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NOVEL APPROACHES IN 3D PRINTED ORAL TABLETS FOR PERSONALIZED MEDICINE: A REVIEW

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ABSTRACT

Three-dimensional (3D) printing technology has emerged as a transformative approach in the pharmaceutical field, particularly in the development of personalized oral tablets. Conventional manufacturing techniques often fail to address individual patient needs such as age, genetic profile, disease condition, dose variability, and swallowing difficulties. In contrast, 3D printing offers precise control over tablet size, shape, drug dose, release pattern, and combination therapy, thereby supporting the concept of personalized medicine. This review highlights the novel approaches and recent advancements in 3D printed oral tablet formulations, emphasizing their potential to revolutionize patient-centric drug delivery systems. Various 3D printing techniques, including fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), inkjet printing, and semi-solid extrusion (SSE), have been extensively explored for pharmaceutical applications. These technologies enable the fabrication of complex dosage forms with immediate, sustained, delayed, or multi-drug release characteristics. The review also discusses the role of novel excipients, printable polymers, and computer-aided design in improving formulation performance and manufacturing efficiency. Special attention is given to the application of 3D printed tablets in pediatric, geriatric, and chronic disease management, where individualized therapy is highly beneficial. Furthermore, the approval of the first FDA-approved 3D printed drug, Spritam, has accelerated research interest in this field. Despite significant progress, challenges related to regulatory guidelines, printing accuracy, drug stability, large-scale production, and cost-effectiveness remain major concerns. This review summarizes the current status, advantages, limitations, and future perspectives of 3D printed oral tablets in personalized medicine. Overall, 3D printing represents a promising and innovative strategy for the advancement of tailored therapeutics and precision healthcare, offering improved patient compliance, therapeutic efficacy, and flexible pharmaceutical manufacturing.

KEYWORDS: 3D Printing, Personalized Medicine, Oral Tablets, Pharmaceutical Technology, Drug Delivery System, Fused Deposition Modeling, Patient-Centric Therapy, Precision Medicine.

INTRODUCTION

3D Printed Oral Tablets: - Three-dimensional (3D) printed oral tablets are innovative pharmaceutical dosage forms created layer by layer using advanced printing technology, akin to stacking microscopic building blocks. Unlike traditional mass-produced pills, 3D printing allows customization of size, shape, drug dosage, and release profile to suit individual patient needs. This approach is particularly beneficial for pediatric, geriatric, or patients with rare conditions requiring precise dosing. For instance, individuals with dysphagia can receive fast-dissolving tablets, enhancing adherence. As a cornerstone of personalized medicine, 3D printing tailors treatments to individual pharmacokinetics, moving away from one-size-fits-all solutions. Tablets are predominantly manufactured through three primary techniques, chosen based on the stability and flow properties of the drug.

A. Direct Compression: Direct compression is the simplest tablet manufacturing method, in which all

ingredients are uniformly blended and compressed directly into tablets without prior granulation. This technique is particularly suitable for drugs that are sensitive to heat and moisture. However, it is applicable to only about 20% of pharmaceutical formulations because many active ingredients and excipients lack sufficient flowability and compressibility on their own.

B. Wet Granulation: Wet granulation is the most widely used tablet manufacturing method, accounting for more than 70% of pharmaceutical formulations. In this process, a liquid binder is added to the powder blend to form granules, which are subsequently dried and compressed into tablets. This method enhances powder flow, improves content uniformity, and ensures consistent drug distribution within the final dosage form.

C. Dry Granulation (Slugging or Roller Compaction): Dry granulation is employed for drugs that are sensitive to moisture and heat. In this technique, powders are compressed into large compacts (slugs or ribbons) under high pressure and then milled into smaller granules before final tablet compression. This process improves flow properties and compressibility without the use of liquid binders or elevated temperatures.[2]

Figure 1: 3D Printed Oral Tablet

Figure 1 shows a 3D printed oral tablet produced using an additive manufacturing (3D printing) technology. In this process, a computer-aided design (CAD) model of the tablet is created, and the formulation containing the active drug and excipients is loaded into the printer. The 3D printer deposits the material layer by layer through a computer-controlled nozzle according to the programmed design. Each layer is precisely placed and fused with the previous one to form a solid structure. This layer-by-layer fabrication enables exact control over the tablet's shape, size, porosity, and drug dose. The printed tablet shown in the figure has a uniform structure, smooth surface, and accurate dimensions, highlighting the potential of 3D printing for personalized medicine and advanced drug delivery systems.

History of 3D Printed Oral Tablets

Early Foundations of 3D Printing (1980s–1990s)

1984–1986: Chuck Hull invents stereolithography (SLA), the first 3D printing technology, and founds 3D Systems. This patents the foundational layer-by-layer process. Late 1980s–1990s: Other techniques emerge, including fused deposition modeling (FDM) by Scott Crump (1989) and selective laser sintering (SLS). Early experiments explore photosensitive polymers and powders. 1990s: Pharmaceutical researchers begin adapting 3D printing for drug delivery, inspired by industrial uses. Initial concepts focus on controlled-release systems and precise deposition.

Pharmaceutical Exploration and Pioneering Work (2000s)

Early 2000s: MIT researchers (associated with Theriac's Inc.) develop binder jetting for pharmaceuticals. This involves spreading powder layers and selectively depositing binder to form porous structures—key for high-dose loading.

2000s–2010: Academic and industry patents grow, focusing on powder-based printing for oral dosage forms. Early studies demonstrate feasibility for orodispersible (fast-dissolving) tablets.

Break through Approval: Spritam® (2010s)

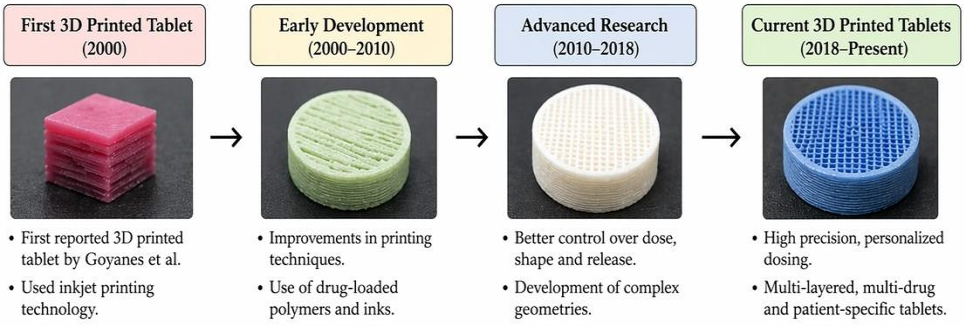
2015: The U.S. FDA approves Spritam® (levetiracetam) by Aprecia Pharmaceuticals—the world's first and, as of 2026, only fully FDA-approved 3D printed oral tablet. Spritam treats epilepsy seizures and uses Aprecia's proprietary ZipDose® technology (binder jetting) to create highly porous tablets (up to 1,000 mg dose) that disintegrate rapidly with minimal water. 2016: Spritam launches commercially, proving regulatory and manufacturing viability for 3D printed drugs. Late 2010s: Research expands globally. Universities (e.g., UCL School of Pharmacy) and companies explore extrusion-based methods (FDM, SSE) for polypills and personalized dosing.

Research Boom and Commercial Advancements (2020s)

2020: FabRx (UK) launches the M3DIMAKER™, the first commercial 3D printer designed specifically for personalized medicines. 2021–2024: Triastek (China) emerges as a leader, developing Melt Extrusion

Deposition (MED) technology. Multiple products enter pipeline. 2024–2025: Triastek receives FDA IND clearances (e.g., T20G for gastric retention in 2025) and opens one of the world's largest 3D printed pharmaceutical facilities in Nanjing, China (production license awarded 2025). 2025: Additional studies highlight cost reductions (e.g., FabRx research shows up to 35% savings for small-batch production) and collaborations (e.g., Triastek with BioNTech for RNA therapeutics).

Figure 2: History and Development of 3D Printed Oral Tablets



Difference Between First 3D Printed Tablet and Current 3D Printed Tablets		
First 3D Printed Tablet (2000)	Parameter	Current 3D Printed Tablets (2018–Present)
Inkjet printing	Printing technology	Inkjet, extrusion, SLA, SLS and other advanced techniques
Simple, single-layer structure	Structure	Multi-layered, complex 2D/3D structures
Limited materials	Materials	Wide range of printable polymers and excipients
Low drug loading	Drug loading	High drug loading capacity
Proof of concept	Purpose	Personalized medicine and controlled release

This figure indicates the evolution of 3D printed oral tablets from the first reported tablet in 2000 to the current advanced stage. It also shows the key differences between the first and current 3D printed tablets.

Current Status (2026)

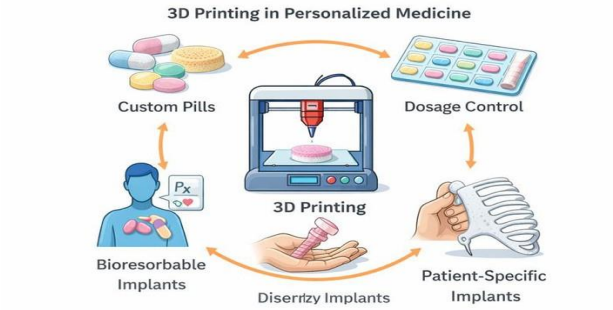
As of early 2026, Spritam® remains the only FDA-approved 3D printed oral drug. No new full approvals reported, though pipelines (e.g., Triastek's T19–T23 series) advance in clinical trials. Market growth accelerates, with projections estimating USD 370–400 million by 2026, driven by personalization and regulatory support (FDA's Emerging Technology Program).

Scientific Principle of 3D Printed Oral Tablets (Novel App roach for Personalized Medicine)

3D printed oral tablets are developed based on the principle of additive manufacturing (layer-by-layer fabrication), where a drug formulation is deposited in successive layers to build a solid dosage form according to a computer-aided design (CAD). Unlike conventional tablet manufacturing methods such as compression or granulation, this technology allows precise spatial placement of the drug and excipients within the tablet structure.

In this process, a digital model of the tablet is first designed using specialized software, which defines parameters such as shape, size, porosity, and internal geometry. The formulation containing the active pharmaceutical ingredient (API) and suitable excipients is then fed into a 3D printer. Depending on the technique used (e.g., inkjet printing, fused deposition modeling, stereolithography, or selective laser sintering), the material is deposited or solidified layer by layer. Each layer is accurately positioned and bonded with the previous one to form a complete tablet with uniform structure.

As a novel approach, 3D printing overcomes several limitations of traditional manufacturing, including lack of dose flexibility and inability to produce complex geometries. It allows fabrication of tablets with tailored doses, which is especially useful for pediatric, geriatric, and chronic disease patients who require individualized therapy. Despite its advantages, challenges such as high equipment cost, regulatory concerns, and material limitations still exist. However, ongoing research and technological advancements are expected to make 3D printed oral tablets a significant part of future pharmaceutical manufacturing.[3]



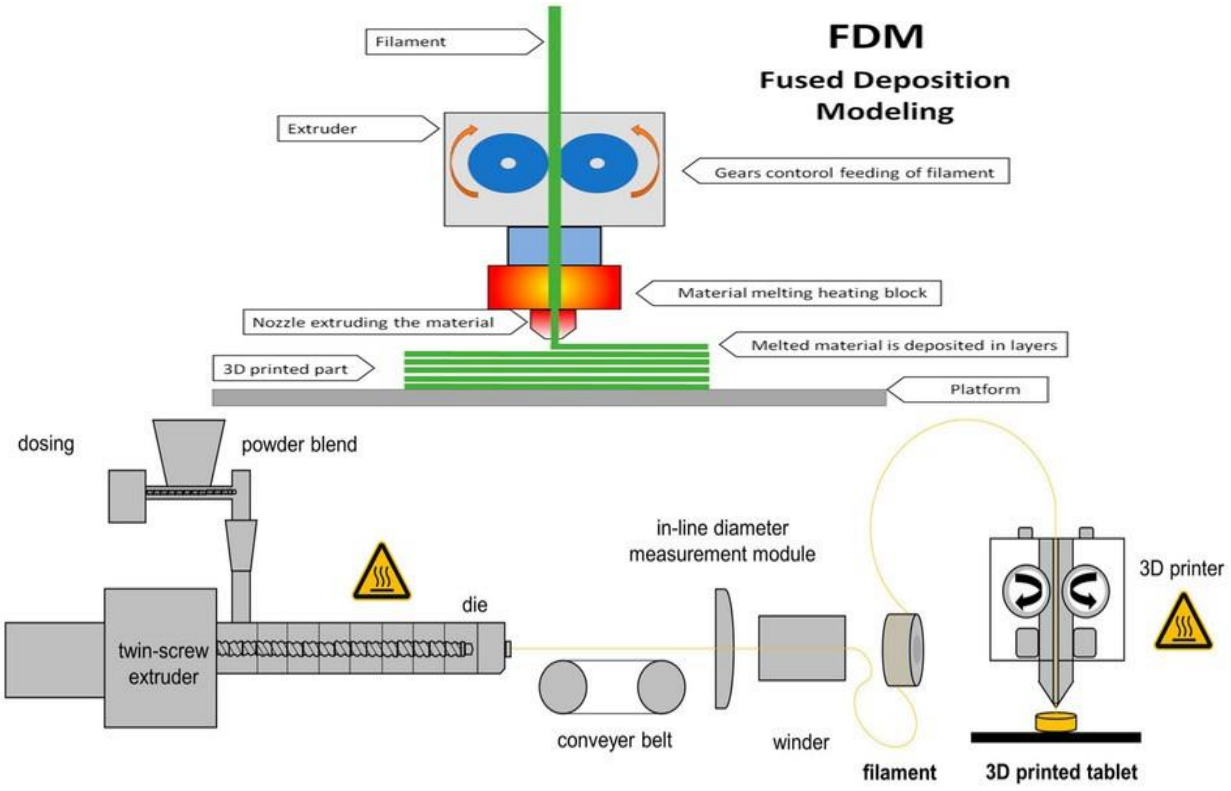
MAJOR 3D PRINTING TECHNOLOGIES FOR ORAL TABLETS

3D printing, also known as additive manufacturing, has emerged as a promising and innovative technology in pharmaceutical sciences for the fabrication of oral dosage forms. It allows precise control over drug dose, tablet geometry, and drug release characteristics. This technology is especially useful for developing personalized medicines tailored to individual patient needs. Several 3D printing techniques have been explored for oral tablet formulation, among which Binder Jetting, Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Stereolithography (SLA) are the most important.

1. Binder Jetting

Binder jetting is one of the earliest and most widely used techniques in pharmaceutical 3D printing. In this method, a liquid binding agent is selectively sprayed onto a powder bed containing drug and excipients. The binder causes the powder particles to adhere together, forming a solid layer. This process is repeated layer by layer until the final tablet is formed. This technique was used to manufacture the first FDA-approved 3D printed drug, Spritam (levetiracetam). Tablets produced by binder jetting are highly porous, which allows rapid disintegration and fast drug release. However, the mechanical strength of these tablets may be relatively low.

2.Fused Deposition Modeling (FDM)- Fused Deposition Modeling is a widely used extrusion-based technique. In this method, drug-loaded polymer filaments are heated and passed through a nozzle, where they are deposited layer by layer to form the tablet structure. The material solidifies upon cooling. FDM allows the production of tablets with complex geometries and controlled drug release profiles. By modifying the infill density and design, sustained or controlled release formulations can be achieved. However, high processing temperatures may not be suitable for heat-sensitive drugs.



3. Selective Laser Sintering (SLS)
Selective Laser Sintering is a laser-based technique in which a high-energy laser selectively fuses powdered materials to form a solid structure. The laser scans the powder bed according to the digital design and sinters the particles layer by layer.This method does not require a liquid binder and can produce tablets with good mechanical strength and uniformity. It also allows control over porosity and drug release. However, the use of high temperatures may affect drug stability.

4. Stereolithography (SLA)
Stereolithography is a photopolymerization-based technique that uses ultraviolet (UV) light to cure liquid resin into solid structures. The printer selectively exposes specific regions of the resin to UV light, forming each layer of the tablet. SLA offers very high precision and smooth surface finish, making it suitable for complex and detailed tablet designs. It enables accurate control of drug release patterns. However, the availability of biocompatible and safe photopolymers is a major limitation.[4]

BENEFITS OF 3D PRINTING IN ORAL TABLET FORMULATION
1. 3D printing enables the preparation of personalized oral dosage forms by allowing precise control over tablet dose, size, shape, and internal structure. This is especially useful for pediatric and geriatric patients who require dose adjustments and for patients needing specific pharmacokinetic profiles. Personalized tablets help in reducing dosing errors and improving therapeutic effectiveness.

2. The technology supports the development of polypills, in which multiple drugs can be combined into a single tablet. This approach is particularly beneficial in chronic conditions such as cardiovascular diseases and diabetes, where patients often take several medicines daily. Polypills reduce pill burden, simplify treatment regimens, and significantly improve patient adherence.

3. 3D printing allows the design of tablets with customized drug release profiles such as immediate release, sustained release, delayed release, and gastro-retentive systems. By altering tablet geometry and porosity, drug release can be controlled more effectively than with conventional manufacturing methods, leading to improved therapeutic outcomes.

4. Highly porous 3D printed tablets show rapid disintegration and are suitable for patients suffering from dysphagia or difficulty in swallowing. A well-known example is the FDA-approved 3D printed tablet Spritam, which rapidly disperses in the mouth without the need for water, improving patient comfort and compliance.

5. 3D printing enables on-demand and decentralized production of medicines in hospitals and pharmacies. This reduces dependence on large-scale centralized manufacturing, minimizes drug wastage, and helps overcome supply chain problems and medicine shortages, especially during emergencies or in remote areas.

6. Recent studies have demonstrated that 3D printing can be cost-effective for small-batch and personalized drug production, showing approximately 20–35% cost savings compared with conventional pharmaceutical manufacturing. Reduced material wastage, simplified processing steps, and elimination of large-scale storage contribute to improved cost efficiency.[5]

APPLICATIONS OF 3D PRINTING IN ORAL TABLET FORMULATION
3D printing has been successfully applied in the treatment of epilepsy and other neurological disorders through the development of high-dose, fast-dissolving tablets. A prominent example is the FDA-approved 3D printed tablet Spritam, which rapidly disintegrates in the mouth and is especially useful for patients who have difficulty swallowing and require high drug doses.

•In chronic diseases, 3D printing is being explored for the production of controlled-release and targeted drug delivery systems. Pharmaceutical companies such as Triastek are developing 3D printed tablets for anticoagulant therapy and ulcerative colitis, demonstrating the potential of this technology for long-term disease management and site-specific drug release.

•The technology is highly suitable for managing polypharmacy, where patients require multiple medications daily. 3D printing allows the fabrication of a single polypill containing several active pharmaceutical ingredients with different release patterns, which helps in the treatment of conditions such as hypertension and diabetes while reducing pill burden and improving patient adherence.

•In pediatric and geriatric care, 3D printing enables the development of patient-friendly dosage forms such as flavored tablets, chewable formulations, and mini-tablets with flexible dosing. These customized formulations improve acceptability, ensure accurate dosing, and enhance compliance in populations that are sensitive to conventional tablet sizes and tastes.

•For mental health disorders, 3D printing offers the possibility of personalized dosing to address variations in patient response and drug tolerance. Tablets can be designed with precise doses and modified release profiles to optimize therapy for conditions such as depression and anxiety, where individualized treatment is often required.[6]

CHALLENGES AND FUTURE OUTLOOK OF 3D PRINTING IN ORAL TABLET FORMULATION

Regulatory approval remains one of the major challenges for pharmaceutical 3D printing. Although regulatory agencies such as the U.S. Food and Drug Administration support innovation in additive manufacturing, they require strict validation of product quality, safety, and reproducibility. In more than ten years of development, only one 3D printed oral tablet (Spritam®) has received full regulatory approval, highlighting the complexity of meeting pharmaceutical regulatory standards.

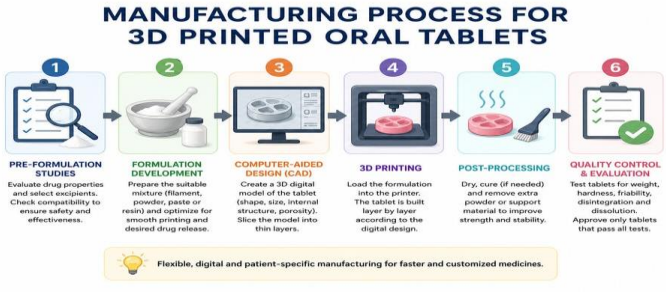
•Scalability is another important limitation, as current 3D printing processes are slower compared to conventional mass-production methods such as tablet compression. While traditional manufacturing can produce thousands of tablets per minute, most 3D printers operate at much lower speeds. However, recent industrial-scale facilities developed by companies such as Triastek aim to overcome this limitation by introducing automated and high-throughput 3D printing systems suitable for commercial production.

•The availability of suitable pharmaceutical-grade materials is still limited. There is a need for a wider range of polymers that are classified as GRAS (Generally Recognized as Safe) and are compatible with different 3D printing techniques. Many existing printing materials were originally developed for engineering purposes and are not ideal for drug formulation due to concerns related to toxicity, stability, and regulatory acceptance.

•Despite these challenges, the future outlook of pharmaceutical 3D printing is highly promising. From 2026 onwards, an increase in investigational new drug (IND) applications and regulatory approvals is expected as more clinical data become available and manufacturing standards improve. Integration of artificial intelligence with 3D printing is anticipated to optimize tablet design, predict drug release behavior, and accelerate formulation development.•Another important future direction is decentralized and point-of-care manufacturing, where hospitals and pharmacies may produce customized medicines on demand for individual patients. This approach can reduce dependence on centralized factories, improve access to medicines for rare diseases, and enhance the role of personalized therapy in routine clinical practice.(7)

Manufacturing Process for 3D Printed Oral Tablets

The manufacturing of 3D printed oral tablets involves a series of well-defined steps, starting from formulation design to final quality evaluation. Unlike conventional tablet compression, 3D printing relies on digital design and layer-by-layer fabrication, allowing precise control over dose, shape, and drug release characteristics. The overall process integrates pharmaceutical formulation science with computer-aided design and advanced printing technologies.



1. Pre-formulation Studies

The process begins with pre-formulation studies, where the physicochemical properties of the drug are evaluated. These include solubility, stability, melting point, particle size, and flow properties. The selection of suitable excipients such as polymers, binders, plasticizers, and disintegrants is also carried out. Compatibility studies (e.g., FTIR, DSC) ensure that there is no interaction between the drug and excipients. This step is essential for ensuring stability and effectiveness of the final dosage form.

2.Formulation Development

In this stage, the drug is incorporated into a formulation suitable for the selected 3D printing technique. The type of formulation depends on the printing method: Filaments for Fused Deposition Modeling (FDM) : Powder blends for Binder Jetting and Selective Laser Sintering (SLS) Liquid resins for Stereolithography (SLA) The formulation is optimized to achieve proper flowability, printability, mechanical strength, and desired drug release characteristics.

3. Computer-Aided Design (CAD)

A digital model of the tablet is created using computer-aided design (CAD) software. In this step, important parameters such as tablet size, shape, internal geometry, porosity, and infill density are defined. The design is then converted into a standard file format (such as STL) and further processed using slicing software, which divides the model into multiple thin layers for printing.

4. 3D Printing (Fabrication Step)

This is the core step in which the tablet is fabricated using a 3D printer. The prepared formulation is loaded into the printer, and the tablet is built layer by layer according to the digital design. Different printing technologies may be used.

Binder Jetting: liquid binder sprayed onto powder bed FDM: melted filament extruded through nozzle

SLS: powder fused using laser SLA: liquid resin cured using UV light.

This step determines the final structure, uniformity, and accuracy of the tablet.

5. Post-processing

After printing, the tablets may undergo post-processing steps to improve their quality and stability. These include: Drying to remove residual moisture or solvents. Curing (especially in SLA) to strengthen the structure Removal of excess powder (in powder-based methods). Post-processing ensures proper hardness, mechanical strength, and uniformity of the tablets.

6. Quality Control and Evaluation

The final tablets are subjected to standard quality control tests to ensure safety and efficacy. These include: Weight variation test, Hardness and friability test, Disintegration test, Dissolution test (drug release profile). These tests confirm that the tablet meets required pharmaceutical standards and performs as intended.[8]

Technology -Specific Manufacturing Process

Binder Jetting Technology (Commercially Used Method)

Binder jetting is one of the most widely used technologies in pharmaceutical 3D printing and is particularly suitable for producing highly porous tablets that dissolve rapidly in the mouth. This method is used in the manufacturing of the FDA-approved drug Spritam, developed using Aprecia Pharmaceuticals' ZipDose® technology.

Step 1: Powder Layer Deposition

The process begins by spreading a thin and uniform layer of powder containing the active drug and pharmaceutical excipients onto the build platform of the printer. The powder must have good flow properties to ensure even distribution and consistent layer thickness.

Step 2: Selective Binder Deposition

A computer-controlled print head moves across the powder layer and selectively deposits tiny droplets of liquid binder. These droplets bind the powder particles together in the specific pattern defined by the digital tablet design.

Step 3: Layer-by-Layer Construction

After the first layer is completed, the build platform lowers slightly and a new layer of powder is spread across the surface. The binder deposition process is repeated according to the digital design. Hundreds of such layers are gradually deposited, resulting in the formation of a three-dimensional tablet structure.

Step 4: Powder Removal (Depowdering)

Once the printing process is completed, the surrounding unbound powder is carefully removed from the printed tablets. This powder can often be recycled and reused in subsequent printing cycles, which helps reduce material waste.

Step 5: Drying and Final Processing

The printed tablets are then subjected to drying to remove residual solvent from the binder solution and to strengthen the tablet structure. The final tablets typically possess very high porosity, sometimes exceeding 90%, which allows them to disintegrate rapidly when placed in the mouth.[10]

Supply Chain of 3D-Printed Oral Tablets: How They Reach Patients

The supply chain of 3D-printed oral tablets differs significantly from conventional pharmaceutical manufacturing. Traditional tablet production relies on centralized manufacturing plants where large batches of medicines are produced, packaged, and then distributed through multiple intermediaries such as wholesalers, distributors, and pharmacies. In contrast, 3D printing technology allows decentralized and on-demand production, which can simplify the pharmaceutical supply chain and reduce storage and transportation requirements.

1. Digital Prescription and Data Transfer

The supply chain begins with the digital prescription generated by a healthcare professional. The physician determines the required drug dose, release profile, and formulation based on the patient's clinical condition. This information is converted into a digital design file (CAD model) that contains the exact structural parameters of the tablet such as layer thickness, geometry, and drug distribution within the tablet matrix.

These digital files are then transmitted securely to the printing facility, which may be located in a hospital pharmacy, compounding center, or specialized pharmaceutical manufacturing unit. This digital approach ensures that each tablet can be customized for individual patients, supporting the concept of personalized medicine (Norman et al., 2017).

2. Raw Material Supply The next stage involves the supply of pharmaceutical-grade raw materials, including active pharmaceutical ingredients (APIs) and excipients. These materials must meet strict quality standards such as Good Manufacturing Practice (GMP) and are typically classified as generally recognized as safe (GRAS) by regulatory authorities. Depending on the printing technology used, the materials may be prepared in different forms.

Powder blends for binder jetting. Polymer filaments for fused deposition modeling (FDM) Semi-solid pastes or hydrogels for extrusion-based printing. Proper material preparation is essential because the flow properties, particle size, and thermal stability of the materials directly influence the printing process and final tablet quality (Trenfield et al., 2019).

3. On-Demand Tablet Printing

Once the digital file and raw materials are available, the tablets are manufactured using a 3D printing system. The printer fabricates the tablet layer-by-layer according to the digital design. Unlike traditional batch manufacturing, this process enables on-demand production, meaning tablets are produced only when required. This significantly reduces the need for large inventories and decreases the risk of drug wastage due to expiration. Furthermore, different doses or combinations of drugs can be printed using the same system, allowing the development of polypills that combine multiple medications in a single tablet for improved patient compliance (Goyanes et al., 2015).

4. Post-Processing and Q uality Control

After printing, the tablets undergo several post-processing steps to ensure safety and quality. These may include: Drying to remove residual solvents or binders. Removal of excess powder in powder-bed printing methods, Mechanical strength testing, Dissolution and drug content analysis.

5. Distribution to Patients: - Once quality testing is completed, the tablets can be dispensed directly to patients. In decentralized manufacturing models, tablets may be printed directly in hospital pharmacies or community pharmacies, allowing patients to receive their medication almost immediately after prescription. This approach reduces multiple steps in the conventional supply chain such as: Large-scale warehousing. Long-distance transportation Bulk packaging**.** As a result, the supply chain becomes shorter, more flexible, and more responsive to patient needs.

6. Advantages of the 3D Printing Supply Chain

The supply chain of 3D-printed tablets offers several advantages compared with traditional pharmaceutical distribution systems: Personalized dosing tailored to individual patient requirements.

- Reduced inventory and storage costs
- Faster production and delivery of medicines Lower risk of drug shortages
- Reduced pharmaceutical waste

These benefits make 3D printing a promising approach for the future of precision medicine and patient-specific drug therapy.

7. Future Perspective

Advancements in digital manufacturing and regulatory frameworks are expected to further improve the supply chain of 3D-printed medicines. Researchers are currently exploring continuous printing systems, automated quality control, and point-of-care printing in hospitals. Such developments could transform pharmaceutical manufacturing from a centralized industrial model into a patient-centered, digital healthcare system.[11]

ADVANTAGES OF 3D PRINTED ORAL TABLETS

➢ **Personalized Drug Therapy**

3D printing allows tablets to be designed according to the specific needs of individual patients. The dose, size, shape, and even flavor of the tablet can be modified to suit different age groups such as children and elderly patients. This approach is especially useful in precision medicine where patients require unique pharmacokinetic profiles or dose adjustments. Personalized tablets can help optimize therapeutic outcomes and reduce the risk of dosing errors. Personalized drug manufacturing is one of the most promising applications of pharmaceutical 3D printing.[12]

➢ **Development of Polypills**

3D printing technology enables the production of polypills, which contain multiple drugs in a single tablet with different compartments or layers. Each drug can be released at a specific time or location in the body. This approach is particularly beneficial for patients suffering from chronic diseases such as hypertension, diabetes, or cardiovascular disorders who need to take several medications daily. By combining multiple drugs into one dosage form, pill burden is reduced and patient adherence to therapy improves significantly.

➢ **Ability to Create Complex Drug Release Profiles**

Unlike conventional tablet manufacturing methods, 3D printing makes it possible to design tablets with complex internal structures. These structures allow precise control over drug release patterns such as immediate release, sustained release, delayed release, or site-specific release in the gastrointestinal tract. For example, gastro-retentive or floating tablets can be designed to remain in the stomach for a longer period, improving drug absorption and therapeutic effectiveness.

➢ **Rapid Disintegration with High Drug Loading**

3D-printed tablets can be produced with highly porous structures, which allows them to disintegrate very quickly in the mouth or stomach. This feature is particularly useful for patients who have difficulty swallowing conventional tablets. A well-known example is Spritam, the first FDA-approved 3D-printed drug, which can contain doses up to 1000 mg while still dissolving within seconds when taken with a small amount of water.

➢ **On-Demand Manufacturing**

One of the most significant advantages of 3D printing is the possibility of producing medicines on demand. Instead of mass manufacturing in large factories, tablets can potentially be printed in hospitals or pharmacies when needed. This approach reduces drug wastage, simplifies the supply chain, and allows rapid preparation of patient-specific medicines. On-demand manufacturing is particularly valuable for rare diseases and emergency treatments.

➢ **Cost Efficiency for Small-Batch Production**

Recent research suggests that 3D printing can reduce production costs for small-volume batches of medicines. Since the technology eliminates the need for large-scale manufacturing equipment and complex tooling, it becomes economically advantageous for personalized medicines and drugs used for rare diseases. Studies have reported potential cost savings of approximately 20–35% when producing small batches using additive manufacturing techniques.

➢ **Environmentally Friendly Manufacturing**

3D printing uses a layer-by-layer manufacturing process, which means only the required amount of material is used to produce the tablet. This reduces raw material wastage compared with traditional pharmaceutical manufacturing methods such as compression or molding. As a result, additive manufacturing can contribute to more sustainable and environmentally friendly pharmaceutical production processes.(par 13).

DISADVANTAGES OF 3D PRINTED ORAL TABLETS

➢ **Regulatory Challenges**

One of the major limitations of pharmaceutical 3D printing is the complex regulatory pathway required for approval. Regulatory agencies demand strict validation of manufacturing processes, product quality, and reproducibility before allowing commercial use. Despite many years of research and development in this field, only one 3D-printed oral tablet, Spritam, has received approval from the U.S. Food and Drug Administration. This highlights the challenges associated with demonstrating consistent quality and safety for printed pharmaceutical products.

➢ **Limited Scalability**

Although 3D printing offers flexibility and customization, its production speed is relatively slow compared with conventional tablet manufacturing methods such as compression and granulation. Traditional pharmaceutical equipment can produce thousands of tablets per minute, while most current 3D printing systems fabricate tablets individually or in small batches. This limitation makes large-scale commercial production challenging and restricts the technology mainly to personalized or small-batch medicines.

➢ **Material Restrictions**

The availability of suitable pharmaceutical-grade materials for 3D printing is still limited. Many polymers used in additive manufacturing were originally developed for engineering applications rather than pharmaceutical formulations. In addition, some printing techniques such as fused deposition modeling involve high temperatures, which may degrade heat-sensitive drugs. Therefore, only certain active pharmaceutical ingredients and excipients are compatible with specific 3D printing technologies.

➢ **Quality Control and Reproducibility Issues**

Ensuring consistent quality in 3D-printed tablets can be challenging due to potential variations between printed layers. Differences in powder distribution, binder deposition, or extrusion rates may result in defects such as uneven drug content, weak mechanical strength, or structural irregularities. As a result, advanced analytical techniques and strict process monitoring are required to maintain uniformity and ensure regulatory compliance.

➢ **Need for Post-Processing Steps**

Many 3D printing technologies require additional processing steps after the printing stage. These steps may include drying, removal of excess powder (depowdering), curing, or thermal treatment to improve mechanical strength and stability. Such post-processing procedures increase the total manufacturing time and add complexity to the production workflow.

➢ **Risk of Counterfeiting and Data Security Issues**

Since 3D printing relies on digital design files for tablet production, there is a potential risk of unauthorized copying or distribution of these designs. If digital files are not adequately protected, counterfeit medicines could be produced easily. Therefore, strong cybersecurity measures and secure digital transmission systems are necessary to prevent misuse of pharmaceutical design data.

➢ **Limited Long-Term Stability Data**

Pharmaceutical 3D printing is still an emerging technology, and long-term data regarding the stability, shelf life, and storage conditions of printed medicines remain limited. Additional studies are required to evaluate how different printing methods and materials influence the chemical stability and therapeutic

effectiveness of drugs during extended storage periods.[14]

APPROVED PRODUCTS AND PIPELINES IN 3D-PRINTED ORAL TABLETS

At present, only one oral drug produced using 3D printing technology has received full regulatory approval for clinical use. The first and most notable example is Spritam, developed by Aprecia Pharmaceuticals. This medicine contains the antiepileptic drug levetiracetam and was approved in 2015 by the U.S. Food and Drug Administration. It represents a significant milestone because it was the first pharmaceutical product manufactured using additive manufacturing technology to reach the market. Spritam® is used as an adjunctive therapy for various seizure disorders, including partial-onset seizures, myoclonic seizures, and primary generalized tonic-clonic seizures in patients aged four years and above. The tablet is produced using the ZipDose® binder jetting technology, which creates a highly porous structure capable of holding large drug doses while still dissolving rapidly. Due to its unique internal structure, the tablet disintegrates within seconds when taken with a small amount of water, making it particularly beneficial for patients who experience difficulty swallowing conventional tablets. Another notable feature of this product is its ability to accommodate very high drug loading. Tablets are available in strengths of 250 mg, 500 mg, 750 mg, and 1000 mg, which is considerably higher than the dose capacity of many conventional orally disintegrating tablets. The product is also flavored to improve palatability and patient acceptance.

Recent updates have further expanded its clinical use. In 2025, the product labeling was updated to allow administration through nasogastric (NG) and gastrostomy (G) feeding tubes, which is beneficial for hospitalized patients who cannot take medications orally. Despite extensive research in pharmaceutical 3D printing, Spritam® remains the only fully approved 3D-printed oral tablet worldwide as of 2026, making it the primary benchmark for future developments in this field.[15,16]

NOVEL APPROACHES IN PERSONALIZED MEDICINE

One of the most promising aspects of pharmaceutical 3D printing is its potential to support personalized medicine. Traditional drug manufacturing generally produces standardized tablets with fixed doses, which may not be optimal for every patient. In contrast, 3D printing enables tablets to be designed according to individual therapeutic requirements, similar to how clothing can be tailored for a specific person.

By modifying digital design parameters, healthcare professionals could theoretically adjust the drug dose, release profile, and tablet geometry for individual patients. For example, pediatric patients might receive smaller tablets with lower doses and pleasant flavors, while geriatric patients might receive highly porous tablets that dissolve rapidly in the mouth. Similarly, patients with chronic conditions requiring multiple medications could receive polypills containing several drugs within a single tablet structure.

Despite these advantages, further clinical studies and regulatory developments are required before personalized 3D-printed medicines become widely available in routine healthcare practice.[17,19]

REGULATORY ASPECTS FOR 3D PRINTED ORAL TABLETS

The regulatory evaluation of 3D-printed medicines is an important consideration for the successful commercialization of this technology. Because additive manufacturing introduces new production methods and complex internal tablet structures, regulatory agencies require detailed documentation of the manufacturing process, product consistency, and quality control measures. The first regulatory milestone in this area occurred when Spritam, developed by Aprecia Pharmaceuticals, received approval from the U.S. Food and Drug Administration in 2015. This approval demonstrated that 3D-printed pharmaceuticals could meet regulatory standards for safety, efficacy, and manufacturing quality. Regulatory authorities now emphasize the importance of process validation, reproducibility, and real-time monitoring when evaluating 3D printing systems for drug manufacturing. Manufacturers must demonstrate that each printed tablet contains the correct drug dosage, uniform structure, and consistent release characteristics. In addition, digital design files and printing parameters must be carefully controlled to prevent variability between production batches. As research and clinical trials continue, regulatory frameworks are expected to evolve further to accommodate personalized medicines produced using additive manufacturing. Clear guidelines for quality assurance, digital file security, and decentralized production may eventually allow hospitals and pharmacies to manufacture certain medicines using approved 3D printing systems.[20]

Market Analysis and Forecasts for 3D-Printed Oral Tablets

The market for 3D-printed oral tablets is still in the early stage of commercialization, but it is expanding rapidly due to increasing interest in personalized medicine and advanced drug-delivery technologies. Pharmaceutical companies, research institutes, and healthcare systems are investing heavily in additive manufacturing because it enables customized drug doses, complex release profiles, and rapid prototyping of new formulations. As the demand for patient-specific therapy continues to grow, the commercial potential of 3D-printed medicines is expected to increase significantly in the coming years. Recent market studies indicate that the global market for 3D-printed drugs was valued at approximately USD

338–368 million around 2024–2025. The market is projected to grow steadily as pharmaceutical companies adopt additive manufacturing technologies for specialized drug products.

Forecast reports suggest that the market may reach around USD 789 million by 2034, reflecting continuous expansion driven by technological advancements and increasing clinical applications.

Several key factors are contributing to this growth. One of the most important drivers is the increasing demand for personalized medicine. Conventional pharmaceutical manufacturing produces standardized tablets with fixed doses, which may not be optimal for all patients. In contrast, 3D printing allows modification of drug dosage, tablet shape, and release profile according to individual patient needs. This capability is particularly useful in fields such as neurology, pediatrics, and geriatric medicine, where patient-specific dosing can significantly improve treatment outcomes. From a regional perspective, North America currently dominates the 3D-printed drug market due to strong research infrastructure, regulatory support, and the presence of pioneering companies such as Aprecia Pharmaceuticals, which developed the first approved 3D-printed drug Spritam. However, the Asia-Pacific region is expected to experience the fastest growth in the coming years because of increasing pharmaceutical innovation and investments in additive manufacturing facilities.

As regulatory frameworks evolve and more pharmaceutical-grade printing materials become available, the commercialization of 3D-printed oral tablets is expected to accelerate significantly.
Overall, the market outlook for 3D-printed oral tablets is highly promising. Continued technological innovation, increasing demand for personalized therapies, and growing investment from pharmaceutical companies are expected to drive strong growth in this sector over the next decade .[22]

PROBLEMS AND CHALLENGES OF 3D-PRINTED ORAL TABLETS

Although 3D-printed oral tablets provide innovative solutions such as personalized dosing and complex drug-release patterns, several challenges still limit their widespread adoption in pharmaceutical manufacturing. These challenges are mainly related to production efficiency, material limitations, quality control, and regulatory uncertainty. Overcoming these barriers is essential before this technology can be used on a large commercial scale.

Scalability and Production Limitations

One of the major challenges of pharmaceutical 3D printing is the difficulty in achieving large-scale production. Unlike conventional tablet manufacturing, where millions of tablets can be produced within a short time using high-speed compression machines, 3D printing follows a layer-by-layer deposition process. In addition, several operational factors can reduce printing efficiency. Problems such as nozzle clogging, inconsistent powder spreading, or interruption in binder deposition may occur during printing. These technical issues can lead to defective tablets or interruptions in the production process.

Furthermore, some printing technologies require high energy consumption or specialized environmental conditions, which may increase manufacturing costs. Because of these limitations, 3D printing is currently considered more suitable for small-batch production, clinical trials, or personalized medicines rather than mass manufacturing.

Material and Drug Compatibility Issues

Another important challenge is the limited availability of suitable pharmaceutical materials for 3D printing. The excipients used in additive manufacturing—such as polymers, binders, and plasticizers—must be compatible with both the printing technology and the active pharmaceutical ingredient (API). However, many materials commonly used in industrial 3D printing are not approved for pharmaceutical use or are not classified as Generally Recognized as Safe (GRAS). This restricts the selection of excipients that can be safely incorporated into drug formulations.

Mechanical Strength and Quality Control Issues

Maintaining consistent quality in 3D-printed tablets is another major concern. Because tablets are produced by depositing successive layers of material, the bonding between these layers may sometimes be weak. Poor interlayer adhesion can reduce the mechanical strength of the final product, making tablets fragile and more susceptible to breakage during handling, packaging, or transportation. Additionally, printed tablets often show surface roughness and variability in internal structure. These variations may affect critical quality attributes such as hardness, friability, drug content uniformity, and dissolution rate. Environmental factors like humidity and temperature during printing can also influence the quality of the final product. In many cases, additional post-processing steps such as drying, curing, or depowdering are required to improve tablet stability and performance. However, these extra steps may introduce further variability in the manufacturing process. This requirement becomes even more challenging if 3D printing is implemented in decentralized locations such as hospital pharmacies. In such cases, maintaining Good Manufacturing Practice (GMP) compliance, controlling digital design files, and ensuring secure data handling are essential.[23]

Infection Causes and Risks

3D-printed oral tablets are designed for safe oral administration and rapid dissolution in the gastrointestinal tract. Therefore, the tablets themselves do not inherently cause infections in patients. For

example, Spritam is formulated to disintegrate within seconds when taken with a small amount of water, which reduces the possibility of microbial growth during use. Most potential risks associated with infection are related to the manufacturing process or handling conditions rather than the tablet once it is consumed.

Contamination during Production

One possible source of risk is contamination during the production stage. In pharmaceutical 3D printing, equipment such as printers, nozzles, and material reservoirs must be thoroughly cleaned between manufacturing cycles. If cleaning and validation procedures are inadequate, cross-contamination may occur. This is particularly relevant in technologies such as Fused Deposition Modeling, where the same extrusion nozzle may be used for multiple drug-loaded filaments. Without proper sanitation, residues from previous materials or microbial contaminants could affect the next batch of tablets.

The risk of contamination also increases when printing is performed outside controlled pharmaceutical environments. Facilities that do not follow Good Manufacturing Practice (GMP) guidelines may lack strict environmental monitoring, sterile airflow systems, or validated cleaning protocols. However, when pharmaceutical manufacturing standards are properly implemented, the likelihood of microbial contamination remains very low.

Microbiological Stability

Compared with liquid oral formulations, solid dosage forms such as tablets generally provide better microbiological stability because they contain minimal water content. Similarly, many 3D-printed tablets maintain low moisture levels, which reduces the ability of microorganisms to grow. As a result, the risk of microbial contamination during storage is typically lower than in liquid medicines. Nevertheless, improper storage conditions—such as exposure to high humidity, contaminated packaging materials, or the use of non-sterile excipients—may still introduce microorganisms into the product. Therefore, maintaining appropriate storage conditions and using pharmaceutical-grade raw materials is essential to ensure the microbiological safety of the tablets.

Risk Mitigation and Safety Measures

In regulated pharmaceutical settings, infection risks associated with 3D-printed tablets are minimized through strict quality-control procedures. Regulatory authorities such as the U.S. Food and Drug Administration require manufacturers to validate all production steps, including equipment cleaning, environmental monitoring, and microbiological testing. These controls ensure that printed tablets meet the same safety standards as conventionally manufactured drugs. Additional preventive measures include the use of sterile or pharmaceutical-grade raw materials, controlled manufacturing environments, and regular microbiological testing of finished products. Special care is also necessary if 3D printing is performed in decentralized locations such as hospital pharmacies. In such settings, standardized operating procedures and trained personnel are required to maintain product quality and prevent contamination.

Overall, current evidence indicates that infection risks associated with 3D-printed oral tablets are very low and are primarily related to manufacturing or handling conditions rather than the tablets themselves.[24]

SIDE EFFECTS AND RISKS OF 3D-PRINTED ORAL TABLETS

The side effects associated with 3D-printed oral tablets are generally related to the active pharmaceutical ingredient (API) rather than the printing technology itself. In other words, the safety profile of the medicine depends mainly on the drug it contains. For example, Spritam, which contains levetiracetam, may produce side effects such as drowsiness, dizziness, fatigue, or mood changes, similar to conventionally manufactured levetiracetam tablets. These effects are caused by the pharmacological action of the drug and not by the 3D printing process used to manufacture the tablet.

Interestingly, 3D printing technology may actually help reduce certain drug-related side effects. Because additive manufacturing allows precise control over tablet structure and drug dose, it enables the development of personalized medications tailored to the needs of individual patients. By adjusting the dosage and drug-release profile, healthcare providers may be able to avoid problems such as overdosing or underdosing, which are common causes of adverse drug reactions in conventional fixed-dose medicines.

Drug Interactions in Multi-Drug Formulations

One of the promising applications of 3D printing in pharmaceutical science is the development of polypills—tablets that contain multiple drugs in a single dosage form. While this approach can simplify treatment for patients who take several medications, it also introduces the possibility of interactions between different active ingredients or between drugs and excipients used in the printing process.

Public Concerns and Long-Term Safety

Public perception also plays an important role in the acceptance of new pharmaceutical technologies. Some surveys have shown that patients and healthcare professionals may initially express concerns about potential side effects of 3D-printed medicines. However, many of these concerns are related to unfamiliarity with the technology rather than evidence of actual risks.

Cost of Manufacturing 3D-Printed Oral Tablets

The manufacturing cost of 3D-printed oral tablets is an important factor that influences their adoption in the

pharmaceutical industry. Several studies conducted between 2022 and 2025 have evaluated the production cost of 3D-printed tablets, particularly using model drugs such as hydrocortisone. These analyses generally estimate the cost per tablet by including expenses related to raw materials, labor, equipment depreciation, facility overhead, and quality assurance procedures. However, they usually exclude research and development costs, regulatory approval expenses, and distribution costs.

When converted to Indian currency using an approximate exchange rate of 1 € ≈ ₹108, most studies suggest that the per-tablet manufacturing cost of 3D-printed medicines ranges between ₹170 and ₹340, depending on the printing technology used, production efficiency, and batch size. In countries like India, the cost may be lower because of reduced labor expenses and locally sourced materials. For example, in regions such as Rewa, labor costs in pharmaceutical compounding or hospital pharmacies may range from ₹100 to ₹200 per hour, which is significantly lower than labor costs reported in European studies. As a result, the estimated manufacturing cost for small-batch production in India could decrease to approximately ₹130–₹220 per tablet. However, certain factors may offset these savings. Import duties on specialized 3D printing equipment, the need for pharmaceutical-grade materials, and compliance with regulatory requirements from authorities such as the Central Drugs Standard Control Organization may increase operational expenses.

Therefore, while labor costs may be lower in developing countries, infrastructure and regulatory compliance costs still play a significant role in determining the overall manufacturing expense.

Cost Components of 3D-Printed Tablets

A detailed cost analysis was reported in a 2022 case study involving M3DICORT, a sustained-release hydrocortisone tablet produced using Fused Deposition Modeling in a hospital pharmacy setting. The study evaluated various cost components involved in the production of individual tablets.

1. Personnel Costs

Personnel expenses form the largest portion of the manufacturing cost. These costs include the time required for filament extrusion, printer setup, and the printing process itself. On average, personnel costs ranged from ₹138 to ₹214 per tablet, depending on the efficiency of the process. For example, extrusion of the drug-loaded filament required approximately 0.64 minutes per tablet, while the actual printing process required about 0.5 minutes per tablet when producing around 120 tablets per hour.

2. Material Costs

Material costs mainly include the active pharmaceutical ingredient and excipients such as pharmaceutical polymers. Commonly used polymers include polyvinyl alcohol (PVA) and hydroxypropyl methylcellulose (HPMC). These materials contribute a relatively small portion of the total cost, typically around ₹14 to ₹16 per tablet.

3. Equipment Costs

Equipment costs are calculated based on the depreciation of the 3D printer and filament extruder over their expected operational lifetime, usually estimated at about 10 years. Maintenance expenses are also included in this category. On average, equipment costs range from ₹7 to ₹18 per tablet.

4. Facility and Operational Costs

Facility costs include expenses related to the manufacturing environment, such as electricity, workspace, environmental controls, and general overhead. These costs typically range between ₹18 and ₹34 per tablet, depending on the facility setup and operational scale.

5. Quality Assurance (QA) Costs

Quality assurance procedures are essential to ensure that each printed tablet meets pharmaceutical standards. These procedures include process validation, documentation, and analytical testing. QA costs are usually estimated at 5–10% of staff time, which corresponds to approximately ₹3 to ₹7 per tablet.

Comparison with Traditional Compounding

Another study using Semi-Solid Extrusion to produce hydrocortisone tablets reported manufacturing costs below ₹325 per tablet for both immediate-release and sustained-release formulations. These costs are comparable to those of traditional pharmacy compounding for small-batch medicines.

However, 3D printing offers several additional advantages over conventional compounding techniques. The technology enables precise dose customization, improved drug-release control, and reduced formulation variability. In some cases, especially for specialized doses or personalized treatments, 3D printing may reduce manufacturing costs by 20–35% compared with conventional capsule preparation methods.

Overall Economic Perspective

Although the cost of producing individual tablets through 3D printing may initially appear higher than mass-produced conventional tablets, the technology becomes economically advantageous in scenarios involving personalized medicine, rare diseases, pediatric dosing, or hospital-based on-demand manufacturing. As printing technologies become more efficient and pharmaceutical-grade materials become widely available, the cost of 3D-printed oral tablets is expected to decrease further, improving their feasibility for broader clinical applications.[25]

CONCLUSION

The development of 3D printed oral tablets represents a transformative advancement in modern pharmaceutical science, particularly in the field of personalized medicine. Traditional pharmaceutical manufacturing methods typically rely on mass production techniques that provide standardized drug dosages for the general population. However, these approaches often fail to address the specific therapeutic needs of individual patients, leading to issues such as under-dosing, over-dosing, and reduced treatment effectiveness. In contrast, 3D printing technology offers a highly flexible and innovative solution by enabling the fabrication of oral tablets with precise control over drug dosage, release profiles, geometry, and internal structure.

One of the most significant advantages of 3D printed oral tablets is their ability to support personalized drug therapy. Through advanced design software and digital modeling, tablets can be customized to deliver patient-specific doses based on factors such as age, weight, metabolism, disease severity, and genetic profile. This level of personalization has the potential to significantly improve therapeutic outcomes while reducing the risk of adverse drug reactions. For example, patients with chronic diseases such as epilepsy, cardiovascular disorders, or diabetes may benefit greatly from customized medications that meet their exact pharmacological requirements.

Another major innovation associated with 3D printing in pharmaceuticals is the development of complex drug delivery systems. Using technologies such as fused deposition modeling (FDM), binder jet printing, stereolithography (SLA), and semi-solid extrusion (SSE), researchers can fabricate tablets with intricate internal architectures. These structures allow the creation of immediate release, sustained release, delayed release, and multi-drug combination tablets within a single dosage form. Such advancements can simplify treatment regimens for patients who require multiple medications, thereby improving medication adherence and overall treatment efficiency.

The approval of Spritam® (levetiracetam) by the U.S. Food and Drug Administration (FDA) marked a major milestone in the pharmaceutical application of 3D printing technology. This approval demonstrated that 3D printed medications could meet regulatory standards for safety, quality, and efficacy. Since then, significant research efforts have focused on expanding the applications of 3D printing in drug delivery, exploring new printable materials, improving printing accuracy, and developing scalable manufacturing processes.

Despite its immense potential, several challenges still limit the widespread adoption of 3D printed oral tablets in the pharmaceutical industry. One of the key challenges involves material compatibility, as only a limited number of pharmaceutical excipients and polymers currently possess the necessary properties for successful 3D printing. In addition, regulatory guidelines for 3D printed drugs are still evolving, which creates uncertainty for large-scale commercial implementation. Other challenges include maintaining consistent product quality, ensuring long-term stability of printed tablets, and optimizing manufacturing speed to meet industrial production demands.

Future research is expected to focus on overcoming these challenges through the integration of advanced materials, artificial intelligence, and digital health technologies. Artificial intelligence and machine learning may help optimize drug formulation design, predict drug release patterns, and automate personalized dosage selection. Furthermore, the integration of 3D printing with hospital pharmacies and on-demand drug manufacturing systems could enable healthcare providers to produce patient-specific medications directly at the point of care.

In conclusion, 3D printed oral tablets represent a promising and revolutionary approach for the future of pharmaceutical manufacturing and personalized medicine. By enabling precise drug customization, complex dosage designs, and improved patient-centric therapies, this technology has the potential to reshape the way medications are developed and delivered. Although several technical and regulatory challenges remain, continued advancements in research, materials science, and digital technologies are expected to accelerate the adoption of 3D printing in pharmaceutical applications, ultimately paving the way for a new era of individualized healthcare.[26]

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