas. By enabling precise customization of dose, dosage form geometry, and drug release profiles, 3D printed pharmaceuticals offer significant advantages over conventional medicines, particularly in patient populations with unmet clinical needs. Increasing evidence from preclinical and early clinical studies highlights the therapeutic potential of additive manufacturing to improve treatment outcomes, adherence, and safety.

Personalized therapy in pediatric and geriatric populations represents one of the most compelling clinical applications of pharmaceutical 3D printing. Children and elderly patients often require flexible dosing regimens that are not adequately addressed by commercially available dosage strengths. 3D printing enables the fabrication of age-appropriate dosage forms with individualized doses, palatable formulations, and patient-friendly designs such as or dispersible or chewable tablets. This level of customization supports safer dosing, reduces the need for tablet splitting or compounding, and enhances medication adherence in vulnerable populations.

Chronic disease management is another area where 3D printed drug delivery systems demonstrate substantial therapeutic potential. Patients with long-term conditions such as cardiovascular disorders, diabetes, or neurological diseases frequently require multiple medications with complex dosing schedules. The ability to manufacture personalized polypills that combine several active pharmaceutical ingredients into a single dosage form can simplify treatment regimens and improve adherence. Moreover, 3D printing allows independent control of release profiles for each drug within a polypill, enabling optimized therapeutic coverage while minimizing drug–drug interactions.

Rare diseases and precision medicine applications further highlight the clinical value of 3D printed pharmaceuticals. For many rare conditions, patient populations are small and dosing requirements are highly individualized, making large-scale manufacturing economically and practically challenging. Additive manufacturing provides a flexible platform for producing small batches or single-unit doses tailored to individual patients. When combined with pharmacogenomic data and clinical response monitoring, 3D printing supports precision dosing strategies that align closely with the principles of personalized medicine.

Hospital- and pharmacy-based manufacturing is an emerging clinical model that leverages the on-demand capabilities of 3D printing. In this decentralized approach, customized medicines can be produced at or near the point of care based on digital prescriptions. This model is particularly advantageous in settings requiring rapid dose adjustments, such as oncology, transplant medicine, or intensive care. On-demand printing also reduces drug waste and inventory burdens, contributing to more efficient and responsive healthcare delivery systems.

Beyond oral drug delivery, 3D printed implantable and localized drug delivery systems offer promising therapeutic opportunities. Patient-specific implants designed to match anatomical requirements can deliver drugs directly to

targeted sites, achieving sustained local concentrations while minimizing systemic exposure. Such approaches have shown potential in areas including cancer therapy, orthopedic applications, and post-surgical pain management. The customization afforded by 3D printing enhances both therapeutic efficacy and patient comfort.

Despite these promising applications, the widespread clinical adoption of 3D printed pharmaceuticals remains at an early stage. Most reported studies are limited to preclinical evaluations or small-scale clinical investigations. Nevertheless, the growing body of evidence supports the feasibility and therapeutic value of additive manufacturing in addressing clinical challenges that are difficult to resolve with conventional pharmaceutical technologies.

In summary, the clinical applications and therapeutic potential of 3D printed pharmaceuticals extend across personalized dosing, chronic disease management, rare diseases, decentralized manufacturing, and localized drug delivery. As regulatory frameworks mature and clinical evidence continues to accumulate, 3D printing is poised to play an increasingly important role in delivering individualized, effective, and patient-centered therapies.28–32

10.1. Future Perspectives

The future of three-dimensional (3D) printing in personalized pharmaceuticals is closely aligned with broader transformations occurring in healthcare, digitalization, and precision medicine. As technological capabilities continue to mature and interdisciplinary integration deepens, additive manufacturing is expected to transition from a largely experimental and niche approach to a more established component of pharmaceutical development and clinical practice. Future perspectives emphasize not only technological refinement but also systemic changes in how medicines are designed, produced, regulated, and delivered to patients.

One of the most anticipated developments is the emergence of digital pharmacies and on-demand manufacturing models. In this paradigm, personalized medicines could be produced locally at hospitals, clinics, or community pharmacies based on digital prescriptions and patient-specific data. Such decentralized production systems have the potential to significantly reduce supply chain complexity, minimize drug shortages, and enable rapid dose adjustments in response to clinical needs. As infrastructure and regulatory clarity improve, point-of-care manufacturing is likely to become a practical extension of personalized healthcare delivery.

Advances in materials science are expected to play a decisive role in shaping the next generation of 3D printed pharmaceuticals. The development of novel pharmaceutical-grade polymers, biodegradable materials, and stimuli-responsive matrices will expand the range of drugs and dosage forms suitable for additive manufacturing. These innovations may enable more sophisticated control over drug release, including site-specific, time-dependent, or feedback-responsive delivery systems. Such capabilities would further align 3D printed drug products with the goals of precision medicine and targeted therapy.

The integration of computational tools and data-driven approaches will also define future progress in this field. Predictive modeling, artificial intelligence, and simulation-based design are likely to become standard components of the formulation and manufacturing workflow. These tools can accelerate development timelines, reduce experimental variability, and support rational decision-making for personalized dosage form design. In the long term, closed-loop systems that combine patient monitoring data with automated manufacturing platforms may enable adaptive drug delivery tailored to real-time therapeutic response.

Regulatory evolution will be critical in determining the pace and extent of adoption of pharmaceutical 3D printing. Future regulatory frameworks are expected to move toward more flexible, risk-based approaches that account for individualized production while maintaining rigorous standards for safety and quality. International harmonization of guidelines, coupled with clearer definitions of responsibility in decentralized manufacturing settings, will be essential to support global implementation. Collaboration between regulators, industry, and academic institutions will play a central role in shaping these frameworks.

From a clinical perspective, future applications of 3D printed pharmaceuticals are likely to expand beyond oral dosage forms to include complex implantable systems, combination therapies, and integrated drug–device products. These innovations may be particularly impactful in areas such as oncology, chronic disease management, and rare disorders, where individualized treatment strategies are critical. As clinical evidence accumulates, the therapeutic value of personalized 3D printed medicines is expected to become more clearly defined and widely accepted.

In summary, the future of 3D printing in personalized pharmaceuticals is characterized by convergence—of digital technologies, advanced materials, regulatory adaptation, and patient-centered care. While challenges remain, continued

innovation and collaborative efforts are likely to position additive manufacturing as a key enabling technology in the evolution of precision medicine. As the field progresses, 3D printing has the potential to fundamentally reshape pharmaceutical manufacturing and redefine how individualized drug therapy is delivered in modern healthcare systems.33,34

11. Conclusion

Three-dimensional (3D) printing has emerged as a transformative technology in pharmaceutical sciences, offering a fundamentally new approach to the design, manufacture, and delivery of personalized drug products. By enabling precise control over dosage form geometry, internal architecture, and drug distribution, additive manufacturing addresses many of the limitations associated with conventional, standardized pharmaceutical production. Throughout this review, it has been evident that 3D printing provides a versatile platform for tailoring drug therapy to individual patient needs, aligning closely with the principles of personalized and precision medicine.

Advancements in printing technologies, printable materials, and digital design strategies have collectively expanded the scope of 3D printed drug delivery systems. Innovations in oral dosage forms, polypills, gastro-retentive systems, and implantable devices demonstrate the capacity of additive manufacturing to enhance therapeutic flexibility and patient adherence. Moreover, the integration of emerging technologies such as artificial intelligence, digital twins, and smart materials further strengthens the potential of 3D printing to deliver adaptive and data-driven pharmaceutical solutions.

Despite these significant achievements, the translation of 3D printed pharmaceuticals into routine clinical and commercial practice remains contingent upon addressing key challenges. Regulatory uncertainty, manufacturing scalability, quality assurance, and ethical considerations continue to influence the pace of adoption. Ensuring consistent product quality, safeguarding patient data, and promoting equitable access to personalized medicines are critical issues that must be resolved through coordinated efforts among regulators, industry, healthcare providers, and researchers.

Looking forward, the future of personalized pharmaceuticals through 3D printing is marked by the convergence of technological innovation and healthcare transformation. As regulatory frameworks evolve and clinical evidence accumulates, additive manufacturing is expected to play an increasingly prominent role in decentralized and on-demand drug production. The continued development of pharmaceutical-grade materials and digital manufacturing tools will further support the realization of patient-centric therapies.

In conclusion, 3D printing represents a powerful enabler of innovation in drug delivery and dosage form design, with the potential to redefine pharmaceutical manufacturing paradigms. While challenges remain, the progress achieved to date underscores the feasibility and clinical relevance of this technology. With sustained research, regulatory adaptation, and ethical stewardship, personalized pharmaceuticals produced through 3D printing are poised to become an integral component of future healthcare systems, advancing the goal of safer, more effective, and individualized drug therapy.

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