Journal of Chemical Health Risks

www.jchr.org

JCHR (2026) 16(2), 1480-1498 | ISSN:2251-6727

Personalized Medicine via 3D Printing in Pharmaceutics: Advancements, Applications, and Future Prospects

[1] **Amrita Thakur***, [2] **Neeta Rai**, [3] **Supriya Unavane**, [4] **Sabeena Syed**, [5] **Snehal Hase**, [6] **Lida Sajimon**, [7] **Jayesh Baldota**, [8] **Prathmesh Gudgila**, [9] **Omkar Kokate**, [10] **Sumita Mandal**

[1,2,3,4,5,6,7,8,9] School of Pharmacy, Vishwakarma University, Pune, India

[10] Yugantar Institute of Pharmacy, Somni, Rajnanadgaon, Chhattisgarh, India

(Received: 16 January 2026 Revised: 25 February 2026 Accepted: 17 March 2026)

KEYWORDS

3D Printing, Personalized Medicine, Additive Manufacturing, Patient-Specific Dosage Forms, Polypills, Pharmaceutical Technology

ABSTRACT:

Personalized medicine has emerged as a transformative approach in modern healthcare, focusing on tailoring therapeutic interventions according to individual patient characteristics such as genetics, physiology, age, and disease profile. Conventional pharmaceutical manufacturing primarily relies on mass production of standardized dosage forms, which often fails to accommodate patient-specific dose requirements and variable therapeutic responses. In this context, three-dimensional (3D) printing, also known as additive manufacturing, has gained significant attention as an innovative technology capable of producing customized drug delivery systems. 3D printing enables the fabrication of pharmaceutical dosage forms with precise control over drug dose, geometry, and release characteristics through layer-by-layer deposition guided by computer-aided design models. Various printing technologies have been explored in pharmaceutics, including Fused Deposition Modeling (FDM), Stereolithography (SLA), inkjet printing, Selective Laser Sintering (SLS), and semi-solid extrusion. These technologies facilitate the development of complex and patient-specific dosage forms that are difficult to achieve using conventional manufacturing methods. Recent research demonstrates the application of 3D printing in the production of polypills, pediatric and geriatric formulations, controlled-release tablets, drug-loaded implants, and personalized drug delivery devices. Despite its promising potential, several challenges remain, including regulatory uncertainties, limited availability of suitable pharmaceutical-grade printable materials, scalability concerns, and the need for robust quality control strategies. Nevertheless, continuous advancements in materials science, digital manufacturing, and regulatory frameworks are expected to accelerate the integration of 3D printing into personalized pharmaceutical therapy, paving the way for more patient-centric drug delivery systems.

1. Introduction

1.1 Concept of Personalized Medicine

Personalized medicine, also referred to as precision medicine, represents an emerging paradigm in healthcare that focuses on tailoring therapeutic strategies according to the individual characteristics of patients, including genetic background, physiological condition, lifestyle, and disease profile. Unlike the traditional "one-size-fits-all" approach, personalized medicine aims to optimize therapeutic outcomes by delivering the right drug at the right dose for the right patient at the right time. Advances in genomics, pharmacogenomics, and biomarker research have significantly contributed to the development of personalized therapeutic strategies, enabling clinicians to predict drug response and adjust treatment regimens accordingly (1,2). The importance of personalized medicine has grown rapidly in recent years due to the increasing prevalence of chronic diseases and the recognition that patients often exhibit variable responses to the same medication. Genetic polymorphisms, metabolic differences, and environmental factors can significantly influence drug absorption, distribution, metabolism, and excretion. Consequently, standardized pharmaceutical formulations may not always provide optimal therapeutic outcomes for all patients. Precision therapy therefore seeks to overcome these limitations by incorporating patient-specific data into treatment decisions, thereby improving efficacy while minimizing adverse drug reactions (3,1). Despite these advancements, the practical implementation of personalized medicine in routine clinical practice remains challenging. One of the major barriers is the lack of flexible pharmaceutical manufacturing technologies capable of producing individualized dosage forms. Conventional drug manufacturing systems are designed for large-scale production of standardized medicines rather than customized drug products tailored to individual patients.

1.2 Limitations of Conventional Drug Manufacturing

Traditional pharmaceutical manufacturing relies on batch production techniques that emphasize uniformity, consistency, and large-scale manufacturing efficiency. While these methods are effective for producing large quantities of medications, they present significant limitations when applied to personalized therapy. One major drawback is the production of fixed dosage strengths that may not align with the specific therapeutic needs of individual patients. In clinical practice, physicians often adjust doses through tablet splitting or combining multiple formulations, which can compromise dosing accuracy and patient adherence. Another limitation is the restricted ability of conventional manufacturing techniques to produce patient-specific dosage forms. Standard pharmaceutical processes such as tablet compression, capsule filling, and coating are designed to produce uniform drug products with predetermined characteristics. As a result, these techniques provide limited flexibility in designing customized formulations or incorporating multiple drugs within a single dosage form. Patient compliance is another critical issue associated with conventional dosage forms. Pediatric and geriatric populations often face difficulties in swallowing conventional tablets or capsules, which may lead to poor medication adherence. Additionally, patients with chronic diseases frequently require multiple medications administered at different times throughout the day. Such complex dosing regimens increase the risk of medication errors and reduce treatment compliance. The development of multi-drug formulations, commonly referred to as polypills, has been proposed as a strategy to simplify therapy; however, conventional manufacturing techniques offer limited capability for producing complex multi-drug formulations with different release profiles (4,5). These limitations highlight the need for innovative pharmaceutical technologies that can enable flexible, patient-specific drug manufacturing. In recent years, additive manufacturing technologies—particularly three-dimensional (3D) printing—have emerged as promising solutions to address these challenges.

1.3 Emergence of 3D Printing in Pharmaceutics

Three-dimensional (3D) printing, also known as additive manufacturing, is an advanced fabrication technology that constructs objects layer by layer using digital design models. Initially developed for industrial prototyping, 3D printing has rapidly expanded into biomedical applications, including tissue engineering, medical device manufacturing, and pharmaceutical drug delivery systems. In pharmaceutics, this technology offers the ability to fabricate complex dosage forms with precise control over geometry, drug loading, and release kinetics (2,4). One of the most significant milestones in pharmaceutical 3D printing was the approval of Spritam® (levetiracetam) by the United States Food and Drug Administration (FDA). Developed using binder-jetting technology, Spritam® was the first commercially approved 3D-printed drug product. The tablet possesses a highly porous structure that enables rapid disintegration with a small amount of liquid, making it particularly suitable for patients who experience difficulty swallowing conventional tablets (6,7). Following this landmark approval, research in pharmaceutical 3D printing has expanded significantly. Several printing technologies have been explored for drug delivery applications, including fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), and inkjet printing. These technologies enable the fabrication of complex dosage forms with customized shapes, internal structures, and drug release profiles that are difficult to achieve using conventional pharmaceutical manufacturing methods (1,3). Furthermore, 3D printing allows the production of personalized dosage forms such as polypills containing multiple drugs with distinct release characteristics, drug-loaded implants, transdermal patches, and microneedle arrays. The integration of digital design software with pharmaceutical formulation techniques enables researchers to precisely control drug dosage, geometry, and release behavior, making 3D printing a promising platform for personalized drug delivery systems (2,4).

1.4 Aim and Scope of the Review

Given the rapid advancements in additive manufacturing technologies and their potential to revolutionize pharmaceutical development, a comprehensive analysis of 3D printing in personalized medicine is essential. The present review aims to provide an updated overview of

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 1480-1498 | ISSN:2251-6727

the role of 3D printing technologies in the development of personalized pharmaceutical dosage forms. Specifically, this review discusses the fundamental principles of 3D printing in pharmaceutics and the various printing technologies employed for drug formulation, including fused deposition modeling, stereolithography, selective laser sintering, and inkjet printing. The article further explores the application of these technologies in developing patient-specific drug delivery systems such as polypills, pediatric formulations, controlled-release tablets, and implantable drug delivery devices. In addition, the advantages and challenges associated with pharmaceutical 3D printing—including regulatory considerations, material limitations, and scalability issues—are critically evaluated. Finally, the review highlights emerging trends and future perspectives, including the integration of artificial intelligence, multi-material printing, and point-of-care manufacturing, which may further enhance the implementation of personalized medicine in pharmaceutical practice.

2. Fundamentals of 3D Printing in Pharmaceutics

2.1 Definition of Additive Manufacturing

Three-dimensional (3D) printing, also referred to as additive manufacturing (AM), is a modern fabrication technology that constructs objects layer-by-layer from digital design models. In contrast to conventional subtractive manufacturing processes that remove material to produce a final structure, additive manufacturing builds complex structures through the sequential deposition of materials according to computer-generated instructions. This technology enables precise control over geometry, internal architecture, and material distribution within the fabricated object (4,8). In pharmaceutical sciences, additive manufacturing has emerged as a transformative approach for the development of personalized drug delivery systems. By integrating computer-aided design (CAD) with advanced printing technologies, pharmaceutical dosage forms can be produced with customized shapes, drug loading, and release profiles tailored to individual patient requirements. Compared with traditional pharmaceutical manufacturing techniques, 3D printing provides greater flexibility in formulation design and enables rapid prototyping of complex dosage forms that would otherwise be difficult to achieve using conventional processes (4,9). Furthermore, additive manufacturing technologies allow the fabrication of intricate internal structures that can regulate drug release behavior, improve bioavailability, and support the development of patient-specific drug delivery systems. As a result, 3D printing has gained increasing attention in pharmaceutical research for producing customized medicines, polypills containing multiple drugs, and drug delivery devices with controlled release characteristics (4,10).

2.2 Workflow of Pharmaceutical 3D Printing

The process of pharmaceutical 3D printing involves several sequential steps that transform a digital design into a physical dosage form. These steps include computer-aided design modeling, slicing, printing, and post-processing.

2.2.1 Computer-Aided Design (CAD) Modeling

The first step in pharmaceutical 3D printing involves the creation of a digital model of the dosage form using computer-aided design (CAD) software. This stage allows researchers to design the geometry, dimensions, and internal structure of the dosage form. Parameters such as tablet shape, porosity, and infill density can be modified to achieve the desired drug release profile and mechanical properties. The CAD model serves as the blueprint for the printing process and determines the final characteristics of the printed product (4,10).

2.2.2 Slicing

Once the CAD model is generated, it is converted into a printable format, typically an STL (stereolithography) file. Specialized slicing software divides the digital model into multiple thin layers and generates the toolpath instructions required for the printer. These instructions guide the movement of the printing nozzle or laser during the fabrication process. Slicing also allows adjustment of printing parameters such as layer thickness, printing speed, and infill pattern, which significantly influence the mechanical strength and drug release properties of the printed dosage form (4,9).

2.2.3 Printing

During the printing stage, the selected material—such as a polymer filament, powder, or liquid resin—is deposited layer by layer according to the instructions generated during slicing. Several 3D printing technologies are used in pharmaceutics, including fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), and inkjet printing. Each technique differs in terms of the materials used, printing mechanism, and achievable resolution. For example, FDM involves the extrusion of drug-loaded polymer filaments, whereas SLA uses light-induced polymerization of liquid resins to fabricate high-resolution structures (4,9).

2.2.4 Post-Processing

After printing, the fabricated dosage forms may undergo post-processing steps to improve their mechanical strength, drug stability, and overall quality. These processes may include drying, curing, sintering, or surface finishing depending on the printing technique used. For example, photopolymerization-based printing methods often require ultraviolet curing to complete the polymerization process and stabilize the structure of the printed object. Post-processing also ensures that the dosage form meets pharmaceutical quality standards before administration (10).

2.3 Types of Printable Dosage Forms

One of the most significant advantages of pharmaceutical 3D printing is its ability to fabricate a wide range of dosage forms with customized structures and drug release profiles. Several types of pharmaceutical products have been successfully produced using additive manufacturing technologies.

Tablets

Tablets are the most commonly studied dosage forms in pharmaceutical 3D printing. The ability to modify tablet geometry, porosity, and internal structure enables precise control over drug release kinetics. Researchers have developed immediate-release, sustained-release, and multi-drug polypill tablets using 3D printing technologies (4).

Capsules

3D printing has also been used to fabricate customized capsules with tailored drug loading and release characteristics. In some cases, capsule shells and internal compartments can be printed to incorporate multiple drugs with distinct release profiles. This approach is particularly beneficial for patients requiring combination therapies or complex dosing regimens.

Implants

Implantable drug delivery systems produced through 3D printing have gained considerable attention due to their ability to provide localized and sustained drug release. Photopolymerization-based printing techniques have been used to fabricate drug-eluting implants and stents designed for controlled therapeutic delivery in chronic diseases (10).

Transdermal Patches

3D printing also enables the fabrication of personalized transdermal patches that deliver drugs through the skin. These patches can be designed with specific geometries and drug loading capacities to optimize drug permeation and release characteristics.

Microneedles

Microneedle arrays are minimally invasive devices that penetrate the outer layer of the skin to deliver drugs directly into the dermal region. Additive manufacturing technologies have enabled the fabrication of microneedles with precise geometries and improved mechanical properties. These systems are particularly promising for vaccine delivery, insulin administration, and transdermal drug therapy (11,12).

2.4 Materials Used in Pharmaceutical Printing

The selection of suitable materials is a critical factor in the development of pharmaceutical 3D printing systems. Materials used in additive manufacturing must possess appropriate physicochemical properties such as biocompatibility, printability, mechanical strength, and compatibility with active pharmaceutical ingredients.

Polymers

Polymeric materials are widely used in pharmaceutical 3D printing due to their versatility and ability to control drug release. Common polymers include polyvinyl alcohol (PVA), polycaprolactone (PCL), and polyethylene glycol (PEG). These polymers can be processed into filaments, powders, or resins depending on the printing technique employed. Polymeric excipients also play a crucial role in determining the mechanical properties and dissolution behavior of printed dosage forms (13).

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 1480-1498 | ISSN:2251-6727

Hydrogels

Hydrogels are three-dimensional polymer networks capable of absorbing large amounts of water while maintaining structural integrity. Due to their biocompatibility and tunable properties, hydrogels are widely used in biomedical 3D printing applications, including drug delivery systems and tissue engineering scaffolds. Hydrogels can respond to environmental stimuli such as temperature or pH, making them suitable for controlled drug release applications (10).

Biodegradable Polymers

Biodegradable polymers are particularly important for implantable drug delivery systems and microneedle arrays. Materials such as poly(lactic-co-glycolic acid) (PLGA), polycaprolactone (PCL), and polylactic acid (PLA) are commonly used because they degrade into non-toxic by-products within the body. These polymers provide mechanical strength and controlled degradation rates, making them suitable for sustained drug release systems and biodegradable medical devices (11,12). Overall, the development of suitable pharmaceutical printing materials remains a critical area of research. Advances in polymer science and biomaterials are expected to expand the range of printable pharmaceutical formulations and improve the clinical applicability of 3D-printed drug delivery systems.

3. 3D Printing Technologies in Drug Delivery

Three-dimensional (3D) printing, also known as additive manufacturing, has transformed pharmaceutical formulation development by enabling the fabrication of complex drug delivery systems with precise control over geometry, drug distribution, and release characteristics. Unlike conventional pharmaceutical manufacturing methods that rely on compression or molding techniques, 3D printing constructs dosage forms layer by layer based on digital design models. This approach allows the production of highly customized drug products tailored to individual patient needs, which is a fundamental objective of personalized medicine (4,14). Several additive manufacturing techniques have been investigated for pharmaceutical applications. Among them, fused deposition modeling (FDM), inkjet printing, selective laser sintering (SLS), stereolithography (SLA), and semi-solid extrusion (SSE) are the most widely used technologies for developing drug delivery systems. Each technology differs in terms of working principle, materials used, resolution, and suitability for pharmaceutical formulations. Understanding these technologies is essential for selecting appropriate methods for designing personalized dosage forms.

3.1 Fused Deposition Modeling (FDM)

Fused deposition modeling is one of the most widely used 3D printing technologies in pharmaceutical research due to its simplicity, cost-effectiveness, and compatibility with thermoplastic polymers. In this technique, drug-loaded polymer filaments are melted and extruded through a heated nozzle, depositing material layer by layer to form the desired dosage form according to a computer-generated design (15).

Working Principle

The FDM process begins with the preparation of drug-loaded filaments, typically produced through hot-melt extrusion (HME). These filaments are then fed into the printer, where they are heated above their melting temperature and extruded through a nozzle. The printer head moves along the X-Y plane, depositing the molten material onto a build platform where it solidifies upon cooling. Successive layers are deposited until the final three-dimensional structure is obtained. The integration of hot-melt extrusion with FDM printing enables the formation of amorphous solid dispersions, which can enhance the solubility and bioavailability of poorly water-soluble drugs (16).

Polymers Used

Several thermoplastic polymers have been employed in FDM-based pharmaceutical formulations. Commonly used polymers include:

- Polyvinyl alcohol (PVA)
- Polylactic acid (PLA)
- Polycaprolactone (PCL)
- Hydroxypropyl methylcellulose (HPMC)
- Ethyl cellulose

These polymers are selected based on their thermal properties, mechanical strength, and compatibility with active pharmaceutical ingredients.

Advantages

FDM printing offers several advantages for pharmaceutical applications:

- Cost-effective and widely accessible technology
- Capability to produce complex internal geometries
- Ability to modify drug release profiles through structural design
- Compatibility with various thermoplastic polymers

Applications

FDM has been widely used to produce personalized tablets, multilayer drug delivery systems, and polypills. Researchers have successfully fabricated controlled-release tablets, floating drug delivery systems, and gastro-retentive formulations using FDM printing technology (17). Furthermore, FDM enables the fabrication of patient-specific dosage forms with customizable drug doses and shapes. Despite its advantages, FDM has limitations, particularly for thermolabile drugs that may degrade during the high-temperature extrusion process.

3.2 Inkjet Printing

Inkjet printing is another promising additive manufacturing technique used in pharmaceutical applications. This technology involves the deposition of liquid droplets containing drug formulations onto a substrate or powder bed in a controlled manner. Inkjet printing is particularly useful for producing dosage forms with precise drug loading and complex drug distribution patterns.

Drop-on-Demand Printing

In drop-on-demand inkjet printing, small droplets of liquid formulation are generated and deposited only when required. The droplets are ejected through a nozzle using thermal or piezoelectric actuation mechanisms. This method allows precise control over droplet size and deposition location, enabling accurate drug dosing. Drop-on-demand printing has been used to fabricate orodispersible films, transdermal patches, and micro-dosed drug delivery systems (18).

Binder Jetting

Binder jetting is a specific type of inkjet printing technology in which a liquid binder is selectively deposited onto a powder bed containing pharmaceutical excipients. The binder causes the powder particles to adhere together, forming a solid layer. After each layer is printed, a new layer of powder is spread over the surface, and the process is repeated until the final structure is obtained. Binder jetting technology was used to manufacture the first FDA-approved 3D-printed drug, Spritam® (levetiracetam), which demonstrates the clinical feasibility of inkjet-based pharmaceutical printing (19).

Applications

Inkjet printing has been widely used for:

- Printing precise drug doses for personalized medicine
- Coating tablets with active pharmaceutical ingredients
- Fabricating multilayer drug delivery systems
- Producing fast-dissolving oral films

The major advantages of inkjet printing include high precision, low material wastage, and suitability for heat-sensitive drugs.

However, the technology is limited by the viscosity requirements of printable inks and potential nozzle clogging issues.

3.3 Selective Laser Sintering (SLS)

Selective laser sintering is a powder-based additive manufacturing technique that uses a laser beam to selectively fuse powder particles into solid structures. In this method, a thin layer of powder is spread across the build platform, and a laser beam scans the surface according to a digital design pattern. The laser energy partially melts or sinters the powder particles, causing them to fuse together and form a solid layer.

Once a layer is completed, another layer of powder is deposited, and the process is repeated until the final object is formed (20).

Advantages

Selective laser sintering offers several advantages in pharmaceutical manufacturing:

- High resolution and precision
- Ability to print without additional support structures
- Suitable for complex internal architectures
- Capability to produce porous drug delivery systems

The porous structures generated through SLS can significantly influence drug release behavior by increasing surface area and enhancing dissolution rates.

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 1480-1498 | ISSN:2251-6727

Applications

SLS has been used to fabricate various pharmaceutical dosage forms, including:

- Immediate-release tablets
- Controlled-release tablets
- porous drug delivery systems
- transdermal patches

The technique is particularly useful for designing dosage forms with tailored dissolution properties.

However, SLS requires expensive equipment and careful optimization of laser parameters to prevent degradation of heat-sensitive drugs.

3.4 Stereolithography (SLA)

Stereolithography is a photopolymerization-based 3D printing technology that uses ultraviolet (UV) light to cure liquid resin materials into solid structures. In this process, a photosensitive resin containing polymerizable monomers and photoinitiators is selectively exposed to a UV laser beam or light source. The light triggers polymerization reactions that solidify the resin layer by layer.

Working Principle

In SLA printing, a build platform is immersed in a resin bath. A UV laser selectively scans the surface of the resin according to the digital model, causing the resin to polymerize and form a solid layer. The platform then moves vertically, allowing the next layer of resin to be cured. This process continues until the final three-dimensional structure is obtained.

Advantages

Stereolithography offers several advantages for pharmaceutical applications:

- High printing resolution
- Smooth surface finish
- Ability to fabricate intricate geometries
- Suitable for micro-scale drug delivery devices

SLA printing also generates less thermal stress compared to extrusion-based printing techniques, making it suitable for certain heat-sensitive drugs (21).

Applications

SLA has been used to fabricate:

- drug-loaded implants
- microneedle arrays
- intravesical drug delivery devices
- controlled-release tablets

For example, SLA has been used to create antibiotic-loaded implants capable of delivering localized antimicrobial therapy, demonstrating the potential of this technology for targeted drug delivery applications (21). Despite its high precision, the technology is limited by the availability of biocompatible photopolymerizable materials suitable for pharmaceutical use.

3.5 Semi-Solid Extrusion (SSE)

Semi-solid extrusion is an extrusion-based 3D printing technique that uses paste-like or gel-based formulations as printing materials. Unlike FDM printing, which requires thermoplastic filaments, SSE operates at relatively low temperatures, making it suitable for temperature-sensitive drugs. In this technique, semi-solid formulations are loaded into a syringe or cartridge and extruded through a nozzle using pneumatic pressure or mechanical force. The material is deposited layer by layer to build the final structure.

Advantages

The main advantages of SSE printing include:

- Compatibility with a wide range of pharmaceutical formulations
- Ability to print heat-sensitive drugs
- Simplified formulation preparation
- High drug loading capacity

Applications

SSE printing has been used to produce:

- multilayer tablets
- chewable tablets
- pediatric dosage forms
- hydrogel-based drug delivery systems

Recent studies have demonstrated the use of SSE technology to fabricate dual-release tablets containing immediate-release and extended-release layers, highlighting the potential of this technique for complex drug delivery systems (22). However, SSE printing may suffer from limitations related to mechanical strength and printing resolution compared with other techniques. The

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 1480-1498 | ISSN:2251-6727

below table no.1 explains comparison between major 3D printing technologies.

Table1.: Comparison of Major 3D Printing Technologies in Pharmaceutics

Technology	Printing Material	Key Advantages	Limitations	Pharmaceutical Applications
FDM	Thermoplastic filaments	Cost-effective, widely used	High temperature may degrade drugs	Tablets, polypills
Inkjet	Liquid inks / binders	High precision dosing	Limited viscosity range	Oral films, coatings
SLS	Powder materials	No support structures required	Expensive equipment	Porous tablets
SLA	Photopolymer resins	High resolution	Limited biocompatible materials	Microneedles, implants
SSE	Semi-solid pastes	Suitable for heat-sensitive drugs	Lower mechanical strength	Hydrogels, multilayer tablets

Additive manufacturing technologies thus provide diverse tools for fabricating innovative drug delivery systems. Each printing method offers unique advantages and limitations, and the selection of an appropriate technology depends on factors such as drug properties, material compatibility, desired dosage form, and required release characteristics. As research progresses, improvements in printing materials, process optimization, and regulatory frameworks are expected to accelerate the clinical translation of 3D-printed pharmaceuticals.

4. Role of 3D Printing in Personalized Medicine

Personalized medicine aims to tailor therapeutic interventions according to the specific characteristics of individual patients, including genetic profile, disease condition, age, metabolism, and physiological parameters. Conventional pharmaceutical manufacturing relies on fixed-dose formulations that are designed for large populations rather than individual patients. However, variability in pharmacokinetics and pharmacodynamics often leads to suboptimal therapeutic outcomes or adverse drug reactions. Three-dimensional (3D) printing has emerged as a promising technology capable of addressing these limitations by enabling the fabrication of customized drug delivery systems with adjustable doses, complex release profiles, and patient-specific designs (1,23). Unlike conventional manufacturing methods, 3D printing enables the layer-by-layer fabrication of pharmaceutical dosage forms directly from digital models. This approach provides precise control over the composition, geometry, and internal structure of drug delivery systems, thereby enabling the production of personalized medicines tailored to the needs of individual patients (24).

4.1 Patient-Specific Dose Customization

One of the most significant advantages of 3D printing in pharmaceutics is the ability to produce patient-specific dosage forms with customized drug doses. In conventional pharmaceutical manufacturing, drugs are typically available in a limited number of fixed doses. Patients requiring intermediate doses often need to split tablets or combine multiple dosage forms, which may lead to inaccurate dosing and poor therapeutic outcomes. 3D printing enables the production of tablets with precise drug loading by adjusting formulation composition, printing parameters, or tablet geometry. This capability allows healthcare providers to tailor medication according to individual patient characteristics such as body weight, metabolic rate, and pharmacogenomic profile (25).

Weight-based dosing

Body weight is an important determinant of drug dosage, particularly for pediatric and oncology patients. 3D printing enables the fabrication of tablets with variable sizes or drug concentrations, allowing clinicians to produce personalized doses tailored to patient weight.

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 1480-1498 | ISSN:2251-6727

Metabolism-based dosing

Individual differences in metabolic activity can significantly influence drug pharmacokinetics. Patients with rapid metabolism may require higher doses, whereas slow metabolizers may need reduced doses to avoid toxicity. By adjusting the drug concentration within the printed dosage form, 3D printing allows precise dose optimization.

Pharmacogenomics-guided therapy

Pharmacogenomics studies the influence of genetic variations on drug response. Genetic polymorphisms affecting drug-metabolizing enzymes such as CYP450 can alter drug efficacy and safety. Personalized dosage forms fabricated through 3D printing can be designed according to pharmacogenomic data, enabling precision therapy tailored to a patient's genetic profile (23). These capabilities highlight the potential of 3D printing to improve treatment efficacy, reduce adverse effects, and support the implementation of precision medicine.

4.2 Polypill Fabrication

Polypharmacy is a common challenge in the treatment of chronic diseases such as hypertension, diabetes, and cardiovascular disorders. Patients often need to take multiple medications daily, which increases pill burden and reduces medication adherence. 3D printing technology has introduced the concept of polypills, which combine multiple drugs within a single dosage form. This approach allows different active pharmaceutical ingredients (APIs) to be incorporated into separate layers or compartments of a single tablet. Each drug can be formulated with distinct release characteristics, enabling complex therapeutic regimens within a single dosage unit (26). Recent research demonstrates that 3D-printed polypills can contain several drugs with independent release profiles. For example, drugs can be arranged in layered structures or compartmentalized geometries to control the sequence and timing of drug release. This approach offers a significant advantage over conventional fixed-dose combinations, which require compatibility among all drug components in a single formulation (27). Furthermore, polypills produced using additive manufacturing can incorporate immediate-release and sustained-release layers within the same tablet. Such designs can optimize therapeutic outcomes by delivering drugs at different rates according to disease requirements. The use of 3D-printed polypills is particularly beneficial for patients with chronic diseases who require multiple medications daily. By reducing the number of tablets a patient must take, polypills can improve medication adherence, simplify treatment regimens, and enhance overall therapeutic outcomes.

4.3 Pediatric and Geriatric Dosage Forms

Pediatric and geriatric patients often require special dosage forms due to physiological differences, swallowing difficulties, and altered pharmacokinetics. Conventional tablets are usually designed for adult patients and may not be suitable for children or elderly individuals. 3D printing offers significant advantages in developing age-appropriate dosage forms tailored to the needs of these populations. One important application is the fabrication of mini-tablets or "spinklets," which are small tablets that can be easily swallowed by pediatric patients (28). In addition to size customization, 3D printing enables the incorporation of flavors, colors, and shapes that improve the acceptability of medications for children. For example, chewable tablets or orodispersible films can be fabricated using additive manufacturing techniques. For geriatric patients, dosage forms can be designed to address issues such as dysphagia (difficulty swallowing) and polypharmacy. Orodispersible tablets, rapidly dissolving films, and personalized polypills can improve medication adherence and simplify complex treatment regimens. Furthermore, 3D printing enables the adjustment of drug dose according to age-related physiological changes, including reduced renal function and altered drug metabolism. This capability supports safer pharmacotherapy for vulnerable populations such as children and elderly patients.

4.4 Tailored Drug Release Profiles

One of the most remarkable capabilities of 3D printing in pharmaceutics is the ability to design dosage forms with customized drug release profiles. By modifying the internal structure, geometry, and composition of printed dosage forms, researchers can control the rate and pattern of drug release.

Immediate Release

Immediate-release formulations are designed to dissolve rapidly after administration, allowing the drug to be absorbed quickly. 3D printing can create porous structures that enhance dissolution rates and enable rapid drug release.

Sustained Release

Sustained-release formulations provide prolonged drug release over an extended period, reducing the frequency of drug administration. Through structural design and polymer selection, 3D-printed tablets can achieve controlled drug diffusion and sustained therapeutic effects.

Delayed Release

Delayed-release formulations are designed to release the drug after a specific time delay or upon reaching a particular region of the gastrointestinal tract. For example, enteric-coated structures can be incorporated into 3D-printed tablets to prevent drug release in the stomach.

Pulsatile Release

Pulsatile drug delivery systems release drugs in multiple bursts separated by lag periods. Such systems are particularly useful for diseases with circadian patterns, such as asthma or hypertension. By designing multi-layer structures with different polymer barriers, 3D printing enables the development of pulsatile drug delivery systems tailored to individual therapeutic requirements (29). The ability to precisely engineer drug release kinetics represents a major advantage of additive manufacturing technologies and opens new possibilities for personalized drug therapy.

4.5 Patient-Specific Implants and Devices

Beyond oral dosage forms, 3D printing also enables the fabrication of patient-specific implants and drug delivery devices. These devices can be designed using medical imaging data such as CT or MRI scans, allowing the creation of implants that match the anatomical structure of individual patients. Drug-loaded implants produced using additive manufacturing can deliver therapeutic agents directly at the target site, providing localized treatment and reducing systemic side effects. Such implants are particularly useful for the treatment of bone infections, cancer, and chronic inflammatory conditions. In addition, 3D printing technology has been applied to the development of microneedles, transdermal patches, and implantable drug delivery systems that provide controlled drug release over extended periods. These devices offer significant advantages in terms of patient compliance, targeted therapy, and improved therapeutic outcomes (30). Another emerging application involves bioprinted tissues and organ models, which can be used for personalized drug testing and disease modeling. These platforms allow researchers to evaluate drug responses in patient-specific tissue models, enabling more accurate prediction of therapeutic outcomes (1). Overall, the integration of 3D printing with personalized medicine has the potential to revolutionize pharmaceutical manufacturing by enabling the production of customized drug delivery systems tailored to individual patient needs.

5. Applications of 3D Printing in Pharmaceutics

Three-dimensional (3D) printing, also known as additive manufacturing, has emerged as a transformative technology in pharmaceutical sciences due to its ability to fabricate complex dosage forms with precise control over drug distribution, geometry, and release characteristics. Unlike conventional pharmaceutical manufacturing, which relies on mass production of standardized dosage forms, 3D printing enables the development of patient-specific formulations tailored to individual therapeutic requirements. This technology facilitates customization of drug dosage, release kinetics, and dosage form architecture, thereby improving treatment efficacy and patient compliance. Recent advancements in printing techniques such as fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), and inkjet printing have expanded the range of pharmaceutical applications of 3D printing (4). 3D printing has been widely explored for the development of oral drug delivery systems, transdermal patches, implantable devices, bioprinted tissues, and drug-loaded medical devices. These innovations offer promising opportunities to improve drug delivery efficiency, enable personalized medicine, and accelerate pharmaceutical research and development (30).

5.1 Oral Drug Delivery Systems

Oral drug delivery remains the most common route of administration due to its convenience, patient compliance, and cost-effectiveness. However, conventional tablet manufacturing methods often lack flexibility in modifying drug release patterns and dosage strength. 3D printing has emerged as a promising solution to overcome these limitations by enabling the fabrication of complex oral dosage forms with controlled geometry, porosity, and internal structure. One of the major advantages of 3D printing in oral drug delivery is the ability to produce personalized tablets with tailored doses based on patient characteristics such as age, body weight, and disease condition. Technologies such as fused deposition modeling and binder jet printing allow precise placement of active pharmaceutical ingredients (APIs) within polymer matrices, thereby controlling drug release profiles. For example, tablets with multilayer structures can be fabricated to achieve immediate, sustained, or pulsatile drug release (31). Another significant application is the development of polypills, where multiple drugs are incorporated into a single dosage form. This approach is particularly beneficial for patients suffering from chronic diseases requiring polypharmacy, such as hypertension or cardiovascular disorders. 3D printing allows different drugs to be placed in separate compartments within the same tablet, each with distinct release kinetics, thereby reducing pill burden and improving adherence. Additionally, 3D printing enables the fabrication of tablets with complex geometries such as porous structures and honeycomb designs that influence drug dissolution rates. By adjusting parameters such as infill density and printing pattern, researchers can modulate drug release from immediate to sustained profiles. The incorporation of nanomaterials and biodegradable polymers has further enhanced the mechanical and release properties of printed oral dosage forms (4). Furthermore, 3D-printed orodispersible films and chewable formulations are being developed for pediatric and geriatric populations who experience difficulty swallowing conventional tablets. These formulations dissolve rapidly in the oral cavity and can be customized with flavors or shapes to enhance patient acceptability. Consequently, 3D printing is expected to revolutionize oral drug delivery by enabling personalized and multifunctional dosage forms.

5.2 Transdermal Drug Delivery

Transdermal drug delivery systems (TDDS) provide an alternative route of administration that bypasses first-pass metabolism and allows sustained drug release through the skin. Traditional transdermal patches are generally limited in terms of structural complexity and drug loading capacity. However, 3D printing technologies enable the fabrication of customized transdermal patches with controlled drug release properties. Using additive manufacturing techniques, researchers can design microneedle arrays, multilayer patches, and porous scaffolds that enhance drug permeation through the skin. Microneedles fabricated through stereolithography or extrusion-based printing create microchannels in the stratum corneum, allowing efficient delivery of drugs such as insulin, vaccines, and analgesics without causing significant pain or tissue damage. Another advantage of 3D printing in transdermal systems is the ability to integrate drug reservoirs and diffusion layers within a single patch. By controlling the geometry and thickness of each layer, drug diffusion rates can be precisely regulated. This enables the development of patches capable of delivering drugs over extended periods ranging from several hours to days. Recent studies have also demonstrated the use of biodegradable polymers and hydrogel-based bioinks for fabricating flexible transdermal systems. These materials improve adhesion to the skin while maintaining structural integrity and drug stability. Additionally, 3D printing allows incorporation of sensors and electronic components within transdermal patches, enabling the development of smart drug delivery systems capable of monitoring physiological parameters and adjusting drug release accordingly (4,30).

5.3 Implantable Drug Delivery Systems

Implantable drug delivery systems are designed to provide localized and sustained drug release over prolonged periods, often ranging from weeks to months. These systems are particularly useful for the treatment of chronic diseases such as cancer, neurological disorders, and bone infections. Conventional implantable devices are typically manufactured using molding or machining techniques, which limit design flexibility and customization. 3D printing has significantly improved the design and fabrication of implantable drug delivery devices by enabling the production of patient-specific implants with complex internal structures. Additive manufacturing allows precise control over device geometry, porosity, and drug distribution within biodegradable polymer matrices. As a result, implantable devices can be tailored to achieve desired drug release kinetics and mechanical properties. For instance, biodegradable implants fabricated using polymers such as polycaprolactone (PCL), polylactic acid (PLA), and poly(lactic-co-glycolic acid) (PLGA) have been

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 1480-1498 | ISSN:2251-6727

developed for localized delivery of anticancer drugs, antibiotics, and anti-inflammatory agents. These implants gradually degrade within the body while releasing therapeutic agents at controlled rates. Another promising application involves bone scaffolds loaded with drugs or growth factors, which promote bone regeneration while simultaneously preventing infection. Such multifunctional implants are particularly useful in orthopedic and dental applications. Moreover, advances in photopolymerization-based printing techniques enable fabrication of high-resolution implants with intricate microstructures suitable for targeted drug delivery (31).

5.4 Bioprinting and Tissue Engineering

Bioprinting represents one of the most exciting applications of 3D printing in pharmaceutics and regenerative medicine. This technology involves the layer-by-layer deposition of living cells, biomaterials, and growth factors to create functional biological tissues or organ-like structures. 3D bioprinting utilizes specialized bioinks composed of cells, hydrogels, and extracellular matrix components to fabricate tissues that mimic natural biological structures. These constructs can be used for drug screening, disease modeling, and tissue regeneration. For example, bioprinted liver and tumor models are increasingly used in pharmaceutical research to evaluate drug toxicity and efficacy, thereby reducing reliance on animal testing. In regenerative medicine, bioprinting has been explored for the fabrication of skin, cartilage, bone, and vascular tissues. By precisely controlling the spatial arrangement of cells and biomaterials, researchers can replicate the structural and functional properties of native tissues. This technology holds immense potential for developing personalized tissue grafts and organ replacements in the future (31). Furthermore, advancements in stem cell technology and biomaterial engineering have improved the viability and functionality of bioprinted tissues. Although challenges such as vascularization and long-term stability remain, bioprinting continues to be a promising area of research in pharmaceutical and biomedical sciences (10).

5.5 Drug-Loaded Medical Devices

Another emerging application of 3D printing in pharmaceutics is the development of drug-loaded medical devices. These devices combine structural functionality with controlled drug release, providing therapeutic benefits while performing their primary mechanical function. Examples include drug-eluting stents, orthopedic implants, dental devices, and wound dressings fabricated using additive manufacturing techniques. In such devices, therapeutic agents are incorporated within polymeric matrices or surface coatings during the printing process. As the device interacts with the biological environment, the drug is gradually released to achieve localized therapeutic effects. For instance, antibiotic-loaded orthopedic implants can prevent post-surgical infections, while drug-eluting stents release antiproliferative agents to prevent restenosis after angioplasty. Similarly, 3D-printed wound dressings containing antimicrobial agents and growth factors have been developed to accelerate wound healing. The ability of 3D printing to fabricate patient-specific devices based on medical imaging data further enhances the effectiveness of these systems. Customized implants ensure better anatomical fit, improved mechanical stability, and targeted drug delivery. As material science and printing technologies continue to evolve, drug-loaded medical devices are expected to play an increasingly important role in personalized healthcare (4,30).

6. Case Studies and Research Developments

The rapid evolution of additive manufacturing technologies has significantly accelerated research in pharmaceutical 3D printing. Several experimental studies and clinical developments have demonstrated the feasibility of fabricating personalized dosage forms with controlled release characteristics and multi-drug combinations. In particular, the approval of the first 3D-printed drug by regulatory authorities has stimulated widespread research interest in developing patient-specific drug delivery systems. Recent investigations have focused on polypill formulations, hydrogel-based printed tablets, and personalized drug delivery systems designed to optimize therapeutic outcomes and improve patient compliance.

6.1 FDA-Approved 3D Printed Drug: Spritam® (Levetiracetam)

A major milestone in pharmaceutical 3D printing was the approval of Spritam® (levetiracetam) by the U.S. Food and Drug Administration (FDA) in 2015. Spritam®, developed using ZipDose® technology, represents the first commercially available 3D-printed pharmaceutical product. The drug is indicated for the treatment of

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 1480-1498 | ISSN:2251-6727

epilepsy and is designed as a rapidly disintegrating oral tablet that disperses quickly upon contact with liquid. The technology allows the production of highly porous tablets that enable rapid drug dissolution while maintaining high drug loading capacity. The manufacturing process involves a layer-by-layer powder bed printing technique, where successive layers of powder are selectively bound using a liquid binder to create a porous matrix structure. This structure enables rapid tablet disintegration, making it particularly beneficial for patients who experience difficulty swallowing conventional tablets. The approval of Spritam® demonstrated the regulatory feasibility of 3D-printed medicines and paved the way for the development of personalized drug products in the pharmaceutical industry (27). Furthermore, the success of Spritam® has encouraged pharmaceutical researchers to explore additive manufacturing technologies for developing patient-specific dosage forms with tailored drug release properties. The regulatory acceptance of 3D-printed drugs highlights the potential of this technology to transform pharmaceutical manufacturing by enabling on-demand production of customized medications.

6.2 Polypill Research Studies

Polypharmacy remains a major challenge in the management of chronic diseases such as cardiovascular disorders, metabolic syndrome, and neurological conditions. Patients often require multiple medications with different dosing schedules, which can lead to reduced adherence and increased risk of medication errors. To address this issue, researchers have explored the development of 3D-printed polypills, which combine multiple active pharmaceutical ingredients into a single dosage form. Several recent studies have demonstrated the feasibility of producing polypills with distinct drug release profiles using additive manufacturing. For example, a four-in-one oral polypill containing caffeine and vitamin B analogues was fabricated using extrusion-based 3D printing, where individual compartments within the tablet enabled different release kinetics for each ingredient (32). Similarly, researchers have developed personalized cardiovascular polypills containing atorvastatin and metoprolol using pressure-assisted microextrusion 3D printing. By modifying geometric parameters and formulation composition, the study demonstrated precise control over drug release behavior, illustrating the capability of 3D printing to create patient-specific multi-drug therapies (33). In another study, a mini-floating 3D-printed polypill for Parkinson's disease was designed to deliver levodopa, benserazide, and pramipexole with adjustable dosing and controlled release characteristics. The floating structure improved gastric retention time, enhancing drug absorption and therapeutic efficacy (34). More recently, researchers engineered 3D-printed polypills for the treatment of metabolic syndrome, incorporating multiple drugs within a single tablet to target different pathological conditions simultaneously (35). These studies highlight the potential of 3D printing to simplify complex medication regimens and improve patient adherence through personalized multi-drug formulations.

6.3 Hydrogel-Based 3D Printed Tablets

Hydrogels have emerged as promising materials for the fabrication of 3D-printed drug delivery systems due to their biocompatibility, tunable mechanical properties, and ability to control drug release. Hydrogel-based tablets are particularly useful for developing controlled-release and stimuli-responsive drug delivery systems. Recent research has focused on printing hydrogel matrices using extrusion-based and stereolithography techniques to create dosage forms with programmable drug release profiles. Hydrogels composed of polymers such as alginate, gelatin, and polyethylene glycol can encapsulate therapeutic agents and release them in response to environmental triggers such as pH or temperature. In advanced designs, hydrogel-based 3D-printed tablets incorporate core-shell architectures, where a hydrogel core containing the drug is surrounded by a polymer shell that regulates drug diffusion. This approach enables precise control over drug release kinetics and improves drug stability. Additionally, hydrogel matrices can be combined with biodegradable polymers to enhance mechanical strength and ensure structural integrity during storage and administration. These innovations demonstrate that hydrogel-based 3D printing offers a versatile platform for developing personalized drug delivery systems capable of delivering drugs with controlled release profiles and improved therapeutic efficiency.

6.4 Personalized Drug Delivery Research

Recent years have witnessed significant progress in the application of 3D printing for personalized drug delivery. Advances in material science, computational modeling, and digital manufacturing have enabled the development of customized dosage forms tailored to individual patient needs. Researchers have explored the use of additive manufacturing to produce patient-specific tablets with adjustable dosage strengths and geometries, allowing healthcare providers to optimize treatment regimens based on patient characteristics such as age, metabolism, and disease severity. Furthermore, the integration of digital health technologies and artificial intelligence has enhanced the design and optimization of personalized drug delivery systems. Recent studies have also demonstrated the feasibility of multi-drug tablets with programmable release profiles, where the geometry and internal structure of the dosage form determine drug dissolution rates. These advancements enable precise control over drug release patterns, ranging from immediate to sustained or pulsatile release. Additionally, 3D printing has been used to fabricate customized dosage forms for pediatric and geriatric populations, where conventional formulations often fail to meet patient-specific dosing requirements. By enabling on-demand manufacturing of personalized medicines, 3D printing has the potential to transform pharmaceutical care and improve therapeutic outcomes. Overall, ongoing research continues to expand the applications of additive manufacturing in personalized medicine. As regulatory frameworks and manufacturing technologies evolve, 3D-printed pharmaceuticals are expected to play an increasingly important role in the future of precision medicine.

7. Advantages of 3D Printing in Personalized Pharmaceutics

Three-dimensional (3D) printing has emerged as a transformative technology in pharmaceutical manufacturing by enabling the production of individualized drug delivery systems tailored to the needs of specific patients. Compared with conventional batch manufacturing, additive manufacturing provides greater flexibility in formulation design, dosing precision, and drug release control. These advantages are particularly valuable in the era of precision medicine, where treatments are increasingly tailored to individual physiological and genetic characteristics.

7.1 Customized Dosing

One of the most significant advantages of 3D printing in pharmaceutics is the ability to produce patient-specific dosage forms. Conventional pharmaceutical manufacturing typically produces fixed-dose formulations, which may not be suitable for all patients due to differences in age, body weight, metabolic rate, or disease severity. 3D printing allows the drug dose to be adjusted by modifying the geometry, volume, or internal structure of the printed dosage form, enabling highly personalized therapy (36,37). This flexibility is particularly useful for pediatric, geriatric, and rare disease patients who require individualized dosing regimens.

7.2 Improved Patient Compliance

3D printing also improves patient adherence by enabling the fabrication of tailored dosage forms with improved acceptability. For example, additive manufacturing allows the design of tablets with customized shapes, sizes, flavors, and textures, which can enhance patient convenience and willingness to adhere to treatment regimens. Additionally, multiple drugs can be incorporated into a single dosage form (polypill), thereby reducing pill burden and simplifying medication schedules for patients with chronic conditions (38). Improved adherence ultimately leads to better therapeutic outcomes and reduced healthcare costs.

7.3 Complex Drug Release Profiles

Another major advantage of 3D printing is its ability to produce complex drug release profiles that are difficult to achieve using conventional manufacturing methods. By manipulating the internal architecture of printed dosage forms, researchers can design tablets that provide immediate, sustained, delayed, or pulsatile drug release. Such programmable release patterns enable optimized drug delivery and improved therapeutic efficacy (39). Controlled release formulations developed through 3D printing have shown significant potential in the management of chronic diseases that require precise dosing schedules.

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 1480-1498 | ISSN:2251-6727

7.4 Reduced Medication Errors

3D-printed personalized medicines may also help reduce medication errors. Patients suffering from polypharmacy often struggle to manage multiple medications with different dosing schedules. By combining several drugs into a single personalized polypill, additive manufacturing can minimize dosing mistakes and improve medication safety. Furthermore, digital prescription systems integrated with 3D printing platforms can ensure accurate dose calculation and production.

7.5 On-Demand Drug Production

Another promising advantage of 3D printing is the possibility of on-demand drug manufacturing. Pharmaceutical dosage forms can be printed directly in hospitals or pharmacies according to individual prescriptions, eliminating the need for large-scale centralized manufacturing and reducing drug wastage. This decentralized manufacturing approach may significantly enhance healthcare accessibility, particularly in remote or resource-limited regions . Overall, these advantages demonstrate the immense potential of 3D printing to transform pharmaceutical manufacturing into a more patient-centric and flexible system.

8. Challenges and Limitations

Despite its promising advantages, the implementation of 3D printing in pharmaceutical manufacturing faces several technical, regulatory, and economic challenges. Addressing these limitations is essential for the widespread adoption of additive manufacturing technologies in the pharmaceutical industry.

8.1 Regulatory Challenges

One of the major barriers to the commercialization of 3D-printed pharmaceuticals is the lack of comprehensive regulatory frameworks. Current regulatory guidelines were developed primarily for conventional mass manufacturing processes and may not adequately address the complexities associated with additive manufacturing. Regulatory agencies such as the FDA and EMA are still developing policies regarding process validation, quality assurance, and approval pathways for 3D-printed drug products (35). The decentralized nature of on-demand drug production also raises questions regarding accountability, traceability, and compliance with Good Manufacturing Practice (GMP) standards.

8.2 Material Limitations

Another critical challenge in pharmaceutical 3D printing is the limited availability of suitable printable materials. Not all pharmaceutical excipients possess the physical and mechanical properties required for additive manufacturing processes. For instance, certain printing technologies require thermoplastic polymers that can withstand high temperatures during extrusion. This requirement restricts the range of drugs that can be used, particularly thermolabile compounds that degrade during heating (38). Researchers are actively exploring new polymers, hydrogels, and biodegradable materials that are compatible with 3D printing technologies.

8.3 Stability Issues

Drug stability is another important concern in 3D-printed formulations. During the printing process, active pharmaceutical ingredients (APIs) may be exposed to elevated temperatures, ultraviolet radiation, or mechanical stress, which could affect their chemical stability and therapeutic efficacy. In addition, the porous structures commonly produced by 3D printing may influence moisture absorption and drug degradation during storage (35). Therefore, comprehensive stability studies are required to ensure the safety and effectiveness of printed medicines.

8.4 Manufacturing Scalability

Although 3D printing is highly effective for small-scale production and personalized medicines, scaling up the technology for industrial manufacturing remains challenging. Conventional pharmaceutical manufacturing processes are optimized for high-volume production with consistent quality and low cost. In contrast, additive manufacturing is relatively slow and may not be economically viable for mass production of widely used drugs (39). Developing high-speed printing technologies and automated production systems will be essential to overcome this limitation.

8.5 Quality Control and Reproducibility

Ensuring consistent quality and reproducibility is another major challenge in pharmaceutical 3D printing. Variations in printing parameters such as temperature, printing speed, and layer thickness may influence the

Journal of Chemical Health Risks
www.jchr.org
JCHR (2026) 16(2), 1480-1498 | ISSN:2251-6727

final properties of the dosage form. As a result, robust quality control methods are required to ensure uniform drug distribution, dosage accuracy, and structural integrity. Advanced analytical techniques such as near-infrared spectroscopy, Raman spectroscopy, and real-time process monitoring are being explored to maintain product quality during manufacturing. Overall, while additive manufacturing offers numerous advantages for personalized medicine, addressing these technical and regulatory challenges will be crucial for its successful integration into mainstream pharmaceutical production.

9. Future Perspectives and Emerging Technologies

The rapid evolution of additive manufacturing technologies continues to expand the potential applications of 3D printing in pharmaceutical sciences. Several emerging innovations are expected to further enhance the capabilities of 3D-printed drug delivery systems and accelerate their integration into personalized medicine.

9.1 Integration with Artificial Intelligence

Artificial intelligence (AI) is increasingly being integrated with 3D printing technologies to optimize formulation design and manufacturing processes. Machine learning algorithms can analyze large datasets related to formulation composition, printing parameters, and drug release profiles to predict optimal printing conditions. AI-driven platforms may significantly reduce the time required for formulation development and improve the efficiency of personalized drug production. Recent studies have demonstrated the potential of AI models to recommend suitable excipients and predict the mechanical properties of printable pharmaceutical formulations. The integration of AI with digital manufacturing systems could enable automated production of personalized medicines directly from electronic prescriptions, further advancing the concept of precision pharmacotherapy.

9.2 4D Printing in Drug Delivery

An emerging extension of additive manufacturing is 4D printing, where printed structures are designed to change their shape or function over time in response to external stimuli such as temperature, pH, or moisture. In pharmaceutical applications, 4D printing can be used to develop stimuli-responsive drug delivery systems that release drugs only under specific physiological conditions. For example, pH-responsive polymers can enable site-specific drug release in the gastrointestinal tract, while temperature-responsive hydrogels may enable controlled drug delivery in targeted tissues. These smart drug delivery systems may significantly improve therapeutic efficacy and reduce systemic side effects. The development of advanced smart polymers and stimuli-responsive materials will play a crucial role in advancing 4D printing technologies in pharmaceutics.

9.3 Multi-Material Printing

Another promising direction in pharmaceutical additive manufacturing is multi-material printing, which allows multiple drugs and excipients to be deposited simultaneously within a single dosage form. This technology enables the fabrication of complex polypills with different drug release profiles for each active ingredient. Multi-material printing can also facilitate the creation of layered structures that control drug diffusion and dissolution rates. Recent research has demonstrated the feasibility of producing tablets containing multiple drugs with both immediate and sustained release characteristics within the same dosage form. Such advanced formulations may significantly simplify treatment regimens for patients suffering from chronic diseases requiring combination therapy.

9.4 Point-of-Care Manufacturing

One of the most transformative applications of pharmaceutical 3D printing is point-of-care manufacturing, where medications are produced directly at hospitals, clinics, or community pharmacies. This decentralized manufacturing model could allow healthcare providers to prepare patient-specific medicines on demand, based on individual prescriptions. Point-of-care manufacturing may be particularly beneficial in emergency medicine, pediatric care, and treatment of rare diseases where conventional dosage forms are unavailable. Additionally, decentralized manufacturing could reduce supply chain complexities and improve access to medicines in remote regions (36).

9.5 Bioprinting and Organ-on-Chip Technologies

Bioprinting represents another exciting frontier in pharmaceutical 3D printing. This technology involves the printing of living cells, biomaterials, and growth factors to create tissue-like structures that mimic human organs. Bioprinted tissues can serve as organ-on-chip

models for drug testing and disease modeling, providing more accurate predictions of drug efficacy and toxicity than traditional in vitro models. Recent research has demonstrated the potential of 3D-printed tissue models for studying bone diseases and evaluating localized drug delivery systems (40). Such technologies may reduce the need for animal testing and accelerate drug development processes. Overall, the integration of advanced materials, artificial intelligence, and bioprinting technologies is expected to significantly enhance the capabilities of pharmaceutical 3D printing and further advance the field of personalized medicine.

10. Conclusion

Personalized medicine represents a paradigm shift in modern healthcare, focusing on tailoring therapeutic strategies according to the unique physiological, genetic, and clinical characteristics of individual patients. Conventional pharmaceutical manufacturing methods are primarily designed for large-scale production of standardized dosage forms, which often fail to accommodate the diverse needs of patients. In this context, three-dimensional (3D) printing has emerged as a promising technology capable of transforming pharmaceutical manufacturing into a more flexible and patient-centric process. Additive manufacturing enables the fabrication of customized drug delivery systems with precise control over dosage strength, geometry, and drug release characteristics. The ability to produce personalized polypills, pediatric formulations, and complex controlled-release dosage forms demonstrates the immense potential of 3D printing in improving therapeutic outcomes and patient adherence. Furthermore, emerging technologies such as multi-material printing, 4D printing, and artificial intelligence-assisted formulation design are expanding the possibilities of personalized pharmaceutical manufacturing. Despite these promising developments, several challenges must be addressed before 3D printing can be widely adopted in clinical practice. Issues related to regulatory approval, material compatibility, drug stability, manufacturing scalability, and quality control remain significant obstacles for large-scale implementation. Continued collaboration between researchers, pharmaceutical companies, and regulatory agencies will be essential to establish standardized guidelines and ensure the safety and effectiveness of 3D-printed medicines. Overall, the integration of advanced manufacturing technologies with personalized medicine has the potential to revolutionize pharmaceutical therapy. As research and technological advancements continue to evolve, 3D printing is expected to play a critical role in enabling on-demand, patient-specific drug delivery systems, ultimately contributing to the development of more precise and effective healthcare solutions.

Reference:

1. Kapoor DU, Pareek A, Uniyal P, Prajapati BG, Thanawuth K, Sriamornsak P. Innovative applications of 3D printing in personalized medicine and complex drug delivery systems. *iScience*. 2025;28(10):113505. https://doi.org/10.1016/j.isci.2025.113505.
2. Murugan M, Ramasamy SK, Venkatesan G, Lee J, Barathi S, Kandasamy S, Sarangi PK. The comprehensive review on 3D printing-pharmaceutical drug delivery and personalized food and nutrition. *Food Chemistry*. 2024;459:140348. https://doi.org/10.1016/j.foodchem.2024.140348
3. Prakash A, Malviya R, Singh DP. Transformative potential and healthcare applications of 3D printing. *Current Pharmaceutical Design*. 2024;30(42):3311-3321. https://doi.org/10.2174/011381612832476124082806 4443
4. Wang S, Chen X, Han X, Hong X, Li X, Zhang H, Li M, Wang Z, Zheng A. A review of 3D printing technology in pharmaceutics: Technology and applications, now and future. *Pharmaceutics*. 2023;15(2):416. https://doi.org/10.3390/pharmaceutics15020416
5. Telrandhe MP, Sahithyareddy BV, Nagini T, Nithisha CH, Sravani V. Review on 3-D printed drug delivery systems. *Asian Journal of Pharmaceutical Research and Development*. 2025;13(2):157-163.
6. Mortha LP, Mohammad R, Raju VBVSN. Advances in 3D printing technology for personalized drug delivery systems. *Journal of Pharma Insights and Research*. 2025.
7. Krishna S, Vudikala P. Innovations in three-dimensional printing for personalized drug delivery systems. *Journal of Pharma Insights and Research*. 2025.
8. Repka MA, Langley N. *3D printing: Emerging technologies and functionality of polymeric excipients in drug product development*. Springer; 2024.
9. Thakur H, Patel M, Mistry B. Comparative evaluation of fused deposition modeling and stereolithography for 3D printing of personalized oral

drug delivery systems. *International Journal of Applied Pharmaceutics*. 2025;17(5):74-84.
10. Hu Y, Luo Z, Bao Y. Trends in photopolymerization 3D printing for advanced drug delivery applications. *Biomacromolecules*. 2025;26:85-117.
11. Olowe M, Parupelli SK, Desai S. A review of 3D-printing of microneedles. *Pharmaceutics*. 2022;14(12):2693.
12. Madhusoodanan G, Roy AA, Kalkundri T, Preman NK, Rana K, Datta D, Dhas N, Mutalik S. Evolving transdermal therapeutics: A review on self-dissolving polymeric microneedles via 3D printing. *RSC Advances*. 2025;15(40):33312-33335.
13. Muehlenfeld C, Duffy P, Yang F, Zermeño Pérez D, El-Saleh F, Durig T. Excipients in pharmaceutical additive manufacturing: A comprehensive exploration of polymeric material selection for enhanced 3D printing. *Pharmaceutics*. 2024;16(3):317.
14. Murugan M, Manivannan R, Venkatesan J. Comprehensive review on 3D printing in pharmaceutical drug delivery. *Food Chemistry Advances*. 2024;4:100585.
15. Daly R, Harrington T, Martin G. 3D printing in pharmaceutical manufacturing. *International Journal of Pharmaceutics*. 2022.
16. Zidan AS, Aldawsari HM, Alalaiwe A, Alsulays BB. Hot-melt extrusion and fused deposition modeling (FDM) 3D printing for drug delivery applications. *International Journal of Pharmaceutics*. 2023;635:122728.
17. Kumar, V., Kaur, H., Kumari, A., Hooda, G., Garg, V., & Dureja, H. (2023). Drug delivery and testing via 3D printing. *Bioprinting, 36*, e00298. https://doi.org/10.1016/j.bprint.2023.e00298.
18. Scoutaris N, Ross S, Douroumis D. Inkjet printing as a pharmaceutical manufacturing technology. *Journal of Controlled Release*. 2021;330:58-70.
19. Norman J, Madurawe RD, Moore CM, Khan MA, Khairuzzaman A. A new chapter in pharmaceutical manufacturing: 3D-printed drug products. *Advanced Drug Delivery Reviews*. 2023;196:114782.
20. Madžarević M, Medarević Đ, Ivković B, Ibrić S. Selective laser sintering for pharmaceutical applications. *European Journal of Pharmaceutics and Biopharmaceutics*. 2023;185:183-197.
21. Vaut L, Juszczyk J, Szlęk J, Jachowicz R. Photopolymerization-based 3D printing for drug delivery. *Pharmaceutics*. 2022;14(5):1004.
22. Chen J, Zhang Y, Li X, Wang H, Liu Y. Semi-solid extrusion printing for multilayer pharmaceutical tablets. *RSC Pharmaceutics*. 2024;1(2):184-198.
23. Amekyeh H, Tarlochan F, Billa N. Practicality of 3D-printed personalized medicines in therapeutics. *Frontiers in Pharmacology*. 2021.
24. Mishra J, Pillai M, Jain S. Additive manufacturing in precise drug delivery for personalized medicine. *South Eastern European Journal of Public Health*. 2025.
25. Suthar S, Patel U, Shah S. Precision packaging and personalized medicine using 3D printing technologies. *International Journal of Pharmaceutical Investigation*. 2023;13(2):220-228.
26. Keerikkadu M, Trenfield SJ, Goyanes A, Basit AW. 3D-printed polypills for personalized medicine and precision oral drug delivery. *International Journal of Pharmaceutics X*. 2025;8:100220.
27. Yasin, H., Al-Tabakha, M. M. A., & Chan, S. Y. (2024). Fabrication of polypill pharmaceutical dosage forms using fused deposition modeling 3D printing. *Pharmaceutics, 16*, 1285.
28. Abdelrahman A, Trenfield SJ, Goyanes A, Basit AW. Development of dose-adjustable pediatric and geriatric formulations using 3D printing. *International Journal of Pharmaceutics*. 2024;653:123783.
29. Sharma N, Goyanes A, Madla CM, Basit AW. 3D printing technology in personalized pharmaceutical manufacturing. *International Journal of Pharmaceutical Investigation*. 2021;11(3):241-248.
30. Chua HJB, Rosser AA, Fellows CM. 3D printing with light for personalized drug delivery systems and medical devices. *ACS Applied Polymer Materials*. 2025.
31. Gao G, Ahn M, Cho WW, Kim BS, Cho DW. 3D printing of pharmaceutical applications: Drug screening and drug delivery. *Pharmaceutics*. 2021;13:1373.
32. Kalyan B, Kumar L. 3D printing: Applications in tissue engineering, medical devices, and drug delivery. *AAPS PharmSciTech*. 2022;23:92.
33. Goh WJ, Tan SX, Pastorin G, Ho PCL, Hu J, Lim SH. 3D printing of four-in-one oral polypill with multiple release profiles. *International Journal of Pharmaceutics*. 2021;598:120360.
34. Alayoubi A, Zidan A, Asfari S, Ashraf M, Sau L, Kopcha M. Mechanistic understanding of personalized 3D-printed cardiovascular polypills. *International Journal of Pharmaceutics*. 2022;617:121599.
35. Anaya BJ, Cerda JR, D'Atri RM, Goyanes A, Trenfield SJ, Basit AW. Engineering of 3D-printed personalized polypills for metabolic syndrome treatment. *International Journal of Pharmaceutics*. 2023;642:123194.
36. Windolf H, Chamberlain R, Breitkreutz J, Quodbach J. 3D-printed mini-floating polypill for Parkinson's disease therapy. *Pharmaceutics*. 2022;14:931.
37. Awad A, Fina F, Trenfield SJ, Patel P, Goyanes A, Basit AW. 3D printed medicines: A new branch of

digital healthcare. *International Journal of Pharmaceutics*. 2022;610:121248.
38. Trenfield SJ, Awad A, Goyanes A, Basit AW. 3D printing pharmaceuticals: Drug development to frontline care. *Trends in Pharmacological Sciences*. 2022;43(6):440-451.
39. Mustafa MA, Malik A, Javed E, Khan MA, Ahmad N. A comparative review of 3D printing technologies and their applications in medicine fabrication. *International Journal of Pharmaceutical Investigation*. 2025;15(1):12-24.
40. Timofticiuc IA, Grigore AG, Tomescu ET, Vlaicu TM, Dragosloveanu S, Scheau AE, Caruntu A, Dragosloveanu CDM, Badarau IA, Didilescu AC, Caruntu C, Scheau C. Advances in 3D-printed drug delivery and screening platforms for bone disease therapy. *Pharmaceutics.* 2025;17(11):1372. doi:10.3390/pharmaceutics17111372.