RESEARCH PAPER

3D Printing in Drug Delivery: Personalized Medicine and Controlled Release Systems

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ABSTRACT

Three-dimensional (3D) printing has emerged as an innovative and transformative technology in drug delivery, enabling the fabrication of personalized dosage forms with precise control over drug release characteristics. Unlike conventional manufacturing methods, 3D printing allows customization of dose, geometry, and internal structure, facilitating patient-specific therapy. Various printing techniques, including fused deposition modeling, stereolithography, selective laser sintering, and inkjet printing, have been explored for the development of advanced drug delivery systems. The use of diverse materials such as polymers, hydrogels, and composites enables the design of formulations with immediate, sustained, delayed, or pulsatile drug release profiles. Additionally, 3D printing supports the development of polypills, which combine multiple drugs into a single dosage form, improving patient compliance and therapeutic outcomes. The integration of this technology with personalized medicine and digital health tools further enhances its potential for on-demand drug manufacturing. Despite its advantages, challenges such as limited printable materials, drug stability during processing, regulatory concerns, and scalability issues remain. Overall, 3D printing holds significant promise in advancing drug delivery by enabling precise, customizable, and patient-centric therapeutic solutions.

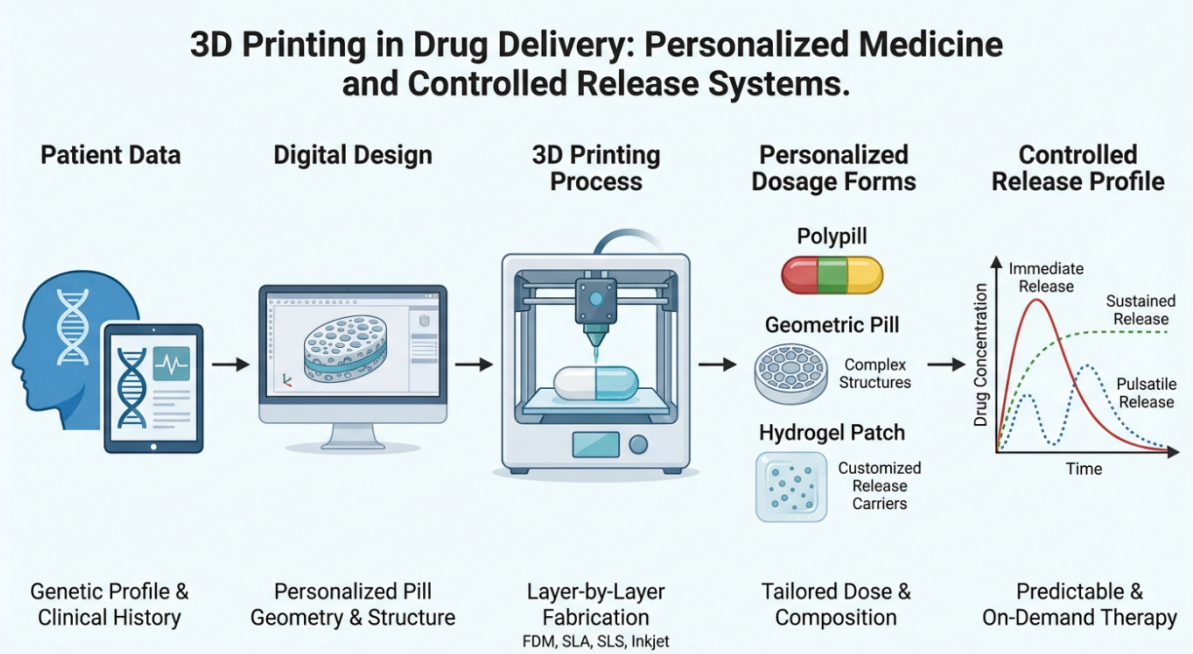
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Graphical Abstract:



1. Introduction

3D printing is another name for additive manufacturing, 3D fabrication, and has dramatically changed the way pharmaceutical companies make their drugs and the way healthcare companies deliver their drugs to patients. Recently, 3D Printing has gained a lot of interest in the healthcare and pharmaceutical sciences as it has now allowed for the possibility of numerous new types of complex dosage forms (medications) to be created with precise controls over how they will be released, their geometric shapes, and their chemical composition. With the introduction of three-dimensional (3D) printing, the model of creating medicines by mass producing them has changed significantly in favor of an individualized approach that takes into consideration the specific needs of each patient[1].

Pharmaceutical manufacturing has not historically had much flexibility in creating customized dosage forms based upon the specific characteristics of the patient who will receive the drug. Patients take their medications based upon many factors, including their age, weight, metabolic rate, their current medical condition, and their genetic makeup. As a result, most medications that are manufactured in a standardized dosage form may not be suitable for all patients and could lead to increased morbidity and/or mortality. The ability to digitally fabricate customized drug formulations via the use of 3D printing technology will allow for the ability to modify the Dosage Number (dosage), shape (geometry), size (weight), and release characteristics of each medication[2].

In an overall view, three-dimensional (3D) printing involves depositing materials in layers to print a drug delivery system that is (1) highly detailed and reproducible and (2) can be accomplished with a variety of technologies that are considered additive manufacturing. All the available technologies for drug delivery purposes can produce 3D printed drug delivery systems and include fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), inkjet printing, and extrusion-based printing systems to produce drug delivery systems. Each of these different technologies will provide specific benefits in regard to compatibility with materials for printing, resolution of printed product, and methods of incorporation of drugs into the products[3].

One key feature associated with 3D printing technology is the ability to create dosage forms that can provide controlled release of a drug. Controlling the internal geometry and composition of the layers of the printed dosage forms produced through 3D printing will permit individualized delivery of drugs with immediate release, sustained release, delayed release, or pulse-dose release profiles. This is particularly helpful with patients who suffer from chronic illnesses and/or to ensure that a specific amount of drug is given to a patient at a predetermined time[4].

The first regulatory agency-approved drug to use 3D printing technology as a drug delivery system is Spritam® (levetiracetam), which demonstrates the applicability of using 3D printing for drug delivery. This medication is unique in that it has a very porous

design and dissolves quickly to allow for patient compliance.

3D printing is also being used to create polypills, which are drugs that are manufactured as a single dosed form that contains a combination of more than one medication (polytherapy). By combining multiple medications into a single dose form, polypills can greatly reduce the complexity of medication regimens that patients must adhere to, thus providing a greater likelihood of compliance.

3D printing of advanced drug delivery systems will also enable the creation of drug delivery devices that can be implanted, have scaffolds, utilize microneedles, and/or include transdermal patches, as well as utilizing all types of biocompatible and/or bioabsorbable materials. Additionally, the use of 3D printing will facilitate the development of advanced drug delivery systems utilizing nanotechnology, which will be designed to deliver drugs to specific disease sites and will have the capacity to respond to the environment in which they will deliver the drug (e.g., changes in pH or temperature) through the means of having been designed to do so[5].

Prior to 3D printing technology as a means for providing drug delivery to be widely used throughout the world, numerous challenges will need to be addressed. These challenges include limitations on the types of materials that can be printed, the potential stability of drugs produced through the 3D printing process, the need to scale up production to meet FDA requirements, and the need for the appropriate quality assurance processes to provide a high-quality output (i.e., most pharmaceuticals must comply with established standards for manufacturing).

The goal of this review is to provide a comprehensive overview of drug delivery systems using 3D printing technology and detail the potential implications for 3D printing technology to personalize healthcare, provide detailed instructions on how to use 3D printing technology in drug delivery (i.e., materials and their selection), and provide an insight into the future use of 3D printing technology for drug delivery. This review will be an information source for readers to utilize in considering the future of the drug delivery and 3D printing technology, how the two can change the manner in which drugs are in fact delivered to patients[4].

2. 3D Printing Technologies in Drug Delivery

An Overview of 3D Printing Procedures

Numerous techniques exist for the production of pharmaceutical 3D printed objects; these techniques have various principles of operation, require different materials, and have different applications. Ultimately, the appropriate procedure is chosen based on the properties of the intended drug (e.g. stability, dosage form), the structure and characteristics of the object (e.g. resolution, release characteristics), and the desired properties of the printed component (e.g. strength, durability). The most commonly used types of 3D printing in drugs include fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), ink-jet printing, and extrusion-based processes[6].

Fused Deposition Modeling

Fused deposition modeling is commonly used to 3-D print pharmaceutical products because it is successful, cost-effective, and easy to use. In FDM, continuous strands of thermoplastic polymer material are heated above their melting point and extruded through a nozzle to create multiple layers that solidify as they cool (Amaro et al., 2017).

Before the drug can be printed using FDM, drug-loaded filaments are manufactured through a hot melt extrusion process. The ability to manipulate infill density, geometry, and composition allows for the fine tuning of drug release profiles. Therefore, FDM is suitable for the production of controlled and sustained release formulations.

The most significant disadvantage of FDM is that thermolabile drugs are subjected to high temperatures during manufacturing, which can result in degradation. Additionally, there are also limitations related to the accuracy of the extruded material, specifically in the area of tolerancing and smooth physical surfaces of the finished component[7].

Stereolithography

Stereolithography uses a light source (laser or ultraviolet light) to cure a polymer photo-resin layer-by-layer to create high resolution, well-finished complex drug delivery systems.Selective Laser Additive Manufacturing (SLA) permits detailed control of microstructure; permitting complex geometries to be produced from which release of an agent can be precisely controlled. This type of manufacturing is particularly effective for the design of implants, scaffolding, and for manufacturing microneedles.

A lack of biocompatible and suitably pharmaceutically acceptable photopolymers remains a significant hurdle[8].

Selective Laser Sintering (SLS)

Selective laser sintering is a powdered material process using a laser beam to weld powdered polymer material or drug containing powder into a solid structure, no use of solvents or binding agents is required, offering a particular advantage for certain pharmaceutical applications.

Selective laser sintering can be used to produce continuous porous structures that allow for the immediate release of an agent or to increase the solubility of the agent. SLS may also be used to generate mechanically robust dosage forms.

Although SLS has a number of positive aspects in that it does not require the use of solvents or binding agents; SLS also requires specialized processing equipment and requires optimization of processing parameters to avoid any potential drug damage associated with localized heating[9].

Inkjet Printing

Inkjet printing is a method of droplet deposition of a drug solution on a substrate in a controlled manner. Inkjet printing is particularly suited for precise dosing and the manufacturing of low-dose formulations.

Inkjet Printing may be divided into either, continuous inkjet, or drop on demand systems. Inkjet printing is a commonly used technology for producing oro-dispersible films, coatings, and for creating individualized dosage forms.

The primary limitations to this technique include a limited drug concentration that can be accomplished in the ink, and challenges related to the clogging of the inkjet nozzle and the stability of the drug formulation[10].

Extrusion Based and Semi-Solid Printing

Extrusion based printing involves depositing semi-solid materials: (e.g., gel, paste, or hydrogel) through a nozzle. Due to the process being operated at lower temperatures than Fused Deposition Modeling (FDM), this is a very appealing method of forming dosage forms using drugs that are sensitive to heat.

Extrusion based printing permits the use of a large array of biological constructs that can be deposited using this process to create complex dosage forms with controlled release properties. Extrusion based printing can be used to produce hydrogels, implants and transdermal systems[11].

Comparison of 3D Printing Technologies

Each of the 3D printing technologies used in drug delivery applications has both advantages and disadvantages. FDM is the most commonly used technology due to its simplicity and scalability, SLA is capable of producing products with great precision and resolution, SLS offers process concentration (solvent free) and the production of mechanically robust products, while inkjet printing is best suited for precise dose manufacture. Extrusion technology has the advantages of being able to print various materials and using drugs sensitive to heat.

When choosing a particular technology for 3D printing application, consideration must be given to the application, the properties of the drug, and the desired release profile.

3D printing technologies provide an incredibly versatile platform from which to develop advanced drug delivery systems that provide precise control of both the structure and function of the dosage form. Each of the multiple methods of 3D printing offers an opportunity to individually customize the dosage form in a manner that best meets the therapeutic objectives. The continued advancement toward availability of new materials, and refinements in the overall printing techniques used, is expected to further enhance the application of 3D printing technologies to pharmaceutical sciences[12].

3. Materials Used in 3D Printed Drug Delivery Systems

The selection of suitable materials for 3D printing is an important factor in successful drug delivery using additive manufacturing technologies. Pharmaceutical properties must be met by raw materials in order to successfully produce drugs using 3D printing. Essential materials must demonstrate appropriate mechanical, rheological and physical properties (printability) as well as biocompatibility (for drug delivery) and the ability to absorb and hold drugs while maintaining drug stability during processing. In order to produce personalized (through 3D printing) and/or controlled release (through additive manufacturing) dosage forms, a variety of polymers, lipids, hydrogels and excipients have been evaluated.

Polymeric Materials are some of the most common materials used to develop 3D printed delivery systems for drugs. This is because of their versatility and tunability in properties, including (biodegradability/biocompatibility), mechanical properties as well as thermal stability. Both synthetic and natural polymers can be used based upon the

applications as well as desired outcomes of the 3D printed system.

Synthetic polymers such as polyvinyl alcohol (PVA), polylactic acid (PLA), polycaprolactone (PCL), and polyethylene glycol (PEG) are frequently used due to their mechanical properties, thermal stability, and ease of processing. These polymers are also highly preferred for use in Fused Deposition Modeling (FDM); therefore, these synthetic polymers need to have thermoplastic properties[13].

Natural polymers such as chitosan, alginate, gelatin and celluloses have excellent biocompatibility and biodegradability. Therefore, they have been widely used as raw materials to produce 3D printed delivery systems particularly through extrusion-based systems and Hydrogel printing systems. Furthermore, many of these natural polymers are highly desired for use in biomedical applications including; tissue scaffolds or wound healing.

Essentially, the type of polymer utilized to produce 3D printed delivery systems has a significant impact on the release behaviour of drugs. The use of hydrophilic polymers generally facilitates release of drug(s) out of the polymeric system quickly, while the use of hydrophobic polymers tends to either prolong the time to release drugs or develop some type of controlled release system[14].

Hydrogels are 3D cross-linked networks of hydrophilic polymeric materials that can retain large quantities of water.Hydrogels are increasingly being used for 3D printing due to their excellent biocompatibility and flexibility. They can also mimic biological tissues.

Hydrogels can be used for extrusion printing and bioprinting. They are capable of encapsulating cell, protein, or drug. This allows for the controlled and localized delivery of drugs, meaning that they can deliver drugs to specific sites within the body. Hydrogels swell when they get wet, which affects how drugs are released from them; this allows for hydrogels to release drugs over extended periods of time after they are injected or implanted into the body.

Common hydrogels used in 3D printing include alginate, gelatin methacrylate (gelma), and polyethylene glycol diacrylate (PEGDA[15])

Hybrid Systems with Lipids and Composites

Incorporating lipids into 3D printing systems improves the solubility of poorly soluble drugs and stabilizes the drugs during the manufacturing process. When combined with polymers, lipid-based excipients can also improve the drug-loading capability and provide controlled release of the drugs.

Composites containing a mixture of polymers, lipids and/or nanoparticles and inorganic materials are increasingly being utilized to improve the mechanical strength and functionality of 3D printed systems. The use of composite materials in drug delivery systems enables the development of multi-functional systems with specific drug-releasing profiles[16].

Pharmaceutical Excipients

Excipients play an important role in improving the performance and printability of 3D printed formulations. Plasticizers (glycerin, polyethylene glycol) can be added to improve flexibility and diminish brittleness. Surfactants can help disperse and stabilize the drugs, while disintegrants and binders can adjust the release profile of the drug.

When using excipients to improve the stability and efficacy of a drug, it is critical that the excipients are compatible with both the drug and the printing process used for 3D printing[17].

Drug Incorporation Techniques

There are many different techniques for incorporating a drug into a 3D printed system based on the properties of the drug and the desired end result of the 3D printed system. Some examples of methods for incorporating a drug into a 3D printed system include:

I. Blending the drug with the material used for printing
II. Loading the drug into a filament before printing
III. Impregnating the drug into the 3D printed system after it has been printed.

If a drug is thermally stable, it can be incorporated into the filament before printing; however, if the drug has a low thermal tolerance, it should be incorporated into an inkjet or extrusion-system under conditions that do not exceed the temperature of the melting point[18].

Considerations Regarding Material Selection

When selecting materials for manufacturing a 3D printed drug delivery system, a number of factors need to be evaluated:

- The thermal stability of the drug
- The mechanical properties of the material required for printing
- The biocompatibility and biodegradability of the selected materials
- The desired drug release profile

- The compatibility of the materials and the selected printing technology

All of these parameters need to be optimized in order to produce safe, effective, and reproducible drug delivery systems.

Material is one of the most important components in determining the performance and functionality of 3D printed drug delivery systems. 3D printed drug delivery systems can produce versatile and customizable dosage forms using a wide variety of polymeric materials, hydrogels, lipids and composites. Continued advances in materials science will ensure continued development of 3D printing technology in the pharmaceutical field, with particular emphasis on personalized medicine and the controlled delivery of drugs[19].

4. Design Strategies for Controlled Release Systems

One of the many advantages associated with using 3D printers to produce medications is the ability to fabricate medicines with highly accurate and variable release patterns. 3D printers allow the amendments of several design parameters including geometry, porosity and composition to create immediate, sustained, delayed and pulsatile release systems, giving rise to improved patient care for patients with chronic illnesses[20].

Geometric-Based Design

The geometric shape of each printed dosage form will dictate how each drug is released. The geometries will vary in surface area, shape, and internal architecture, which will have an impact on both dissolution and diffusion.

For example, the increase in surface area of tablets, typically accomplished by using porous or honeycomb designs, provides increased contact between the drug and the dissolution medium, thereby increasing the speed of drug dissolution into the medium. Alternatively, dense and compact geometries will restrict drug movement, thus allowing for a sustained release of the drug. Additionally, 3D printing can be used to create complex geometries that are either multilayered or compartmentalized, allowing doses to be deleted sequentially or delivered to a specific site[21].

Infill density and Porosity

Infill density, one of the three primary parameters used to define the geometry of a 3D printed object, is defined as the percentage of a printed object that has a solid filled internal structure. By varying the infill density of a printed dosage form, it is possible to create a dosage form that has a varying degree of porosity.The porosity of a structure directly correlates to the infill density during 3D printing, affecting the rate at which a drug is released through a defined amount of fluid penetration. A lower infill density results in a highly porous structure and, as such, will allow for a more rapid release of medication. A high infill density will create a much more solid structure and allow for slower drug diffusion, enabling a longer duration of drug release. This method is simple and effective for tailoring drug release rate without modifying the formulation itself[22].

Multi-layered and multi-compartment dosage forms

Three-dimensional (3D) printing allows for the development of multi-layered and multi-compartment dosage forms. These types of dosage forms, while commonly produced, offer a significant advantage to traditional methods of fabrication. In these dosage forms, a variety of medications and/or at varying doses can be incorporated into a single dosage form, thereby facilitating the design of "polypills."

Each layer or compartment may be constructed from a different type of polymer or contain a varying concentration of medication, thus offering distinct release profiles including immediate release and sustained release. Such an approach provides useful options for those patients that may benefit from combination therapy and/or medication tailored to their individual needs[23].

Material Composition and Drug Distribution

The choice and distribution of materials within a three-dimensional printing system will play a critical role in determining the rate of drug release. For example, the use of hydrophilic polymers will facilitate rapid drug release due to the ability of the polymer to swell and dissolve when exposed to water. Conversely, hydrophobic polymers reduce the rate of drug release due to their ability to limit the penetration of water into the structure.

Gradient structures can also be developed to achieve a controlled rate of drug release by varying the concentration of drug across multiple layers of the printed structure. Additionally, the use of biodegradable materials in conjunction with the above methods can result in sustained drug release due to the rate at which the polymeric material degrades[24].

Stimuli-Responsive Systems

Advanced three-dimensional printed drug delivery systems can be developed to offer stimulation-

responsive (i.e., responsive to external stimuli such as pH, temperature, or enzyme activity) or pH-responding materials (i.e., the ability to release drug(s) in target areas of the gastrointestinal tract) or temperature sensitive materials (i.e. the ability to release drug(s) on demand). The ability to combine these functionalities into one dosage form will greatly enhance both the targeting of drug products as well as the effectiveness of drug therapies[25].

Three-dimensional printing also allows for the design of a variety of different release profiles for example:

Immediate release products can be achieved through the use of highly porous materials and hydrophilic polymers, which dissolve rapidly upon administration. Sustained release products can be developed through the use of dense matrices and hydrophobic polymers, and thus drugs can be released over an extended period of time. Pulsatile release systems can be developed by designing products to release drugs at specific time intervals, thus enabling the development of new technologies for chronic dosing (i.e., when a drug must be administered at specific time intervals).

The ability to develop dosage forms that combine several of these release profiles represents a new frontier in drug delivery.

The innovative design strategies provided by the use of three-dimensional printing will permit the control of drug release by providing unparalleled precision over the manipulation of geometry, porosity, the composition of materials and the internal architecture of dosage forms. These capabilities offer the potential to develop highly individualized and effective drug delivery systems, thereby meeting the unique needs of each patient. As advances are made in both design and material integration, the potential of three-dimensional printing for controlled drug delivery will further expand[26].

5. Applications in Personalized Medicine

3D Printing and its Impact on Personalized Drug Delivery

Personalized medicine is changing the way we think about treating patients, moving away from the "one size fits all" concept and towards patient-specific therapies that consider factors like age, genetics, the condition of the patient, and metabolic profile. 3D printing has emerged as a revolutionary technology in this new era of patient-specific therapy, providing the capability to create customized drug delivery systems with precise control over dosing, composition and release kinetics[27].

Customization of Dosage Forms by 3D Printing

3D printing is an excellent tool in the field of personalized medicine, allowing healthcare providers to create patient-specific dosage forms. In traditional pharmaceutical manufacturing, fixed-dose formulations are typically used, which might not always provide the precise dosage that is needed to effectively treat each individual patient due to differences in physiology between patients.

With 3D printing, manufacturers have the ability to create very precise control over the quantity of the drug that is being manufactured, simply by changing the digital files that are used to create these dosage forms. This has enabled manufacturers to create customized tablets that are manufactured to meet the exact dose that is required, thereby facilitating flexible dosing for the pediatric and elderly populations, where this is essential to treating these populations. Furthermore, manufacturers can create dosage forms in a wide variety of different shapes and sizes, thereby improving patient acceptability and compliance[28].

Polypill Concept as an Example of the Impact 3D Printing has on Personalized Medicine.

The polypill concept, which is to combine multiple medications into a single dosage form, is another impact 3D printing has had on the ability to create patient individualized drug therapy. Chronically ill patients who suffer from a chronic illness (e.g. cardiovascular diseases, diabetes, hypertension) often require multiple medications to control their disease, which significantly complicates their ability to adhere to their prescribed medication regimen because of the number of prescriptions and/or places to obtain medications required. The use of 3D printing allows for the creation of multi-compartment tablets containing various drug products in each individual compartment/layer. Each can have its own unique release profile making it easier for the patient to take the medication as prescribed. Medication regimens are easier to manage, thus improving patient adherence to their prescribed medications and improving overall positive therapeutic outcomes[29].

Customized Drug Release Profiles.

Personalized medicine not only allows for the customization of doses but also allows for the control of drug release profiles. With 3D printing, it is now possible to produce dosage forms with individual patient-specific release kinetics (e.g., immediate, extended, delayed, and/or pulsatile release).

An example of a pulsatile release system would be the drug delivery system for patients suffering from circadian rhythm-related conditions. The same can be said for the development of extended release products that may help reduce the frequency of dosing for patients with chronic conditions, thereby increasing the patient's adherence to their medication regimen[30].

On-Demand Drug Manufacturing:

3D printing allows for the potential on-demand medication manufacturing whereby medications can be produced onsite (at the point of care), such as in hospitals or pharmacies. As a result, there is less need for large-scale manufacturing capabilities and medications can be produced quickly and customized to meet specific needs.

Situations where on-demand manufacturing is beneficial include: emergency situations (e.g., natural disasters, terrorist attacks), rare diseases, and personalized therapies where conventional mass production is not practical; thus, minimizing drug wastage and ensuring an adequate supply of medications[31].

Applications for Special Populations:

3D printing offers many potential applications for special populations of people. For pediatric patients, customized dosage forms with unique shapes, flavors, and dose adjustments can enhance patient acceptance of medication and compliance with their prescribed medication regimens. For geriatric patients, providing easy-to-swallow forms of medication and dosing according to patient-specific needs can help reduce the risk of adverse effects associated with using medication.

Furthermore, patients who have genetic differences in drug metabolism will experience improved delivery of medications through custom-made delivery systems. Therefore, 3D printing is well-suited for helping create personalized medication delivery systems[32].

Integration with Digital Health Technologies (DHTs)

The future of personalized medicine is in the integration of 3D printing technology with DHTs, including electronic health records (EHR), wearable health devices, and artificial intelligence (AI). Each of these technologies can provide real-time data about patients, which can then be utilized in combination with 3D printing methods to manufacture patient-specific medication formulations.

This form of integration will provide the capability to dose patients precisely, monitor their health continuously, and adapt therapy as needed; allowing for fully personalized health care systems to be created[33].

Challenges and Considerations

Although there is a great deal of promise with the use of 3D printing in personalized medicine, some issues must first be resolved prior to widespread commercialization. These issues include: regulatory issues, quality control issues, need for standardization of the printing processes, validation of personalized formulations, and maintenance of consistency and safety in manufactured customized medication products. All of these issues must be resolved if the newly developed products are to gain clinical acceptance.

3D Printing technology has changed how medications can be manufactured and distributed in order to meet specific patient needs by creating customized drug-delivery systems that are tailored to patients. With dose customization, polypill development, and on-demand manufacturing of drugs, all produced using 3D printing, there are tremendous potential advantages related to improving patient therapeutic outcomes and compliance with taking medications. Continued improvements and support from regulatory agencies will be required to help ensure that this technology will be utilized for use in clinical settings[34].

6. Challenges and Future Perspectives

Challenges to Implementing 3D Printing in Drug Delivery

Challenges will limit the global adoption of 3D printing in drug delivery. One example of this challenge is regarding the stability of drugs (drugs will be destroyed at high temperatures) when using the print process called fused deposition modeling (FDM). Also, the limited number of pharmaceutical-grade materials available for printing limits flexibility in this process.

Another major challenge is related to regulations: the current regulations do not support point of use or personalized manufacturing, making it difficult for physicians to provide safe drugs to the patients they serve. Maintaining quality and consistency through various batches of drugs is essential to protect the patient. Challenges exist with producing drugs in large quantities[34].

Future Directions

The future of 3D printing for drug delivery looks bright because of changes in materials science, digital health, and the field of pharmaceutical engineering. With the right combination of patient and digital data (Artificial Intelligence) will allow for customized drug therapy in real-time.

3D printing has the ability to respond to changes in the environment through 4D printing. 3D printing will also allow for point-of-care manufacturing to occur in hospitals and pharmacies; therefore, increasing the use of personalized medicine. The way 3D printing is currently regulated will evolve to allow for the safe use of 3D printing technology.

Challenges in materials, regulations, and production scalability will be overcome through the continued advancement of technologies. The 3D printing process will completely change drug delivery by allowing physicians to deliver a unique treatment for each of their patients in addition to safe, accurate, patient-centered care[35].

7. Conclusion

3D printing has emerged as a transformative technology in drug delivery, offering unprecedented flexibility in the design and fabrication of personalized dosage forms and controlled release systems. By enabling precise control over drug dose, geometry, and internal structure, this technology addresses key limitations of conventional pharmaceutical manufacturing, particularly the lack of customization and adaptability to individual patient needs.

Advanced 3D printing techniques, combined with a wide range of pharmaceutical materials, have facilitated the development of innovative drug delivery platforms, including polypills, implants, microneedles, and transdermal systems. The ability to tailor drug release profiles—ranging from immediate to sustained and pulsatile release—further enhances therapeutic efficacy and patient compliance.

Moreover, the integration of 3D printing with personalized medicine and digital health technologies has opened new avenues for patient-specific therapy and on-demand drug manufacturing. However, challenges related to material limitations, drug stability, regulatory frameworks, and large-scale production must be addressed to enable widespread clinical adoption.

In conclusion, 3D printing represents a promising and evolving approach in pharmaceutical sciences, with significant potential to revolutionize drug delivery and advance precision medicine through customized, efficient, and patient-centric therapeutic solutions.

Ethical Approval and Consent to Participate

This article is a review study and does not involve any human participants or animals. Therefore, ethical approval and informed consent were not required for this work.

Consent for Publication

Not applicable.

Availability of Data and Materials

All data and information presented in this review are derived from previously published studies and publicly available sources. No new datasets were generated or analyzed during the current study.

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Conflict of Interest

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Author Contributions

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Compliance with Ethical Standards

This manuscript complies with all applicable ethical standards for research and publication.

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