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(Research Article)

3D printing in pharmaceutical technology with pharmaceutical applications, challenges and future aspects

Yeddula Mounika [1,*], P. Sailaja [2] and Y. Prapurna Chandra [2]

[1] *Department of Pharmacy, Ratnam Institute of Pharmacy, Pidathapolur (V), Muthukur (M), SPSR Nellore(Dt). 524346. A.P India.*

[2] *Department of Pharmacology, Ratnam Institute of Pharmacy, Pidathapolur (V), Muthukur(M), SPSR Nellore(Dt). 524346. A.P India.*

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Abstract

Three-dimensional (3D) printing, also known as additive manufacturing (AM), has emerged as a transformative technology in the pharmaceutical field, enabling the precise fabrication of dosage forms through a layer-by-layer approach. Over the past three decades, it has evolved from a prototyping tool into a promising platform for personalized medicine and advanced drug delivery systems.

3D printing allows for the customization of drug dosage, geometry, and release profiles, offering solutions for patient-specific treatment, especially in paediatrics, geriatrics, and complex diseases. Various printing techniques—including Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), Semi-Solid Extrusion (SSE), and Inkjet Printing—enable the fabrication of oral tablets, implants, microneedles, and biomedical devices with controlled release characteristics. Despite these advantages, challenges persist related to the selection of suitable pharmaceutical-grade excipients, mechanical strength, regulatory approval, and Good Manufacturing Practice (GMP) compliance.Future perspectives include integrating 3D printing with nanotechnology, artificial intelligence (AI), and bioprinting for on-demand drug manufacturing, tissue engineering, and regenerative medicine. Overall, 3D printing holds immense potential to revolutionize the pharmaceutical industry by facilitating personalized, cost-effective, and sustainable drug development tailored to individual patient needs.

Keywords:3D Printing; Additive Manufacturing; Personalized Medicine; Fused Deposition Modeling (FDM) ; Selective Laser Sintering (SLS); Bio Printing

1. Introduction

3D printing is a rapidly developing digital technology that has been around for nearly three decades. It is now poised to transform pharmaceutical sciences as well as teaching laboratories. A noticeable rise in related research publications was observed in recent years, with 2019 and 2020 showing significant growth, contributing 22.81% and 23.21% of total records, respectively[1]. Among the published studies, the United States emerged as the leading contributor, accounting for 203 papers (20.13% of the total). Moreover, U.S. researchers received the highest citation counts, highlighting their strong influence in this field. 3D printing technology has attracted significant attention from both the medical device and pharmaceutical industries because of its wide range of applications in healthcare. Although the technology has been in existence for several years, it has gained remarkable public interest in recent times, largely due to the approval of 3D-printed tablets and various medical devices[2].

*Corresponding author: YeddulaMounika.

The concept of 3D printing in the pharmaceutical sector gained significant recognition in 2015 with the approval of Spritam the first 3D-printed medication developed by Aprecia Pharmaceuticals. Since then, the adoption of this technology has steadily expanded across various industries, with the pharmaceutical field emerging as one of its most promising areas of application[3].

Three-dimensional printing (3DP) is an advanced technology that enables the creation of objects with diverse geometries through a layer-by-layer approach. Compared to traditional manufacturing methods, 3DP offers several benefits, such as the customization of medicines with patient-specific doses, the production of complex and innovative dosage forms, the possibility of on-demand manufacturing, and overall cost efficiency[4].These techniques involve the application of polymers in 3D printing and the integration of this technology within the pharmaceutical industry. Recent strategies highlight its role in developing both conventional drug formulations and innovative drug delivery systems. Furthermore, a comparison is made between pharmaceutical 3D printing and 3D bioprinting to understand their distinct applications and advancements[5].

In pharmaceutical sciences, the term "drug delivery" is fundamental and widely used. It refers to the process of transporting a therapeutic substance through the body in a controlled manner to achieve the desired therapeutic effect. To enhance patient compliance, drug delivery approaches have advanced from conventional oral dosage forms to more sophisticated targeted release systems. Over the past decade, considerable attention has been directed toward the development of innovative drug delivery technologies and patient-centered pharmaceutical solutions[6].

The pharmaceutical industry is progressing rapidly, driven by innovations that have enabled the discovery of novel active pharmaceutical ingredients (APIs), encompassing both small molecules and biologics, along with advanced delivery systems and technologies. However, conventional manufacturing methods continue to encounter several limitations in delivering new chemical entities, many of which suffer from issues like low solubility and limited permeability, ultimately resulting in poor bioavailability[7].

Since the early 1990s, 3D printing has been recognized as a promising platform for personalized medicine. Significant progress has been made in this field, particularly with 3D-printed medical devices, many of which have been reviewed and approved by the FDA's Center for Devices and Radiological Health (CDRH)[8].In pharmaceutical applications, 3D printing offers the advantage of creating intricate external designs and complex internal geometries. These features can be utilized to regulate various aspects of drug delivery, including the release rate, the specific site of release within the gastrointestinal tract, the onset time, and the overall release mechanism[9].

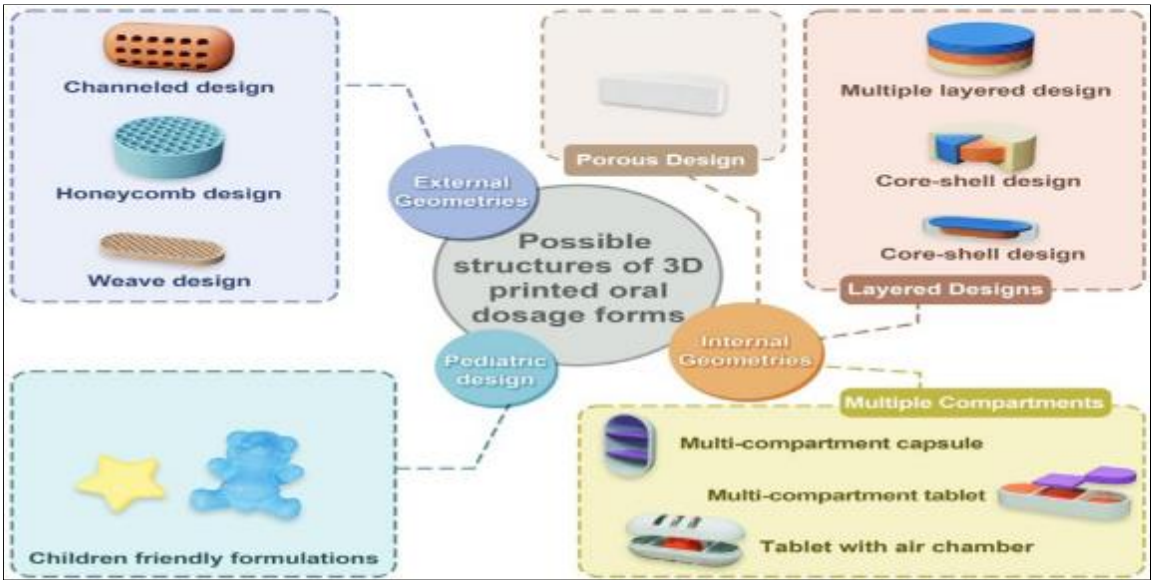

Figure 1 Possible Structures of 3D Printed Oral Dosage Forms.

The concept of health and wellness varies from person to person. Tailoring therapy or medical care to the individual can significantly enhance patient well-being. As the term implies, personalization is essential in all areas, including pharmaceuticals, where it is crucial to deliver medications in a manner that meets each patient's specific needs[10].Conventional batch production often requires extensive optimization of multiple excipients, making the process time-consuming, resource-heavy, and labour-intensive.

Additive manufacturing (AM) helps address these limitations and offers numerous advantages over traditional drug delivery methods, such as the ability to create customized pharmaceutical products with flexible control over dosage, structure, and size to meet individual patient needs. Terms such as multilayered fabrication, computer-aided manufacturing, rapid prototyping, and solid free-form (SFF) technology are commonly used to describe 3D printing[11].

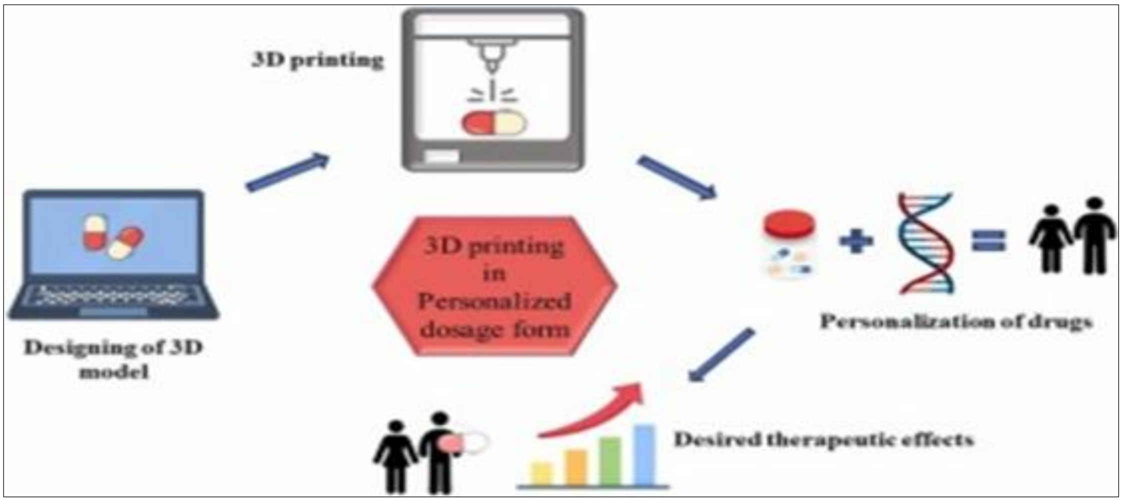

Figure 2 Graphical Representation of 3D Printing In Personalized Dosage Form

The fundamental steps in manufacturing involve transforming raw materials into finished objects using different technologies and methods. The first method, subtractive emanufacturing, shapes a block of raw material into the desired form through a series of removal processes. The second, forming, alters the shape of the material by applying external force or pressure. Third, casting involves melting the material into a liquid state and pouring it into molds to achieve the required shape. Finally, layered manufacturing builds objects incrementally by depositing material layer by layer. Additive manufacturing (AM), also called 3D printing (3DP**)**, is characterized by being three-dimensional, additive, and constructed layer by layer[12].

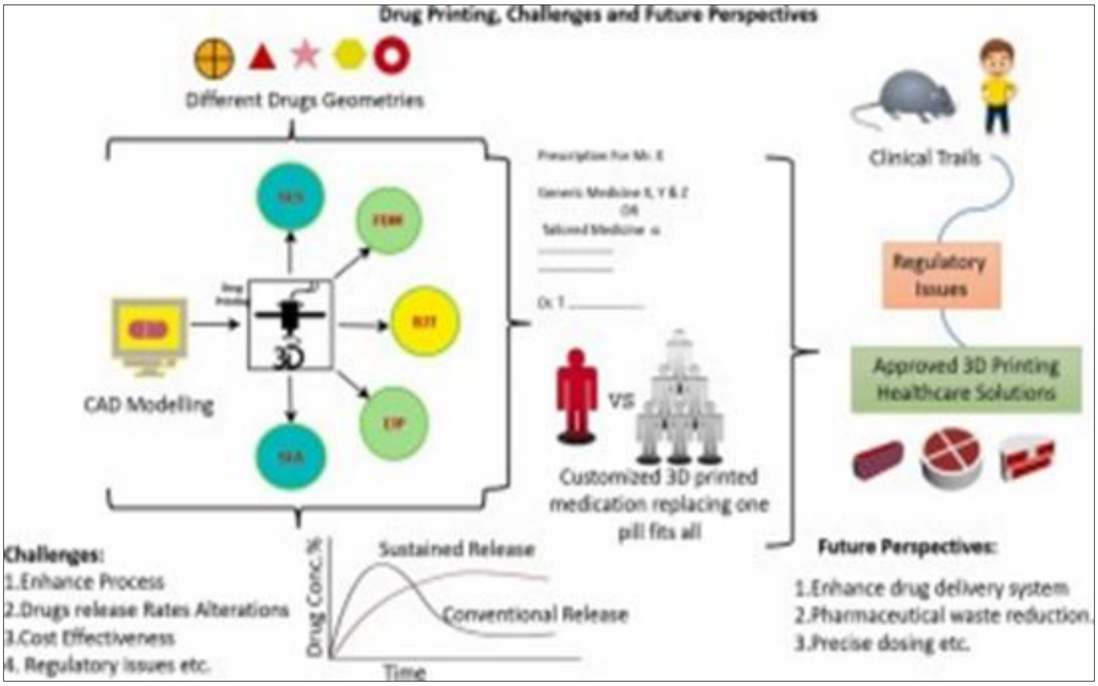

Figure 3 Drug Printing Challenges and future Perspectives

3D printing, a type of additive manufacturing (AM), builds objects by depositing material layer by layer according to a predefined design. This approach allows the creation of complex, customized geometries that enable unique drug release profiles, making it highly suitable for personalized therapy. This study explores various 3D printing techniques, including Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Semi-Solid Extrusion (SSE), Stereolithography (SLA), Thermal Inkjet (TIJ) printing, and Binder Jetting, along with their applications in medicine[13].

2. History

The concept of 3D printing as a platform for personalized medicine was first explored in the 1990s. Since then, notable progress has been made, particularly in the development of 3D-printed medical devices, many of which have been reviewed and approved by the FDA's, Center for Devices and Radiological Health (CDRH). The general concept and procedure to be used in 3D-printing was first described by Murray Leinster in1945 short story "Things Pass By": "But this constructor is both efficient and flexible[14].

2.1. Types of 3D printing

Table 1 Types of 3D Printing

Types of 3D printing	Preprocessing	Print Processing	Post Processing
BinderJetting 3D Printing (BJ 3DP)	Prefabricated powder bed or ink containing drug	Room temperature / heating	Removal and recovery of powders, drying of preparations
Material extrusion FDM	Prefabricated filamentous containing drug	Heating	Removal of support material /none
Semi Solid extrusion (SSE 3DP)	Prefabricated semi sold materials containing drug	Room temperature /heating	Drying/ none
Medical 3D Printing (MED 3DP	None	25–250 °C	None
Stereolithography (SLA 3DP)	Prefabricated polymer monomers containing drugs	Photopolymerization	Separation from unreacted polymer monomers and re-curing

3. Advantages and disadvantages

3.1. Advantages

- Wide range of available excipients, high drug loading capacity no support material required and high printing accuracy can be used to prepare.
- Suitable for immediate release preparations, simple and inexpensive equipment, high precision.
- Ability to create a variety of 3D structured preparations, Use of disposable syringes for easy change of material.
- Simple and inexpensive equipment, can be printed at room temperature.

3.2. Disadvantages

- Lack of flexibility in product design.
- High requirements for packaging and transportation.
- Required to prefabricate drug-containing filaments with suitable mechanical properties.
- The process of material mixing and melting to extrusion needs to be monitored in real time[15].

3.3. Objectives

- To discuss the fundamental principles and techniques of 3D printing used in pharmaceuticals.

- To highlight the major pharmaceutical applications of 3D printing, including drug delivery systems and personalized medicine.
- To identify and evaluate the existing challenges related to materials, mechanical properties, and regulatory aspects.
- To explore future opportunities and innovations integrating 3D printing with nanotechnology, AI, and bioprinting.

4. Fundamental principles and techniques of 3d printing used in pharmaceuticals

The fundamental principle of 3D printing (3DP) in pharmaceuticals is **additive manufacturing**: creating a three-dimensional object, such as a medicine tablet or an implant, by depositing successive layers of material based on a digital computer-aided design (CAD) file. This process allows for unprecedented control over the final product's physical properties, including geometry, size, and internal structure, which can be tailored for **personalized medicine** and customized drug release profiles[16].

4.1. Fundamental Principles

- **Layer-by-Layer Deposition:** The core principle of all 3DP technologies is building an object one layer at a time, guided by digital instructions. This contrasts with traditional manufacturing (which often involves molding or compression).
- **Customization via Digital Design:** A CAD model is created, then "sliced" into layers by software to generate machine-specific code (G-code). This digital control allows for the production of complex geometries, variable drug dosages, and multi-drug combinations (polypills) within a single dosage form, something difficult to achieve with conventional methods.
- **Material Properties as Key:** The interaction between the printing material (containing the active pharmaceutical ingredient, or API, and excipients) and the printing process (e.g., heat, light, solvent) is crucial for the final product's quality, stability, and drug release characteristics.
- **On-Demand Production:** The technology enables rapid, small-batch manufacturing at the point of care (e.g., in a hospital or pharmacy), reducing development time, material waste, and the need for complex supply chains and storage for some medications[17].

4.2. Techniques 3D Printing

Several 3DP techniques have been explored in pharmaceuticals, each with specific mechanisms and applications:

Table 2 Different techniques of 3D Printing

Techniques	Principle	Key Pharmaceutical Application
Fused Deposition Modeling (FDM)	A drug-loaded thermoplastic filament is heated and extruded through a nozzle onto a build platform, solidifying layer by layer.	Sustained/modified release solid dosage forms (tablets, implants, polypills).
Binder Jetting (BJ)	A liquid binder solution is selectively "jetted" onto a powder bed, binding particles together layer by layer. Unbound powder acts as support.	Highly porous, rapidly disintegrating tablets.
Selective Laser Sintering (SLS)	A high-power laser beam sinters (fuses) powder particles in a powder bed. The process is solvent-free.	Orodispersible or controlled-release printletsoften with high resolution.
Stereolithography (SLA)	A UV laser selectively cures a liquid, photosensitive resin (photopolymer) layer by layer into a solid object.	High-resolution medical devices, microfluidic chips, and implants (limited oral use due to potential resin toxicity concerns).
Semi-Solid Extrusion (SSE)	A gel or paste formulation is extruded from a syringe-like system at low temperatures.	Thermolabile drug formulations, chewable pediatric forms, wound dressings[18].

5. Pharmaceutical applications of 3D printing

- Applications in the Pharmaceutical Industry

BJ-3DP is the primary 3D printing technology used for drug production. The printing principle is shown . First, the roller spreads a thin powder layer on the platform, the droplets are sprayed through the removable printhead, and they selectively bind the powder together; then the platform is lowered, the roller spreads a new powder layer, the print head continues to add droplets, using the principle of layer-by-layer printing, and so on until complete; finally, the preparations are removed, the adhering powder is removed, and postprocessing is carried out [19].

- Bio-Medical Applications

The impact of additive manufacturing on biomedical field has increased rapidly since the 3D printing was developed in the early 80′. It is due to the fact that the technique enables formation of individually developed materials of customized architecture and functionalities. It evolved into powerful tool for biomedical engineering providing formation of manufacturing implants that correspond to patient-specific anatomy, phantoms for education and surgical planning and disease models.

  - Wound Dressing
  - Implants and Prostheses
  - Models for Surgical Planning and Training, Phantoms[20].

The release of drug from dosage forms plays a vital role for their subsequent absorption and therapeutic effect. For most oral dosage forms, immediate release (IR) is needed for drug absorption.

  - Polypills
  - 2.Gastrofloating
  - Paediatric Preparation[21].
- Application of-3D-printing in the-production of pharmaceutical dosage-forms:
  - 1.Oral dosage form
  - 2.Gastro-retentive drug delivery system
  - 3.Colon-targeted drug delivery system
  - 4.Intrauterinedrugdelivery system
  - 5.Transdermal drug delivery system[22].
- Application of 3DP technology to pharmaceutical dosage form:

Various 3D printing methods have been developed by varying its energy source, material source, and other mechanical characters. Among them, the common 3DP technologies applicable for pharmaceutical areas are printing- based inkjet (IJ) systems, nozzle-based deposition systems, and laser-based writing systems which further divided into several subtypes, depending on the materials and energy sources.

3DP technologies such as IJ, FDM, and SLS, are currently available for manufacturing adequate pharmaceutical dosage forms.

- TABLETS

Oral dosage formulations are the most preferred form of pharmaceutical products. Tablets and capsules are typical examples of widely used solid oral dosage forms. Particularly, tablets have been extensively examined for the feasibility of 3DP technologies in pharmaceutical manufacturing.

  - Single API tablets

Initially, 3DP technology was applied to fabricate simple immediate release (IR) tablets comprising a single API. In many studies, the FDM method was adopted for producing IR tablets, probably due to its simple fabricating procedures. Selective examples of single API IR tablets obtained by using the FDM method.

  - Multiple API tablets

To combine complex medication regimes into one, multiple API can be loaded in a single tablet, called polypill. In recent studies, 3DP technology has been used to manufacture polypills showing controlled release profiles produced the polypill of captopril, nifedipine, and glipizide by using 3Dextrusion-based printing, to treat patients with diabetes, suffering from hypertension.

- Implants:

An implant is a dosage form containing active drugs within a sustained release delivery matrix, providing the benefits to patients who need long -term treatment of drugs. While the traditional approach for implant development was mainly focused on extended and prolonged drug release, recent 3DP-based implants are designed to have complex micro-and macro-structures in a single device, for multi APIs loading and achieving more sophisticated drug release characteristics.

- Microneedles:

Microneedles are a class of transdermal drug delivery systems, which has arrays of micron- sized needless on the surface of a matrix to enhance the skin penetration of bio-than traditional patches, due to its microstructure. Recent advances in high-resolution 3DP techniques fabricating small and tiny structures, accelerate the application of 3DP in manufacturing the microneedles[23].

- Powder Bed Fusion (PBF):

PBF technologies, including selective laser sintering (SLS) and binder jetting, have gained attention in pharmaceutical 3D printing due to their ability to work with a wide range of materials, including commonly used pharmaceutical excipients used SLS to produce orally disintegrating printlets (ODPs) containing paracetamol. The resulting tablets showed rapid disintegration times and dissolution rates, highlighting the potential of SL in producing fast-acting oral medications.

- Personalized Medicine and Customized Dosing:

One of the mostpromising applications of3Dprintingin pharmaceuticals istheabilitytoproduce personalizeddosageforms tailored to individual patient needs. This approach aligns with the growing trend towards precision medicine, where treatments are optimized based on a patient's genetic profile, lifestyle,and specific health conditions. Furthermore, 3D printing enables the creation of personalized polypills, combining multiple medications into a single dosage form.3D-printedpolypill containing three antihypertensive drugs (irbesartan, hydrochlorothiazide, and amlodipine) with distinct release profiles[24].

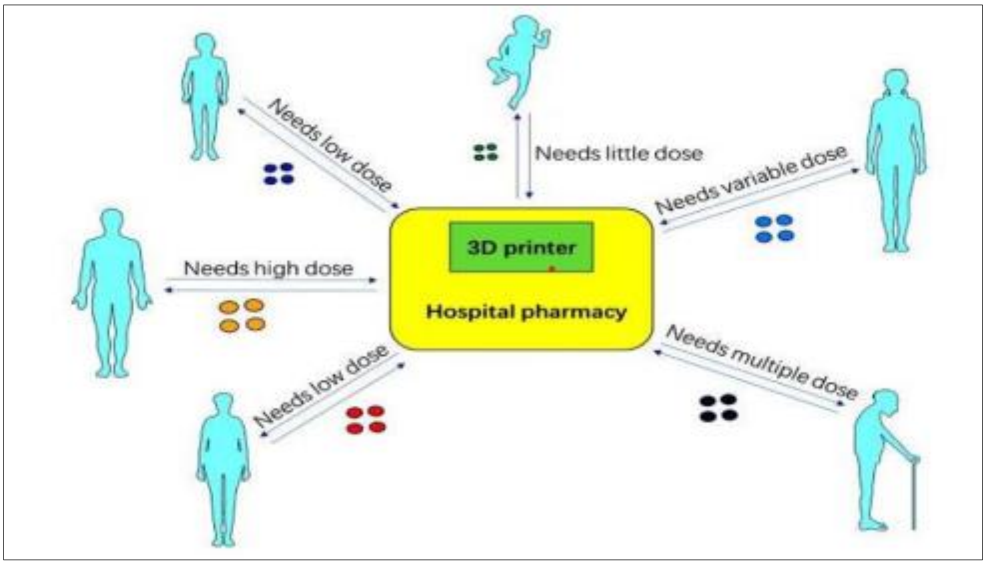

Figure 4 3D Printing In Personalized Medicine

6. Global challenges in 3D printing:

Alongside with the advantages and opportunities provided, 3DP has to overcome major challenges . These challenges can be classified into three categories: 1. Technical challenges; 2. Regulatory challenges; 3. Good manufacturing practice (GMP) challenges.

- Technical challenges:

Depending on the applied printing technology, printed objects might have insufficient mechanical properties and possess a high friability, which makes the further processing of these dosage forms rather difficult.

Especially during packaging of printed tablets defects might occur, which might lead to rejection of complete batches. For some of the 3DP technologies like BJ or SLA, a lot of unprinted material accumulates after the printing process. On the one hand, technical solution must be found to avoid excessive amount of unprinted material and on the other hand clarification is needed whether unprocessed material might be reused for further printing.During conventional production of tablets, in-process control (IPC) is carried out to monitor the production intensively.

- Regulatory Challenges:

From a regulatory perspective, 3D-printed dosage forms have to meet the same requirements as conventionally manufactured dosage forms. However, at this point a big gap is existing in the regulatory framework.

While for established processes guidelines are well implemented and standardized, the process of 3DP is lacking any guidelines from regulatory authorities. Health authorities around the world recognized the lack of guidance and initiated the process of developing standards and defining practical guidelines. The FDA designated two internal laboratories, the Laboratory for Solid Mechanics as well as the Functional Performance and Device Use Laboratory within the FDA´s Office of Science and Engineering Laboratories (OSEL),to explore the future potential of 3DP in pharmaceutics.

- GMP challenges:

Moreover, qualification standards for 3D-printer manufacturers must be defined to meet GMP requirements. Especially, the topic of cleaning validation should be addressed to avoid cross contamination. The mentioned regulatory and GMP challenges must be tackled together by health authorities and pharmaceutical manufacturers to establish 3DP as manufacturing process for pharmaceutical dosage forms.

6.1. Other challenges

- Excipients:

In the preparation process, all types of 3D printing technologies have certain requirements on the properties of excipients due to their unique printing principles. For FDM technology, the heating and melting steps are involved in the printing process, so it is important to select a suitable drug carrier.

The carrier excipient that has been reported most frequently is PVA, but its melting temperature is relatively high, which is not suitable for thermally unstable drugs, such as 4-ASA or levetiracetam. In recent years, an increasing number of researchers have attempted to combine HME technology with 3D printing technology or low-temperature 3D printing technology, using PVP, HPMC, Kollidon talc and triethyl citrate as excipients to prepare low-temperature printed filaments to solve the problem of drug degradation and improve drug loading.

- Printing software and instrument:

The 3D printing process primarily includes four main steps: modelling, slicing, printing, and postprocessing. In the printing process, the computer is first used to establish a printing model and slice it to set the printing path of each layer, and then the formulation with a complex structure is fabricated according to the prefabricated model. Therefore, as the complexity of the required structure increases, the modelingand slicing software need to be constantly updated to meet higher printing standards.

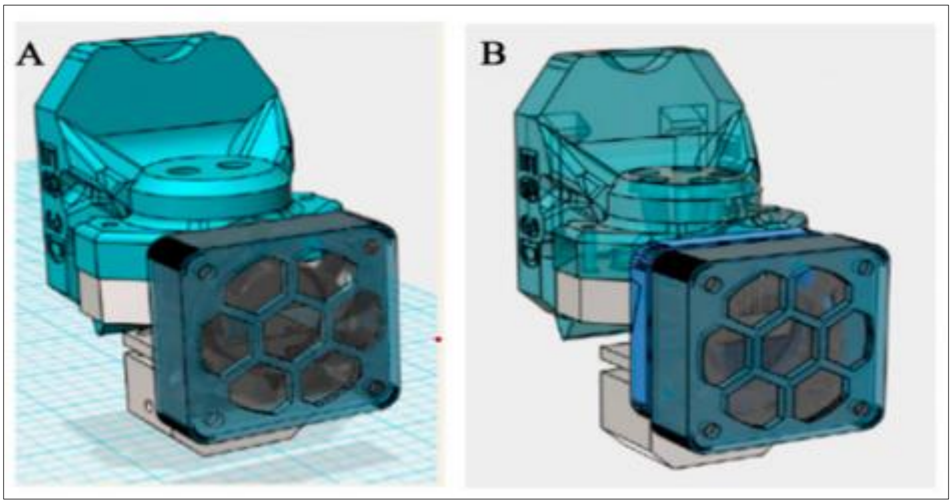

Figure 5 (A) The two-in-one printed nozzle (B) five-in-one printed nozzle

- Mechanical properties:

The mechanical properties of the dosage forms are considered a quality control parameter to ensure that the prepared tablets are reproducible and suitable for postprocessing. In the 3D printing process, because of its unique printing principle, different polymers or powders are stacked on top of each other, resulting in a rough surface and relatively insufficient mechanical strength of the product. Factors such as the viscosity of the adhesive, surface tension, and fineness of the nozzle affect the performance of the product.

6.2. Regulatory landscape

The 3D printing method and its numerous underlying mechanisms for revolutionizing dosage form application and development have attracted the focus of regulatory authorities; at the same time, it has raised many questions regarding the supervision and quality evaluation of 3D-printed products before and after marketing.

7. Future aspects of 3d printing

- Customized medicine: The use of 3D printing makes it possible to create personalized medicine dosages for each patient. Treating complex disorders such as cancer, cardiovascular diseases, and paediatric care requires personalization, which involves delivering tailored doses depending on age, genetics, and medical history. 3D-printing pharmaceuticals are probably going to be a main choice for customized treatments in the future.
- Advancement in Biocompatible Substances: A broader spectrum of biocompatible materials, including biodegradable polymers and smart materials for implants and medication delivery systems, will be developed in the future of 3D printing in medicine. Healthcare applications will be further enhanced using these advanced substances to create scaffolds for tissue engineering and regenerative medicine.
- On-Demand Pharmaceutical Manufacturing: The capacity to print medications on demand eliminates the need for large supply chains by enabling local, decentralized manufacture at pharmacies or hospitals. When supply systems are disrupted during health emergencies like pandemics, such as in rural or isolated areas, this can be quite helpful.
- Integration with Nanotechnology: The combination of nanotechnology with 3D printing to create targeted medication delivery systems has the potential to completely transform medical therapy. These will provide more accuracy and control over the delivery of drugs, particularly in cancer treatments where it is essential to target cells .
- Sustainable and Economical Manufacturing: Compared to traditional manufacturing, 3D printing uses less energy and produces less waste materials, which means that technology will provide more environmentally friendly ways to produce drugs. The method will be a desirable alternative for the development of rare and orphan drugs due to its cost-effectiveness, particularly in small-batch production.
- Innovations in Regulatory and Quality Control: It is predicted that authorities such as the FDA will modify and enhance their protocols for approving 3D printed pharmaceuticals as technology advances. This will speed up the transfer from research to clinical applications by guaranteeing that printed pharmaceuticals fulfil safety and efficacy standards26.

7.1. Key Future Aspects and Innovations

- Personalized Medicine (Mass Customization): The primary future application is the shift from a "one-size-fits-all" approach to medications tailored to individual patient needs. This includes precise dosing (especially for pediatrics and geriatrics), specific shapes, sizes, colors, and flavors to improve patient adherence and outcomes.
- On-Demand, Decentralized Production: 3D printers are expected to be present in hospitals and local pharmacies, allowing for immediate production of customized medications, particularly for rare or orphan drugs where mass production is not cost-effective. This can also help in emergency or resource-constrained settings.
- Complex Drug Release Profiles: The technology enables the creation of intricate internal structures and multi-layered tablets (polypills) that combine multiple drugs with different, programmed release kinetics (e.g., immediate, sustained, or pulsatile release) within a single pill.
- Advanced Drug Delivery Systems:
    - Implants and Devices: Development of customized, patient-specific implantable devices, such as drug-eluting contact lenses, ocular inserts, wound dressings, and biodegradable airway splints for conditions like trachea bronchomalacia.
    - Nanomedicine Integration: Combining 3D printing with nanotechnology to fabricate nanomedicine-based solid dosage forms to improve drug solubility and bioavailability.
    - Microneedles: Production of dissolving microneedle patches for painless and effective transdermal drug delivery, including vaccines.
- Tissue Engineering and Organs-on-a-Chip: Bioprinting using "bioinks" containing living cells and biomaterials to create 3D tissue models (e.g., liver, cardiac, skin) for drug screening, toxicity testing, and potentially, in the distant future, functional organs for transplant[27].
- Integration with AI and 4D Printing: Artificial intelligence (AI) and machine learning (ML) will be used to optimize the design and printing process for dosage forms, ensuring quality and efficiency. Furthermore, 4D printing (3D printed objects from "smart" materials that change shape over time with an external stimulus like temperature or pH) offers potential for targeted drug delivery systems and self-expanding medical devices like stents.
- Regulatory Framework Evolution: Regulatory agencies, such as the FDA and MHRA, are actively working with industry and academia to develop appropriate guidelines for the quality control and approval of 3D-printed pharmaceuticals, which is a key step for wider commercialization and clinical adoption [28].

7.2. Visual Aspects of Future 3DP in Pharmaceuticals

- Intricate, novel-shaped pills: Tablets in shapes like pyramids, stars, or hollow cylinders designed to control drug release kinetics, rather than just standard round pills.
- Multi-layered "polypills": Tablets clearly showing distinct layers of different colors, each potentially containing a different drug or having a different release profile.
- Specialized medical devices: Images of highly detailed, customized implants or patches, such as a nose-shaped mask for acne treatment or a T-shaped intrauterine device, perfectly molded to a patient's anatomy[29].
- Mini-printers in pharmacies: Compact, automated 3D printers shown on a pharmacist's counter, producing a patient's customized medication on the spot.
- Bioprinted structures: Microscopic images or diagrams of complex, cell-laden scaffolds and 3D tissue models used in research labs for drug testing.

8. Conclusion

3D printing technology represents a groundbreaking advancement in pharmaceutical research and manufacturing. It offers unprecedented flexibility in designing patient-specific dosage forms, combining multiple drugs in a single tablet, and creating complex release profiles. The ability to print personalized medications on demand signifies a paradigm shift toward precision and individualized therapy.3D printing holds immense potential to revolutionize drug development, ensuring safer, more effective, and patient-oriented therapeutic solutions for the future.

Looking ahead, the integration of 3D printing with nanotechnology, artificial intelligence (AI), and bioprinting will likely accelerate advancements in on-demand drug manufacturing, tissue engineering, and regenerative medicine. As research continues and regulatory frameworks evolve, 3D printing is expected to transition from laboratory innovation to mainstream pharmaceutical production, transforming the way medicines are designed, produced and delivered.3D printing represents a paradigm shift toward personalized, efficient and sustainable pharmaceutical manufacturing, holding the promise to redefine modern healthcare.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest associated with this work.

Contribution of Authors

The authors declare that this review work was done by the authors named in this article and all liabilities pertaining to claims relating to the content of this article will be borne by them.

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