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A Review Article on: Three-Dimensional Printing Technology; Principles, Techniques and Future Prospects

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Abstract Three-dimensional (3D) printing technology, also known as additive manufacturing, has emerged as a transformative approach for the fabrication of complex and customized structures across various scientific and industrial domains. Unlike conventional subtractive manufacturing methods, 3D printing constructs objects layer by layer directly from digital models, enabling enhanced design flexibility, reduced material wastage, and rapid prototyping. This review provides a comprehensive overview of the fundamental principles underlying 3D printing technology, including computer-aided design (CAD), slicing, and layer-wise fabrication processes. Major 3D printing techniques such as fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), digital light processing (DLP), and inkjet-based printing are critically discussed with respect to their working mechanisms, materials used, advantages, and limitations. Furthermore, the review highlights current applications of 3D printing in pharmaceuticals, healthcare, biomedical engineering, and industrial manufacturing. Emerging trends, including bioprinting, personalized medicine, smart materials, and integration with artificial intelligence, are also explored. Finally, the article addresses existing challenges such as material constraints, regulatory issues, and scalability, while outlining future prospects that position 3D printing as a key enabling technology for next-generation manufacturing and healthcare solutions.

Keywords Three-dimensional printing; Additive manufacturing; Rapid prototyping; 3D printing techniques; Fused deposition modeling (FDM); Stereolithography (SLA); Selective laser sintering (SLS); Bioprinting; Personalized medicine; Future prospects

1. Introduction

Three-dimensional printing (3D) Printing technology represents a rapidly growing fabrication method that originated in the 1980s generally, 3D printing technology consists of four primary component: the design and development of digital models, digital slicing, conversion of g code files, and the manufacturing of 3D printers. This technology offers

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significant advantage in designing complex structure and manufacturing personalized drugs delivery system when compared to traditional manufacturing methods. Over the pass few decades, 3D printing technologies have advanced swiftly and have found extensive application in aerospace, mechanical manufacturing, construction and biomedical engineering nevertheless, its application in the pharmaceutical sector began relatively late. In July 2015, the US food and drug administration (FDA) approved a levetiracetam Tablet (Spritam) produced using 3D printing Technology, marking a significant acknowledgement of 3D printing in the pharmaceutical domain since that time, a new era in the expansion of drug delivery system through 3D printing technology has commenced. An increasing number of pharmaceutical researchers are directing their efforts towards the development of Three dimensional printing preparations and creating a range of personalized formulations. The volume of publish article concerning 3D printing preparation has also been on the rise annually this includes numerous original studies and review articles, which serve as excellent reference for future in depth investigations [1].

However, due to the nature of 3D printing technology as an emerging field, the information related to it is rapidly updated and revised, necessitating timely updated and supplement to the relevant research progress on 3D printing technology. This review aims to summarize the commonly utilized types of 3D printing technologies and their most notable and recent applications within the pharmaceutical sector, focusing on the opportunity presented in drug delivery system as well as the significant challenges associated with this technology. Unlike traditional manufacturing method known as "Subtractive manufacturing", 3D printing represent an "Additive manufacturing" technology. In this process, a model is created using computer-aided design, software, which is then sliced and sent to a printer. The 3D product is built layer by layer, adhering to the principle of layered manufacturing. With ongoing research and advancement in 3D printing technology, numerous new 3D printing method have been developed. Each of these technologies employs various materials, deposition techniques, layering mechanism, and characteristic of the final product. Consequently, the American society for testing and material has categories 3D printing technologies into seven distinct group based on their technical principles. These categories include material extrusion, binder jetting, powder bed fusion, vat photo polymerization, material jetting, directed energy deposition, and sheet lamination [2].

2. Advanced Printing Technology

Several 3D printing methods have been successfully adapted for pharmaceutical use:

(A) Fused Deposition Modeling (FDM)

Extrusion molding printing technology is among the most commonly utilized technologies. Formulation scientists are devoting significant attention to this technology. This technology can be mainly categorized into fused deposition modeling (FDM) and semisolid extrusion molding technology (SSE), based on the various molding materials [3].

The principle of FDM technology FDM technology is extensively utilized in the pharmaceutical industry due to its benefits, including straightforward equipment, affordability, and robust product strength. By employing computer-aided design software, products are created through 3D printing, which involves the layer-by-layer deposition of molten material onto printing platforms the underlying principle is illustrated in the polymer filament that contains the drug is extruded by two rollers through a high-temperature nozzle [4], while the print head navigates in the x-y axis direction, guided by computer software to produce the product; upon finishing one layer of printing, the printing platform descends or the Z axis elevates by a distance equivalent to the thickness of one layer to initiate the subsequent layer of printing, and this process is repeated until the product is fully completed, figure 1.

At present, there are three primary methods for preparing 3D tablets utilizing FDM technology, as illustrated:

(1) Dipping-melting method: the filament is immersed in a solution or dispersion that contains the API to create a filament infused with the API for printing.

(2) FDM: the API is incorporated into the conveyor along with the excipients, resulting in filaments that contain the API, which are produced through the extrusion unit and utilized for the fabrication of 3D-printed medications, currently recognized as the most prevalent method.

(3) Filling and forming method: initially, an empty shell is printed, followed by the introduction of the API, and then the shell printing is continued; the processes of printing and filling may occur either simultaneously or in a sequential manner.

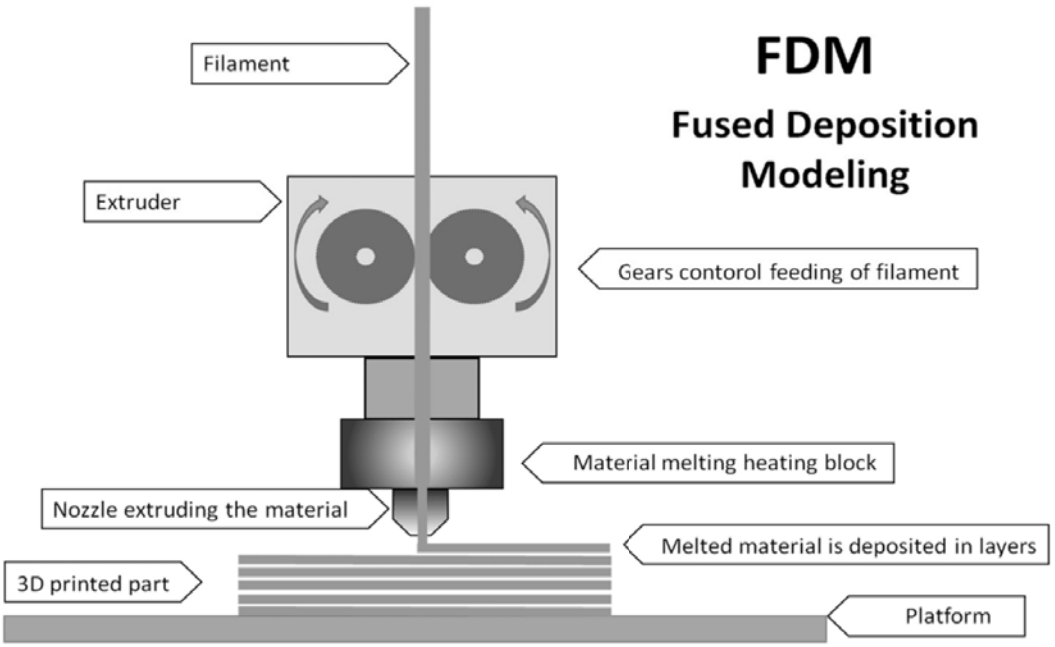

Figure 1: Fused deposition modeling (FDM)

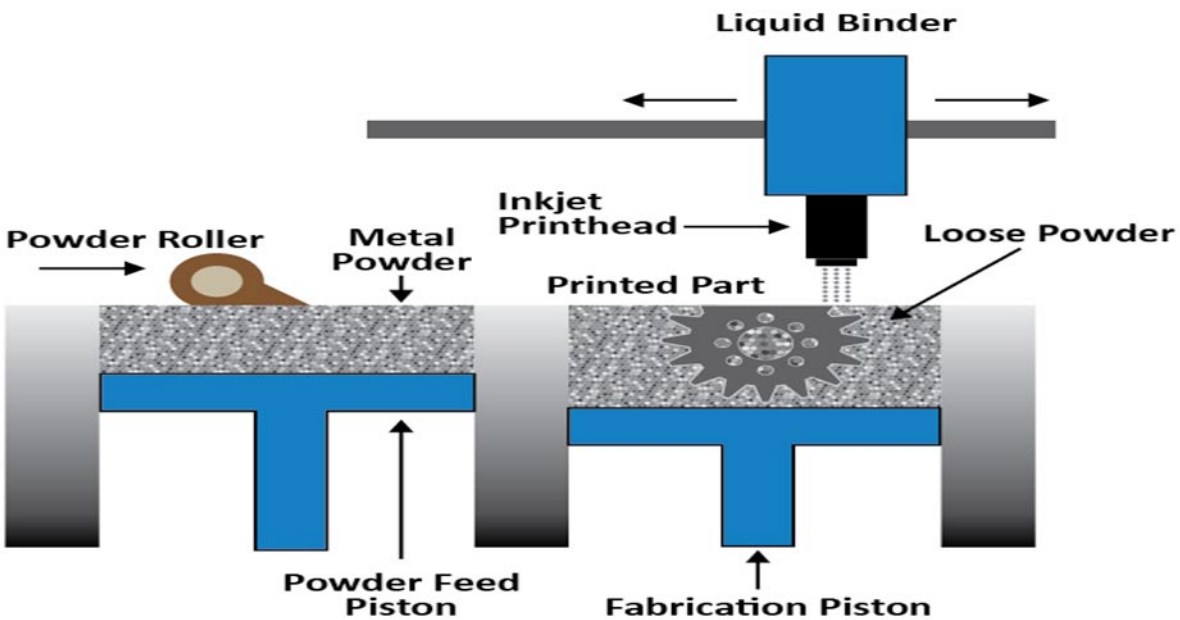

Figure 2: Binder jetting (BJ)/Drop on powder printing (DOP)

(B) Binder jetting (BJ)/Drop on powder printing (DOP)

DOP employs droplets expelled from the print head to adhere the powder particles in a layer of deposited powder on the platform. The manufacturing process initiates with layers of powder, which are uniformly distributed on the build platform by a roller. In accordance with the designated pattern created on the computer, the print head releases droplets containing binders, such as PVP k30 and hydroxyl propyl methylcellulose (HPMC), or active pharmaceutical ingredients onto the powder bed at a precise speed. Once one layer is printed, the platform is lowered by one layer along the vertical axis, and a new layer of powder from the feeding chamber is spread over the previous layer [5]. This procedure is repeated until the dosage forms are completed. Post-processing entails the removal of residual solvent and the recovery of unprocessed powder, which contributes to the overall structure, figure 2.

Based on the various operational mechanisms,

the commonly utilized drop-on-demand print head consists of two primary types, known as piezoelectric and thermal. In comparison to the piezoelectric print head, the thermal print head is less expensive to manufacture but offers fewer options for solvents with high vapor pressure, resulting in easier evaporation of the solvent [6]. The thermal print head utilizes a heater to vaporize a small quantity of fluid by raising the temperature to 200-300°C, causing the formation of bubbles that propel the ejection of droplets. Nevertheless, less than 0.5% of the liquid within the print head is subjected to this elevated temperature for a few microseconds, and it has been demonstrated that no significant degradation of proteins (such as human growth hormone and insulin) occurs with the thermal print head. Attention is directed towards the piezoelectric print head, where piezoelectric crystals are energized under a voltage, resulting in the deformation of the liquid that forces the droplets out of a nozzle is a critical component; consequently, the piezoelectric print head has gained popularity for a variety of materials [7].

Numerous significant parameters are involved in the preparation process, including the diameter of the nozzle, the speed at which the print head moves, the spacing of the droplets, the spacing of the lines, the thickness of the layers, the velocity and frequency of the droplets, and the distance between the print head and the spread powder. By adjusting these parameters, the desired physical properties and drug release behaviors can be achieved. The flowability of the printing ink is primarily influenced by its physical characteristics, such as surface tension, concentration, and viscosity [8]. Therefore, these properties can be altered by incorporating suitable amounts of active pharmaceutical ingredients (APIs) or binders, even in the absence of other substances, to create a homemade ink that is compatible with a specific ink cartridge. In theory, the printing ink can be formulated with various APIs or pharmaceutical-grade binders, including PVP, HPMC, HPC, CMC-NA, and PEO. Thus, examining the impact of different conventional pharmaceutical-grade excipients on the physical properties of printed dosage forms through dop is essential for providing additional insights for future research. Regarding solidification mechanisms, dop shares similarities with wet granulation utilized in tablet preparation. The adhesive facilitates the formation of solid bridges by crystallizing dissolved particles as the solvent evaporates. Since the integrity of the object relies entirely on this weak force rather than mechanical compression, dosage forms can be easily produced with micron-scale interconnected pores, which offer significant advantages in the preparation of orally disintegrating tablets. Currently, the shortcomings of products printed using DOP are mainly evident in two areas: low resolution and high fragility. Therefore, comprehensive research, exploration, and development of printing technology and its associated instruments are imperative [9].

(C) Stereolithography (SLA)

SLA was the pioneering commercially available technology and the foundation of solid-free fabrication, which was invented by Charles in 1986. The criteria for printing using SLA are founded on the selective photo polymerization of liquid photosensitive resins through ultraviolet laser sources. Initially, a thin layer of liquid resin containing a drug and photo initiator is scanned point by point to initiate polymerization. The subsequent layer adheres securely to the foundational layer, as the depth of curing is slightly greater than the thickness of a single layer, leading to polymerization between unreacted groups and resins in the two adjacent layers. This procedure is repeated until the desired objects are formed. Post-processing, which is essential for eliminating the toxicity of the resin and enhancing mechanical strength, plays a crucial role in removing excess resin and photo initiator. Regarding resolution, SLA stands out as the superior 3D printing technology (20 mm compared to 50-200 mm for other fabrication methods), providing significant advantages in modeling precise structures. SLA is predominantly utilized in the production of oral solid dosages, micro needle patches, and hydrogels. Another benefit of SLA is its low requirement for the chemical structure and properties of drugs or excipients. If drugs and excipients are compatible with the resin, they can be integrated into it, as they will be encapsulated during the polymerization and cross-linking process. Despite the limited options for photosensitive resin in the pharmaceutical sector, a significant challenge remains: SLA printers can only utilize a specific resin formulation during a single printing process unless the previous formulation is replaced with a new one when printing is paused. Consequently, it becomes complex to fabricate dosage forms with varying formulations, figure 3. Furthermore, in recent years, although some photo cross linkable polymers, such as PEGDA and GELMA, has been developed, FDA-approved photosensitive polymers continue to be scarce [10].

(D) Semi-Solid Extrusion (SSE)

Semisolid extrusion 3D printing technology (SSE), which is also referred to as pressure-assisted micro

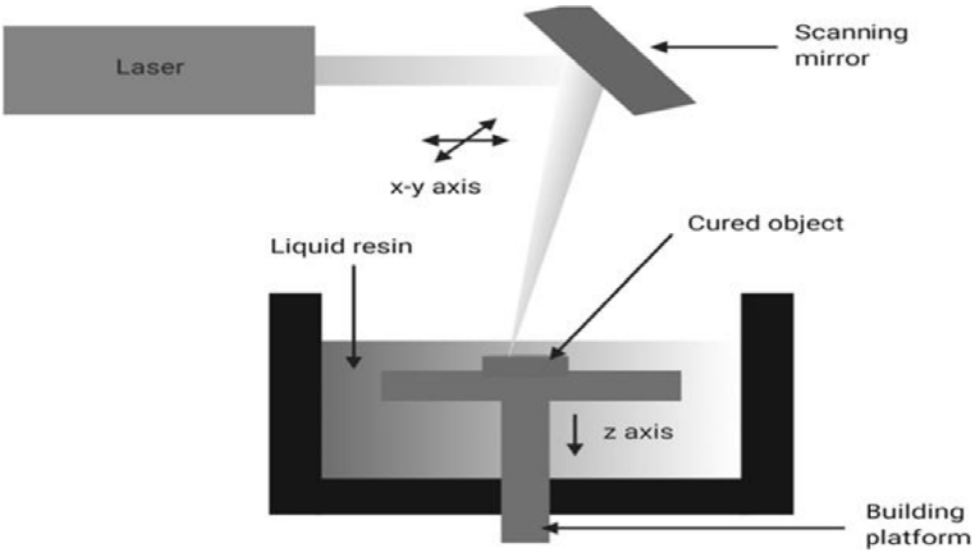

Figure 3: Stereolithography (SLA)

syringe extrusion technology (pam) the paste is extruded uniformly through a syringe-based print head under pressure or through the rotation of a screw gear, depositing material layer by layer onto the printing platform as dictated by the modeling software. The diameter of the print head attached to the syringe varies from 0.35 to 0.85 mm, with the pressure needed during the printing process ranging from 0.4 to 3.8 bar. In comparison to other printing technologies, SSE offers distinct advantages in terms of both the materials used and the printing process itself. Since there is no heating involved for the materials, SSE is particularly suitable for thermo sensitive drugs, such as guaifenesin, thereby mitigating the risk of degradation. Furthermore, a wide array of pharmaceutical ingredients can be utilized in the preparation of the starting materials [11]. Unlike the FDM printing method, SSE directly employs the pressure from screw gear rotation to extrude the semisolid materials into the printer head without causing deformation; thus, the characteristics of the starting materials as a semisolid formulation are crucial in the SSE 3D printing process, figure 4. Specifically, the printability, extrude ability, and shape retention capabilities of the printing materials serve as key evaluation criteria. Previous research indicates that the starting materials should demonstrate shear-thinning behavior and maintain a yield stress of less than 4000 pa, along with a loss factor (Tand z g"/g') ranging between 0.2 and 0.75. Nevertheless, a notable drawback is that the printing process necessitates the use of organic solvents to prepare the paste, which may lead to the issue of residual organic solvents. Additionally, this innovative printing technique must address several challenges, including the requirement for heavy machinery (such as hot extruder motor components), which typically demands sufficient torque for extrusion to ensure an effective extrusion process [12].

3. Development of patient-centric dosage forms

The true strength of 3D printing lies in its ability to facilitate personalized medicine.

(A) Customized Dosing

Apart from personalized medicine, other terms are also used to describe the same concept, such as individualized medicine, precision medicine, stratified medicine, pharmacogenomics, genomic medicine, and p4 medicines, including personalized, predictive, preventive, and participatory. 3D printing technologies have emerged as a powerful tool for manufacturing personalized medicines, providing healthcare professionals with a huge arsenal of different techniques to fabricate custom-made medicines and medical devices. Initially, 3D printing technologies were developed to produce tablets moving from simple formulations, just containing the drug in a specific dose not commercially available to complex systems, containing all drugs required and combining different release profiles within the same tablet adapted to the patient's need. 3D printing also has enabled the manufacturing of personalized metallic prostheses and parenteral implants and other types of medical devices. In the last years, the application of 3D printing technologies in the manufacturing of medicines

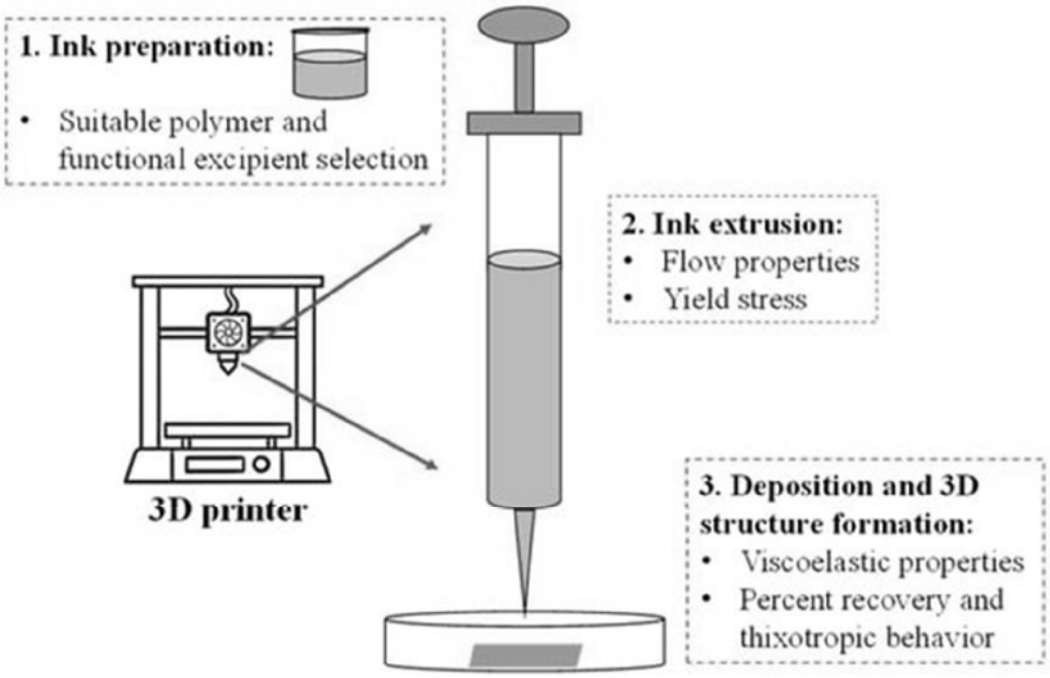

Figure 4: Semi-Solid Extrusion (SSE)

containing biopharmaceuticals or drugs encapsulated with in nano vehicles, known as nano medicines, is attracting more and more attention in the scientific community [13].

(B) Poly pills

A poly pill is a groundbreaking pharmaceutical dosage form that integrates two or more active pharmaceutical ingredients (APIs) into a single tablet or capsule, aimed at treating or preventing multiple diseases or health conditions at once. The primary goal of creating a poly pill is to streamline complex medication regimens and enhance patient adherence to treatment, particularly for individuals with chronic Illness such as hypertension, diabetes, cardiovascular issues, and hyperlipidemia, where it is common to prescribe multiple medications concurrently. Managing several medications daily can be perplexing, time-consuming, and may result in missed doses or medication errors. By consolidating all necessary medications into one pill, a poly pill guarantees that patients receive their entire treatment in a single, convenient dosage form, thereby improving compliance and therapeutic results [14].

Poly pills can be engineered so that each drug component possesses its own release profile—some may be designed for immediate release for rapid action, while others are formulated for controlled or sustained release, ensuring that the desired drug concentration in the body is maintained over an extended period. This controlled release is accomplished through the use of appropriate polymers, coatings, and matrix systems within the formulation. Additionally, the development of poly pills contributes to lower manufacturing, packaging, and distribution costs, making treatment more affordable and accessible [35].

In recent years, the idea of poly pills has attracted increased attention due to advancements in 3D printing technology, which enables precise control over dosage, drug placement, and release profiles within a single tablet. This innovation allows for the creation of personalized poly pills tailored to the specific needs of patients, taking into account their age, medical condition, and therapeutic response [36]. Overall, the concept of poly pills signifies a significant advancement toward personalized medicine, providing enhanced efficacy, safety, and patient convenience, while also alleviating the overall burden on healthcare systems [15].

(C) Tailored Drug release profiles

Customized drug release profiles achieved through 3D printing technology signify a groundbreaking development in pharmaceutical formulation, providing complete control over the rate, timing, and site of drug release within the body.

Traditional manufacturing techniques, such as tablet compression or coating, present limited flexibility in managing drug release, while 3D printing allows for

precise spatial arrangement of drugs and excipients in intricate structures tailored to individual patient requirements.

Employing 3D printing, researchers can create dosage forms layer-by-layer with diverse geometries, porosity, surface area, and material composition—all of which significantly affect the dissolution and diffusion of the drug.

Various 3D printing techniques, including fused deposition modeling (FDM), inkjet printing, stereo lithography (SLA), and selective laser sintering (SLS), are utilized to produce customized drug delivery systems. For example, in FDM, thermoplastic polymers such as polyvinyl alcohol (PVA) or poly lactic acid (PLA) serve as carriers, with the drug incorporated within the polymer filament prior to printing. By altering parameters like infill density, shell thickness, or layer height, formulators can modify the release kinetics—resulting in immediate, sustained, delayed, or pulsatile drug release. Inkjet-based printing can position multiple drugs at specific sites within a single tablet, creating multi-drug poly pill where each drug is released independently according to its designated schedule. Customized drug release through 3D printing also facilitates personalized medicine, where drug dosage, shape, and release characteristics are tailored to the patient's age, weight, metabolic rate, or medical condition. For instance, in chronic conditions such as diabetes or hypertension, a single 3D-printed poly pill can encompass several drugs that release at different intervals throughout the day, enhancing patient adherence and therapeutic effectiveness. Furthermore, 3D printing allows for the integration of biodegradable polymers, nanoparticles [16,37].

4. Key Challenges and Future Outlook

4.1 Material limitations and formulation constraints

One of the primary obstacles in pharmaceutical 3D printing is the restricted availability of polymers and excipients that are pharmaceutically acceptable and exhibit the necessary thermal, mechanical, and flow characteristics for various printing methods. Numerous traditional excipients utilized in tablet production are incompatible with high-temperature or laser-based techniques, resulting in stability challenges, degradation of heat-sensitive active pharmaceutical ingredients (APIs), and inconsistent printability [34, 38]. Consequently, formulation scientists encounter considerable difficulties in striking the appropriate balance between drug loading,

4.2 Process standardization and quality control issues

3D printing systems currently lack universal standards for process parameters, including nozzle speed, layer thickness, extrusion force, and energy input. These discrepancies result in inconsistencies from batch to batch, affecting drug release profiles, mechanical integrity, and the uniformity of dosage units. The establishment of validated and reproducible workflows for each drug product continues to pose challenges. Furthermore, real-time quality monitoring tools (pat tools) remain underdeveloped, complicating efforts to maintain continuous control over the printing process [39].

4.3 Regulatory and compliance barriers

Regulatory bodies worldwide are still in the process of developing frameworks for the assessment of 3D-printed medicines. The challenges include defining specifications for layer-wise manufacturing, establishing stability guidelines, verifying dose accuracy, and ensuring adherence to good manufacturing practices (GMP). The lack of clear regulations hinders commercial adoption and complicates approval pathways, particularly for personalized or on-demand medications [17].

4.4 Decentralized and on-demand Manufacturing Models

In the near future, hospitals, pharmacies, and emergency care facilities may implement 3D printing stations that can produce medications on-site. This approach will decrease reliance on supply chains, reduce waste, and guarantee the availability of tailored formulations for urgent or uncommon medical conditions. Military bases, space missions, and remote healthcare facilities are likely to gain significant advantages from these decentralized production systems.

4.5 Expansion of regulatory frameworks and global adoption

Regulatory agencies such as the FDA and ema are currently working on establishing guidelines for the design, validation, and quality control of 3D-printed dosage forms. As the regulatory landscape becomes clearer, pharmaceutical companies will feel more assured in their investments in this technology [33]. Over the next ten years, 3D printing is anticipated to evolve from a research-oriented tool to a widely

accepted platform for pharmaceutical manufacturing.

4.6 Multi-drug and multi-layer poly pill innovations

Future technologies will enable the development of highly intricate poly pills that incorporate multiple drugs, various release profiles, and compartmentalized structures within a single tablet. This advancement will greatly enhance patient adherence, especially in chronic conditions such as hypertension, diabetes, and cardiovascular diseases. Progress in multi-material printing technology will further improve the accuracy and consistency of these poly pills [18, 40].

5. Regulatory and quality control hurdles

(a) Process validation

In the realm of pharmaceutical manufacturing utilizing 3D printing, process validation plays a crucial role in guaranteeing that the produced drug products consistently adhere to the quality, safety, and efficacy standards mandated by regulatory bodies such as the FDA (food and drug administration) and EMA (European Medicines Agency). Given that 3D printing necessitates precise control over various critical parameters—such as printing temperature, nozzle pressure, print speed [32], layer height, feed rate, and formulation viscosity—minor fluctuations can significantly impact the drug's dose accuracy, mechanical strength, dissolution rate, and stability. Consequently, process validation is essential to ensure that each of these parameters remains within specified limits throughout the production cycle [41].

The process validation comprises three primary stages: installation qualification (IQ), which verifies that the 3D printer and its associated systems are installed correctly in accordance with manufacturer and regulatory standards; operational qualification (OQ), which confirms that the equipment consistently functions within the required parameters; and performance qualification (PQ), which ascertains that the process can reliably produce dosage forms that meet all quality specifications. Furthermore, in-process controls, including real-time monitoring of printing accuracy, surface smoothness, and weight uniformity, are implemented to identify deviations at an early stage. Advanced analytical techniques such as thermal analysis, x-ray micro tomography, and spectroscopic imaging are frequently utilized to assess layer uniformity and drug distribution [19].

Through the execution of process validation, manufacturers can ensure reproducibility, uniformity, and adherence to good manufacturing practices (GMP). This step is vital as regulatory authorities require substantial evidence that each batch of 3D-printed medications is consistent in quality and performance. Therefore, process validation not only aids in reducing defects and variability but also establishes a solid quality assurance framework, facilitating the large-scale approval and commercialization of 3D printing [42].

(b) Good Manufacturing Practice (GMP)

Good manufacturing practice (GMP) in the realm of 3D printing for pharmaceuticals encompasses a thorough quality assurance system that guarantees each 3D-printed dosage form is produced and regulated consistently in accordance with established quality standards.

Given that 3D printing represents a sophisticated and highly adaptable manufacturing method, the implementation of GMP principles is crucial for ensuring product safety, efficacy, uniformity, and adherence to regulatory requirements. While traditional manufacturing emphasizes fixed batch processes, GMP in 3D printing must evolve to accommodate digitally controlled, on-demand, and small-batch production systems, necessitating more stringent oversight of printing parameters and materials [31, 43].

The initiation of GMP in 3D printing involves the qualification and validation of equipment, including the printer, extrusion systems, and software, all of which must undergo testing and certification for pharmaceutical applications. The raw materials, which include polymers, excipients, and active pharmaceutical ingredients (APIs), are required to comply with pharmacopoeia standards and must be stored under controlled conditions to avert contamination. Environmental control, encompassing temperature, humidity, and cleanliness, is critical, particularly since 3D printing frequently involves heat-sensitive medications or biodegradable polymers. Furthermore, the digital design files, such as cad models and g-code, must be securely managed, version-controlled, and validated to ensure precision and prevent tampering, as even minor inaccuracies in the digital model can alter drug dosage or geometry [30].

It is imperative that operators and technicians receive appropriate training, and that comprehensive standard operating procedures (sops) are adhered to for every phase—from printer calibration and material loading to post-printing processes like drying, coating,

or sterilization. Ongoing in-process monitoring is essential to ensure that layer-by-layer deposition, print speed, temperature, and pressure remain within Acceptable parameters. Each printed product undergoes rigorous quality control assessments, which include evaluations of weight variation, content uniformity, mechanical strength, dissolution profile, and stability studies [20,44].

6. Material and economic limitation

(a) Limited excipient selection

In the realm of pharmaceutical 3D printing, a major challenge related to materials and economics is the restricted variety of appropriate excipients that can be utilized for formulating printable products. Excipients are essential in the manufacturing of traditional dosage forms, as they influence the mechanical strength, drug release profile, stability, and patient acceptability of the final product. In the context of 3D printing, however, excipients must not only fulfill these pharmaceutical roles but also satisfy specific physical and rheological properties necessary for the selected printing technology, including viscosity, flow ability, melting point, and mechanical flexibility [21, 29].

Each 3D printing method requires a distinct set of excipient properties:

In fused deposition modeling (FDM), excipients need to be thermoplastic polymers that can melt at a temperature sufficiently low to prevent drug degradation while being high enough to solidify quickly after extrusion. Only a limited number of excipients, such as PVA (polyvinyl alcohol), PLA (poly lactic acid), HPMC (hydroxy propyl methylcellulose), and Eudragit, have demonstrated compatibility with FDM. Many widely used pharmaceutical excipients, such as starch or lactose, are unsuitable due to their degradation or combustion at elevated temperatures.

In inkjet or binder jet printing, excipients must possess specific solubility and viscosity traits to facilitate smooth jetting through fine nozzles without causing blockages. Additionally, they must create stable droplets and dry rapidly to form uniform layers, which restricts the application of conventional binders or fillers [22].

For stereo lithography (SLA) and selective laser sintering (SLS), excipients need to be photosensitive or thermally fusible, significantly limiting the range of materials that can be used in pharmaceuticals [28].

Due to these stringent requirements, researchers have access to only a limited selection of printable polymers and excipients, most of which have not yet received approval from regulatory bodies such as the FDA. The development of new printable excipients necessitates comprehensive testing for biocompatibility, the factors of toxicity, stability, and regulatory compliance significantly elevate the costs associated with research and production. This renders the process economically impractical for large-scale manufacturing, particularly in comparison to traditional techniques such as tablet compression or capsule filling [23].

Moreover, the expense of high-purity, pharmaceutical-grade polymers that are appropriate for 3D printing is considerably greater than that of standard excipients. The scaling of 3D printing for mass production also necessitates specialized printers, ongoing maintenance, and skilled personnel—all of which contribute to increased manufacturing costs. Consequently, pharmaceutical companies encounter a dual challenge: material scarcity and financial strain.

These limitations obstruct the advancement of intricate drug release systems, multi-drug poly pills, and personalized medicines that 3D printing has the potential to transform. Thus, addressing the challenge of limited excipient options is crucial for making 3D printing a viable, large-scale, and economically feasible method for pharmaceutical manufacturing. Researchers are currently concentrating on the formulation of hybrid polymers, the development of printable excipient libraries, and the optimization of process parameters to broaden the spectrum of materials that are suitable for 3D printing while ensuring quality, safety, and adherence to regulatory standards [24].

(b) Cost and Scalability

The cost and scalability present significant obstacles to the widespread implementation of 3D printing within the pharmaceutical sector. The initial capital required for 3D printers, specialized software, and cleanroom environments is considerably higher than that for traditional tablet compression or capsule filling methods. Furthermore, the majority of 3D printers utilized in pharmaceuticals—such as fused deposition modeling (FDM), selective laser sintering (SLS), or inkjet Printing—demand precise regulation of temperature, humidity, and material handling, which escalates operational and maintenance expenses [25].

Raw materials, including pharmaceutical-grade polymers and excipients that are suitable for printing, are scarce and frequently more costly than standard formulation Components. Each formulation may necessitate customization, resulting in increased

research and development (R&D) expenditures. Additionally, the printing speed is relatively sluggish; producing thousands or millions of dosage forms daily (as seen in industrial-scale tablet presses) is currently unfeasible. The variability between batches and the requirement for in-process quality control further contribute to production costs [26].

From a scalability standpoint, maintaining uniformity and reproducibility becomes challenging as production volume rises, since even minor adjustments in printer calibration, layer thickness, or extrusion rate can influence drug dose precision. Although advancements in automation and multi-nozzle printing systems are underway to enhance throughput, the technology still lacks the efficiency required for mass production [27, 45].

7. Conclusion

Three-dimensional printing technology has emerged as a revolutionary manufacturing approach with the potential to redefine traditional fabrication processes across multiple disciplines. By enabling layer-by-layer construction from digital designs, 3D printing offers significant advantages such as design flexibility, rapid prototyping, customization, and reduced material waste. This review has discussed the fundamental principles of 3D printing along with major printing techniques, including fused deposition modeling, stereolithography, selective laser sintering, and inkjet-based methods, highlighting their working mechanisms, materials, advantages, and limitations. The expanding applications of 3D printing in pharmaceuticals, healthcare, biomedical engineering, and industrial manufacturing underscore its growing importance in modern science and technology. Despite its promising potential, challenges related to material limitations, process standardization, regulatory frameworks, and large-scale production remain. Continued research and technological advancements, particularly in smart materials, bioprinting, and integration with digital and artificial intelligence tools, are expected to overcome these barriers. Overall, three-dimensional printing technology is poised to play a crucial role in the future of personalized manufacturing and healthcare, offering innovative solutions that can significantly enhance efficiency, precision, and patient-centered outcomes.

Author Contribution

The authors contributed to the idea and design of the review, with drafting of the article, and revision of the article.

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