3D PRINTING IN PHARMACEUTICAL FORMULATIONS

Reshaping the medicine, layer by layer.

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Abstract*-- Three-dimensional printing is transforming how medicines are made, shifting the pharmaceutical industry from large-scale, standardized production to a flexible, digitally driven model centred on individual patient needs. Instead of producing fixed-dose tablets for the general population, additive manufacturing allows for creating personalized medications tailored to each patient's specific requirements. This approach enables precise dose control, customized release profiles, unique tablet shapes, and even the integration of multiple drugs into one dosage form improvements that greatly benefit children, elderly patients, and those managing complex treatment plans. Beyond personalizing medicine, 3D printing unlocks vast design possibilities. It can produce intricate internal structures that influence how drugs dissolve and are absorbed, incorporate new types of excipients, and accelerate drug development by making it easier to test prototypes quickly. Various additive manufacturing methods such as Fused Deposition Modelling, Stereolithography, and Selective Laser Sintering are being refined for pharmaceutical use, each offering distinct advantages in accuracy, production speed, and material compatibility. Another groundbreaking direction is decentralized drug manufacturing. By installing small-scale 3D printing systems in hospitals, clinics, and remote locations, it becomes possible to produce medicines on demand right where they're needed. This distributed model could revolutionize emergency care, rare disease treatment, and healthcare delivery in resource-limited settings. Although challenges in quality control, regulation, and technology still exist, steady progress is being made. Advances in printable materials, digital design tools, and biocompatible substrates are rapidly bridging the gap between experimental research and real-world medical use. The combination of medical science, digital fabrication, and advanced materials is redefining how we design, produce, and deliver medicines marking a pivotal step toward the era of truly personalized health care.

***Index Terms*--3D Printing, Additive manufacturing, Personalized medicine, Inkjet printing, Poly-pills.**

I. Introduction

3D printing, or additive manufacturing, is an emerging and innovative approach in pharmaceutical development that allows for the precise fabrication of drug dosage forms. By constructing medications layer by layer from digital design models, this technology offers enhanced control over the physical structure, drug load, and release mechanisms of the final product. Unlike conventional production methods that produce uniform doses, 3D printing enables the development of customized treatments tailored to the specific needs of individual patients.

Figure1.*Schematic representation of 3D printing process illustrating layer-by-layer fabrication of cylindrical structures using an extrusion-based printer.*

The adoption of 3D printing technology in pharmaceutical sciences represents a significant innovation in medication design, manufacturing, and delivery. In contrast to traditional mass-production techniques that generate standardized dosage forms, 3D printing also known as additive manufacturing facilitates the development of personalized drug formulations tailored to the specific requirements of individual patients. This approach can enhance therapeutic effectiveness, minimize adverse effects, and boost patient adherence to treatment. Furthermore, 3D printing allows for the integration of multiple drugs into a single dosage unit, which is especially beneficial for managing complex or long-term medical conditions. As technological advancements continue, 3D printing is expected to revolutionize drug delivery by enabling flexible, on-demand production of individualized medications.[1]

The pharmaceutical sector began to seriously investigate the use of 3D printing after the U.S. Food and Drug Administration (FDA) approved Sprit am® (levetiracetam) in 2015—the first medication produced through 3D printing. Since then, advancements have broadened its application across various dosage forms, including oral pills, transdermal patches, and implantable devices. The key advantages of 3D printing in this field include minimizing the use of inactive ingredients, integrating multiple active compounds into a single "polypill," and enabling personalized, on-demand drug manufacturing at hospitals, pharmacies, or even remote locations. Additionally, it supports innovation in how drugs are released in the body allowing for tailored profiles such as immediate, delayed, or multi-phase release and despite its promise, challenges such as regulatory approvals, production scalability, and material compatibility still hinder widespread adoption. Nonetheless, continuous advancements in technology and formulation science are paving the way for 3D printing to play a major role in future drug delivery systems.[2]

II. Types of 3D printing

3D printing has transformed pharmaceutical formulation by enabling the creation of personalized medications, intricate drug release mechanisms, and novel dosage forms. This technology facilitates the production of customized drugs tailored to individual patient needs, allowing for precise control over dosage and release profiles. It also supports the development of complex drug delivery systems that can release medications at controlled rates or in response to specific physiological conditions.

A. Fused Deposition Modelling (FDM)
B. Inkjet Printing
C. Stereo-lithography (SLA)
D. Selective Laser Sintering (SLS)
E. Binder Jetting
F. Semi-Solid Extrusion (SSE)

A. Fused Deposition Modelling (FDM

1) Principle

Fused Deposition Modelling (FDM) is a 3D printing technique where a thermoplastic material is melted and extruded through a heated nozzle to build structures layer by layer. In pharmaceutical applications, drug-loaded filaments made from polymers and active pharmaceutical ingredients (APIs) are used to print solid dosage forms. This method allows precise control over the shape, size, and drug release characteristics of the medicine. It supports the production of personalized medications tailored to individual patient needs. FDM is valued for its flexibility, ease of use, and ability to produce complex dosage designs. However, it requires careful selection of materials to ensure stability and compatibility. Regulatory considerations and reproducibility are also crucial for clinical adoption.[3]

2) Materials used

a) Polymers (Carriers/Excipients): These are used as matrices to carry the drug and help in forming the filament. Examples: Polyvinyl Alcohol (PVA), polylactic Acid (PLA), Hydroxypropyl Methylcellulose (HPMC), Eudragit, polycaprolactone (PCL), ethyl Cellulose.
b) Plasticizers: Added to improve filament flexibility and reduce brittleness. Examples: Polyethylene Glycol (PEG), Tri ethyl Citrate (TEC), Glycerol.
c) Active Pharmaceutical Ingredients (APIs): APIs are uniformly mixed with the polymers during hot-melt extrusion (HME) to prepare printable filaments. Examples: Paracetamol, ibuprofen, theophylline, caffeine and metoprolol.

3) Working

FDM is a layer-by-layer 3D printing technique used to create pharmaceutical dosage forms. It begins with the preparation of drug-loaded filaments using hot-melt extrusion (HME) and in this process, active pharmaceutical ingredients (APIs) are blended with thermoplastic polymers. These filaments are designed to be printable and carry the drug uniformly throughout. The prepared filament is fed into a 3D printer that contains a heated nozzle. The nozzle heats the filament to a semi-molten state suitable for extrusion. The printer extrudes the melted material through the nozzle in fine lines. It deposits the material layer by layer onto a build platform according to a digital design (CAD file).

Each layer cools and solidifies, creating a stable 3D structure. The process continues until the full dosage form is constructed. This method allows precise control over shape, size, and drug release behaviour. It enables the creation of customized tablets for individual patient needs. FDM can also be used to manufacture multi-drug or modified-release formulations. However, material compatibility, thermal stability of the drug, and reproducibility must be considered.[4]

Regulatory acceptance is also essential before clinical application of FDM-printed drugs.

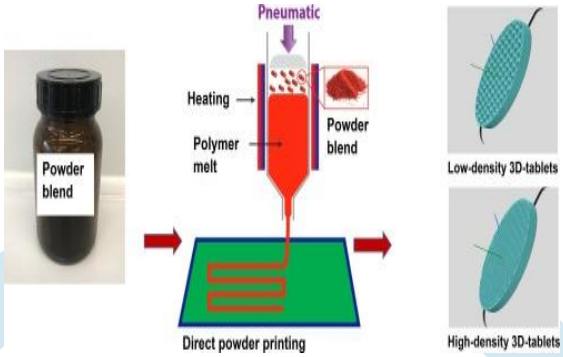

Figure2. *Schematic illustration of the direct powder printing process, showing preparation of a polymer–drug powder blend, its pneumatic extrusion after heating and melting, and formation of 3D-printed tablets with varying densities.*

4) Advantages

a) Eliminates the need for solvent use, making it safer and more eco-friendly.
b) Simplifies the process by allowing direct printing from powder without filament preparation.
c) Supports high drug loading, useful for potent or high-dose formulations.
d) Enables dosage customization through control over tablet structure and density.

5) Disadvantages

a) High processing temperatures may degrade heat-sensitive drugs.
b) Limited to polymers and APIs that can withstand thermal extrusion.
c) Achieving consistent product quality requires strict process control.
d) Regulatory approval pathways are still evolving for such new technologies.

6) Applications

a) Ideal for producing personalized tablets with patient-specific doses and shapes.
b) Useful for fabricating controlled or extended-release dosage forms.
c) Enables polypills containing multiple drugs in a single unit.
d) Suitable for on-demand production in hospitals, especially for paediatric or geriatric care.[5]

B. Inkjet Printing

1) Principle

Inkjet printing works by ejecting very small, accurately measured droplets of a liquid formulation through fine nozzles. Each droplet contains drug solution or suspension, deposited directly onto a substrate such as edible films or tablets. The movement of the print head is digitally controlled, allowing precise placement of each droplet. This enables exact dosing of active pharmaceutical ingredients at micro- to milligram levels and the process can build complex patterns or layers, which can alter drug release or combine multiple drugs in one unit. Thermal or piezoelectric forces are used to generate droplet pressure without damaging the drug. Because no contact occurs between the nozzle and the substrate, contamination risk is minimized. The principle supports on-demand, personalized medicines with high reproducibility and minimal waste.

2) Materials

a) Drug solution or suspension as the main active ingredient.
b) Safe solvents (like water or ethanol) to adjust viscosity.
c) Polymers/film-formers (HPMC, PVA) to stabilize and control release.
d) Surfactants or plasticizers (glycerol, PEG) to improve droplet flow.
e) Printable substrates such as edible films, tablets, etc. [6]

3) Working

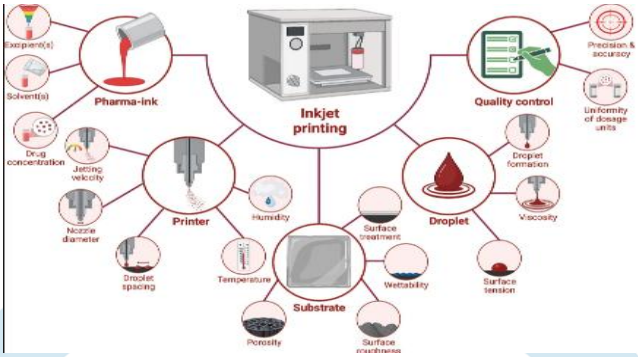

Figure3. *Overview of the inkjet printing process in pharmaceutical applications, highlighting key parameters influencing print quality, including pharma-ink composition, printer settings, droplet behaviour, substrate characteristics, and quality control measures.*

Inkjet printing achieves precise deposition of drug formulations by ejecting very small droplets from a nozzle onto a target substrate in a controlled, non-contact manner. The "ink" is a carefully formulated mixture of active pharmaceutical ingredients and excipients, balanced for viscosity, surface tension, and stability so that it can be jetted reliably. A driving mechanism (e.g. piezoelectric actuation or thermal pulses) generates pressure waves that propel droplets through the nozzle, while parameters like droplet spacing, jetting velocity, and nozzle geometry regulate the placement. The substrate properties—such as wettability, porosity, and surface energy—affect how droplets spread or absorb. As successive droplets are placed, they build up discrete dosage units, allowing control of dose and spatial distribution. Real-time control and feedback can monitor droplet formation and adjust parameters for consistency. The technique's digital nature permits customization, enabling personalized dosage forms. However, challenges include preventing nozzle clogging, satellite droplet formation, and maintaining print fidelity under different environmental conditions. With optimization, inkjet printing is poised to transform pharmaceutical manufacturing by marrying flexibility, precision.[7]

4) Advantages

a) Inkjet printing delivers high accuracy by producing tiny droplets for detailed, high-quality output.
b) It is economical for small-scale or customized printing jobs without expensive setup costs.
c) The method can print on various materials, including paper, plastic, and textiles.
d) Being a non-contact process, it reduces the chance of damaging delicate substrates.
e) Inkjet technology enables quick customization and flexibility without interrupting production.

5) Disadvantages

a) Inkjet printing can suffer from nozzle clogging due to the presence of viscous or particulate drug formulations.
b) It has a low drug loading capacity, which limits its use for high-dose medications.
c) Thermal inkjet systems may cause degradation of heat-sensitive active ingredients.
d) The technique faces scalability issues, making it less suitable for large-scale manufacturing.

6) Applications

a) Inkjet printing enables accurate dose customization for individual patients, supporting personalized therapy.
b) It is used to create fast-dissolving oral films, improving ease of administration for children and elderly patients.
c) The method allows printing of multiple drugs onto a single unit, enabling fixed-dose combination treatments.
d) It supports on-demand manufacturing at healthcare sites, reducing reliance on large-scale production facilities.
e) By modifying printing patterns and formulation ingredients, drug release rates can be precisely controlled.[8]

C. Stereolithography (SLA)

1) Principle

SLA 3D printing operates by curing a photosensitive resin layer-by-layer using a focused light source, typically a UV laser. The laser selectively solidifies specific regions of the resin according to a digital model of the dosage form. Once a layer is cured, the build platform adjusts to allow the next layer of resin to be exposed and cured. This process continues sequentially to form a complete 3D object with high resolution and surface quality. SLA is particularly valuable in fabricating complex geometries not achievable through conventional manufacturing. In pharmaceuticals, this allows precise control over drug distribution within the printed structure. The method also supports the incorporation of controlled release profiles by adjusting internal architectures. Due to its accuracy, SLA is useful for developing personalized or implantable drug delivery systems.

2) Materials

a) Photosensitive resin made of biocompatible photopolymers
b) Photo initiators to initiate polymerization under UV light.
c) Plasticizers or cross-linkers to adjust mechanical properties.
d) Active pharmaceutical ingredients (APIs) incorporated into resin.

e) Solvents or diluents to control resin viscosity
f) Build platform for supporting the printed layers.
g) Recoating blade or mechanism for applying resin layers.[9]

3) Working

SLA 3D printing works by using a UV laser to selectively cure a photosensitive resin layer-by-layer. The process begins with a digital 3D model, which is sliced into thin cross-sectional layers. A build platform is submerged slightly in a vat containing in a liquid photopolymer resin. The laser beam is directed by mirrors (galvanometers) to trace and solidify the first layer of the model. Once a layer is cured, the platform moves to allow uncured resin to flow over it, forming the next layer.

This sequence continues until the entire object is built from successive cured layers. The printed structure is then removed from the resin bath and typically washed with a solvent. Post-curing using additional UV exposure may be performed to enhance the mechanical strength and stability. In pharmaceutical applications, this technique allows for precise shaping of drug-loaded devices. It enables customization of dose, release profile, and geometry for patient-specific therapies. The uncured resin left in the vat after printing can be reused for future prints, reducing material waste. Post-processing steps like cleaning with isopropyl alcohol are essential to remove residual resin from the printed object. A secondary UV curing step enhances the mechanical strength and stability of the printed formulation. Print quality and precision depend on process parameters such as laser intensity, scanning speed, and layer thickness.[10]

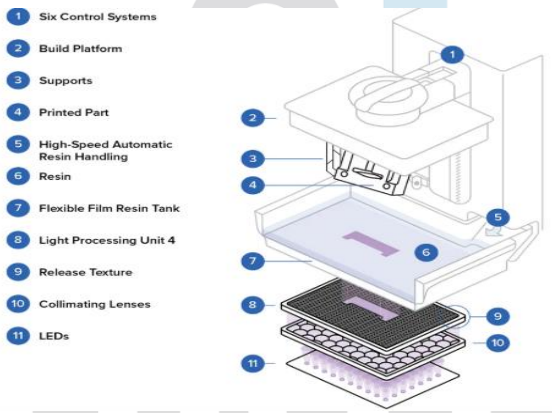

Figure 4. *Overview of the vat polymerization process in pharmaceutical applications, highlighting key subsystems influencing print quality, including the light engine, resin tank, build mechanics, and automated control systems.*

4) Advantages

a) SLA provides extremely high resolution and smooth surface finish, making it suitable for fabricating precise drug delivery systems.
b) It allows complex internal structures and geometries, useful for tailoring drug release profiles.
c) The layer-by-layer curing process offers excellent reproducibility, ensuring consistent quality in dosage forms.
d) SLA is compatible with various photopolymer materials, enabling formulation flexibility for different drug types and release mechanism.

5) Disadvantages

a) SLA resins often contain toxic photo initiators and unreacted monomers that are not suitable for pharmaceutical applications.
b) Only a limited range of biocompatible and pharmaceutically acceptable photopolymers are available for SLA printing.
c) The UV light used in SLA can degrade light-sensitive drugs, reducing their stability and therapeutic effect.
d) SLA requires time-consuming post-processing steps, which increase the risk of contamination and complicate production.

6) Applications

a) SLA is used to fabricate patient-specific drug delivery systems with tailored shapes and release profiles.
b) It enables the production of drug-loaded implants with precise geometries for controlled and localized release.
c) SLA allows the development of oral dosage forms with complex internal architectures to modify drug dissolution rates.
d) It is applied in the fabrication of microneedle arrays for minimally invasive transdermal drug delivery.
e) SLA is also used for rapid prototyping of pharmaceutical devices during formulation development and testing stages.[11]

D. Selective Laser Sintering (SLS)

1) Principle

Selective Laser Sintering (SLS) is a powder-based 3D printing technology that uses a high-energy laser to fuse powdered materials layer by layer into solid structures. In pharmaceutical formulations, SLS enables the fabrication of solid oral dosage forms without

the need for solvents or binders. The drug and excipients are blended into a powder and selectively sintered by a laser, forming a solid matrix. This method allows for high drug loading and complex internal geometries that can control drug release. SLS operates at relatively high temperatures, which may limit the use of thermolabile drugs. However, it offers advantages such as rapid prototyping, precision, and the ability to produce porous structures for immediate or controlled release. The process is also suitable for manufacturing personalized medicines with adjustable doses. Its solvent-free nature makes it attractive for clean and sustainable pharmaceutical production.

2) Materials

a) Polyamide (Nylon) is commonly used due to good mechanical properties and biocompatibility.
b) Polyvinyl alcohol (PVA) is a water-soluble polymer often used for controlled release.
c) Polyethylene glycol (PEG) is used as a binder and to improve drug release profiles.
d) Polylactic acid (PLA) is biodegradable polymer suitable for implants and sustained release.
e) Thermoplastic polyurethanes (TPU) is flexible polymers used in drug-loaded flexible dosage forms.
f) Pharmaceutical powders mixed with polymers and API blended with excipients like lactose mannitol for sintering.
g) Carbon-based additives are sometimes added to improve laser absorption and sintering efficiency.[12]

3) Working

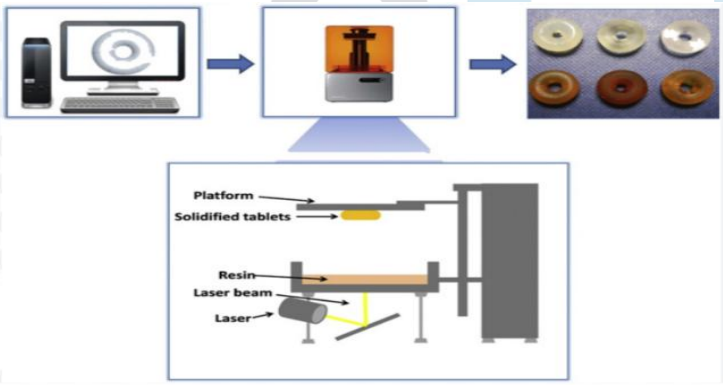

Figure 5. *Overview of SLA-based 3D printing for tablet fabrication, from CAD design to laser-curing of resin and final printed dosage forms.*

A liquid photopolymer resin, which may contain active pharmaceutical ingredients (APIs) and excipients, is spread as a thin layer on the build platform. A UV laser or light source selectively scans and cures (solidifies) the resin in a predefined pattern, causing polymerization at precise locations to form a solid layer. After one layer is cured, the build platform moves down slightly to allow the next layer of liquid resin to cover the previous layer. The laser then cures this new layer, which fuses to the layer below. This process repeats layer-by-layer until the entire 3D structure (e.g., a drug-loaded tablet or device) is built. Finally, the printed object undergoes post-processing steps like cleaning to remove uncured resin and additional UV curing to ensure complete polymerization and stability. This technique allows the creation of complex, precise dosage forms with customizable drug release properties. This method allows for highly accurate fabrication of intricate geometries, making it suitable for designing tablets or devices with complex internal structures. Enables production of structures like hollow tablets, multi-layered systems, or implants that are difficult to produce using conventional method.

4) Advantages

a) SLA technology provides excellent accuracy, enabling the production of highly detailed and complex pharmaceutical structures.
b) It supports the design of patient-specific dosage forms by allowing adjustments in shape, size, and drug content.
c) The method allows for precise control over drug release by enabling multi-layer or compartmentalized designs.
d) It uses only the necessary amount of resin, making the process cost-effective with minimal material waste.

5) Disadvantages

a) The limited selection of biocompatible and pharmaceutically safe photopolymer resins restricts material choices for drug formulations.
b) Some residual photo initiators or uncured resin may pose toxicity risks, requiring thorough post-processing and validation.
c) The curing process involves exposure to UV light, which can degrade light-sensitive drugs and affect stability.
d) The printing process is relatively slow and may not be suitable for large-scale production without significant optimization.[13]

6) Applications

a) SLA is used to create personalized tablets with patient-specific doses and geometries for precision medicine.
b) It allows the fabrication of drug-loaded implants designed for controlled and localized drug delivery over extended periods.
c) SLA can produce oral dispersible films and buccal devices that dissolve quickly for rapid onset of drug action.
d) The technology supports the development of complex polypills containing multiple drugs with distinct release profiles.
e) It is utilized in prototyping and testing novel drug delivery systems during early pharmaceutical research and development.[14]

E. Binder Jetting

1) Principle

Binder jetting is a powder-based 3D printing technique where a liquid binder is selectively deposited onto a powder bed. The process begins by spreading a thin layer of pharmaceutical-grade powder, which may contain active ingredients or excipients. An inkjet print head then sprays the binder in a specific pattern to bind powder particle together at selected regions. Only the areas where the binder is applied become solidified, forming the cross-section of the desired structure. After each layer is completed, the build platform lowers, and a new powder layer is spread over the previous one. This layer-by-layer process continues until the full 3D object is formed, such as a tablet or drug-loaded structure. The unbound powder remains loose and supports the printed object during fabrication, eliminating the need for support structures. After printing, excess powder is removed, and the printed part may undergo post-processing, such as drying or sintering. This method allows for rapid production of porous, customizable dosage forms with precise control over drug content and release.

2) Materials

a) Pharmaceutical powders such as active ingredients and excipients like lactose, microcrystalline cellulose, and starch are commonly used due to their suitable flow and compressibility.
b) The binder liquids are typically solutions of polymers like polyvinyl alcohol (PVA) or polyethylene glycol (PEG), which help bind the powder particles during printing.
c) Additional components such as plasticizers or surfactants may be incorporated to improve the mechanical strength and drug release properties of the final product.
d) Selection of materials focuses on ensuring biocompatibility, stability, and desired release profiles in the finished dosage form.[15]

3) Working

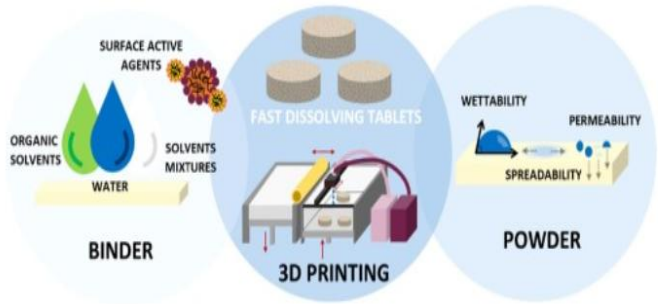

Figure 6. *Key components in binder-jet 3D printing of fast-dissolving tablets, highlighting the roles of binder properties and powder characteristics in successful tablet fabrication.*

Binder jet 3D printing operates by selectively depositing a liquid binding agent onto a powder bed to form solid structures layer by layer. The process begins with a thin layer of pharmaceutical-grade powder spread evenly on the build platform. A print head moves over the surface, dispensing droplets of binder solution in specific regions as per the digital design. The binder causes the powder particles to adhere locally, forming the intended pattern. After each layer is printed, a new layer of powder is spread and the process repeats until the entire dosage form is built. The unbound powder acts as a support during printing and is later removed. Post-processing steps, such as drying or curing, enhance the mechanical strength and stability of the printed tablets. This technique enables the production of personalized dosages, complex geometries, and rapid drug release profiles. Binder jet printing offers high scalability and compatibility with heat-sensitive drugs since it operates at room temperature. Here are six additional paraphrased lines to expand your explanation on the working of a binder jet 3D printer in pharmaceutical formulations. The choice of binder influences tablet hardness, disintegration time, and drug release kinetics. Different powder materials such as lactose, mannitol, or polymers can be used depending on the formulation needs and the printer's resolution and droplet size control the precision and uniformity of the final dosage form. Multi-nozzle systems allow simultaneous printing of different drug layers or combinations for polypharmacy. The process can incorporate both immediate and controlled-release drug formulations in a single tablet. Binder jet printing reduces material wastage and enables on-demand manufacturing directly at the point of care.

4) Advantages

a) Binder jet 3D printing enables precise control over the dose, geometry, and design of pharmaceutical tablets, making it ideal for patient-specific therapies
b) This method allows fabrication of complex internal structures, offering the ability to modulate and optimize drug release profiles for desired therapeutic effects.
c) As the process does not require high heat, it is well-suited for printing thermolabile (heat-sensitive) drugs, preserving their potency and chemical stability.
d) Binder jetting ensures faster fabrication and efficient scale-up for both prototype and small-batch pharmaceutical manufacturing, enhancing productivity.

5) Disadvantages

a) Binder jet 3D printing in pharmaceuticals has several disadvantages.
b) The printed dosage forms usually possess low mechanical strength, making them brittle and prone to breakage during handling.
c) The process often results in poor uniformity of the binder and drug distribution, which can affect dose accuracy.
d) There is also a limitation in the selection of suitable excipients and binders, reducing formulation versatility.
e) Moreover, post-processing steps such as drying can be time-consuming and may compromise the stability of moisture-sensitive active ingredients.

6) Applications

a) Used for making personalized dosage forms for individual patients.
b) Helps in producing controlled or sustained-release tablets.
c) Enables combination or polypill formulation in a single tablet.
d) Useful for rapid formulation and prototype development.
e) Applied in printing porous drug delivery systems for targeted therapy.[16]

F. Semi-Solid Extrusion (SSE)

1) Principle

Semi-Solid Extrusion (SSE) is a 3D printing technique in which a semi-solid material (such as a gel or paste) loaded with the drug and excipients is precisely extruded through a nozzle or syringe head in a layer-wise fashion to build up a desired dosage form. The material is forced out by means of pneumatic, mechanical, or piston/syringe pressure. It does not require the material to be molten, so printing can often occur at ambient or low temperature, which helps preserve thermosensitive active pharmaceutical ingredients. After deposition, the printed layers solidify, typically via drying or solvent evaporation (or gelation), to confer structural integrity. Key to the process are suitable rheological properties of the ink: it should be shear-thinning so it flows under pressure, but regain viscosity or solidity when pressure is removed to maintain shape fidelity. The resolution of the printed object depends on nozzle size, viscosity, and solidification kinetics. Solid particle content, particle size, and polymer composition influence flow behaviour, structural stability, and drug release profiles. Post-processing (drying, sometimes cooling) is often required to remove solvent and stabilize the final form.

2) Materials

a) APIs – Active drugs (e.g., paracetamol, ibuprofen).
b) Polymers – Gelling agents (e.g., HPMC, alginate).
c) Solvents – Help form paste (e.g., water, ethanol, glycerol).
d) Plasticizers – Add flexibility (e.g., PEG, glycerol).
e) Fillers – Bulk & structure (e.g., lactose, mannitol).
f) Stabilizers – Improve shelf-life (e.g., sodium benzoate).
g) Colours/Flavors – For taste & appearance (optional).

3) Working

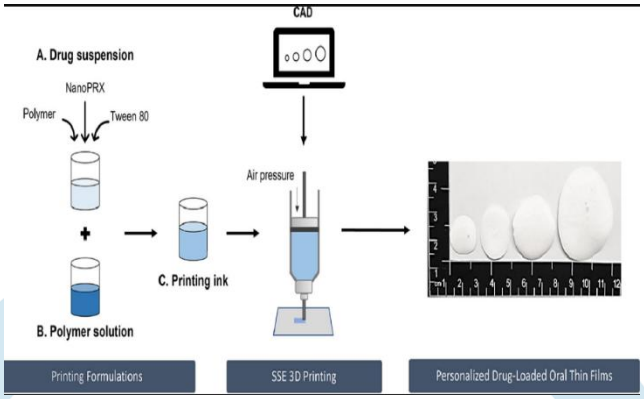

Figure7. *Schematic of SSE 3D printing for personalized drug-loaded oral thin films, showing preparation of printing ink, CAD-based design, and extrusion-based fabrication.*

Semi-Solid Extrusion (SSE) is an additive manufacturing technique in which semi-solid feedstock—such as a gel, paste, or slurry containing the active pharmaceutical ingredient (API) and excipients—is extruded layer by layer through a nozzle or syringe-type print head to build up the desired three-dimensional dosage form. The extrusion may be driven using pneumatic pressure, mechanical (piston/screw) force or other displacement-controlled systems. Prior to printing, the feedstock must have suitable rheological properties: it should be shear-thinning (viscosity decreases under shear for ease of extrusion), and after deposition it must regain structure (i.e. have sufficient yield stress or viscoelasticity) to prevent collapse or slumping. As the layers are deposited, the geometry is controlled via computer-aided design (CAD) slicing, and the nozzle path (in X-Y) followed precisely; after one layer completes, the build platform or nozzle moves in Z to start the next layer. Solidification of the printed form occurs post-deposition through mechanisms like drying (evaporation of solvent or water), gelation, or cooling, leading to structural stability. The process enables printing at ambient or low temperatures (unless heated extruders are used), which benefits thermolabile drugs. Also, by varying the formulation (polymer type, viscosity, solid loading), process parameters (nozzle diameter, extrusion speed, layer height), one can tune structural fidelity (surface finish, pore architecture), mechanical strength, and drug release profiles. Printed items may require post-processing (e.g., drying, curing) to remove residual moisture/solvent and ensure consistent performance. SSE allows for flexible dosage sizes, shapes, and even multi-drug or multilayer (“polypill”) architectures, offering personalised medicine potential. Challenges include maintaining print fidelity, avoiding nozzle clogging, ensuring uniform API distribution, and achieving suitable drying without distortion.[17]

4) Advantages

a) SSE technology allows manufacturing at low temperatures, which helps maintain the stability of temperature-sensitive drugs.
b) It can process a wide variety of semi-solid materials, making it suitable for different pharmaceutical formulations.
c) This method enables precise control over dose and shape, supporting personalized medicine development.
d) Products printed by SSE typically require minimal finishing, simplifying the production workflow.

5) Disadvantages

a) The printing process can be time-consuming, making it less ideal for high-volume manufacturing.
b) Achieving consistent flow properties of the semi-solid material can be challenging, impacting print reliability.
c) It is difficult to maintain exact shape and dimensional accuracy due to the fluid nature of the inks.
d) Removing residual moisture or solvents after printing often requires extended drying, which may distort the final product.

6) Applications

a) SSE enables the fabrication of personalized oral dosage forms with tailored drug release profiles for individual patients.
b) It is used to produce multi-drug combination tablets (polypills), improving patient adherence by combining multiple medications in one unit.
c) SSE allows creation of orally dissolving films with precise thickness and drug loading for fast action.
d) The technique supports development of controlled-release implants by layering polymers with different release characteristics.
e) SSE is applied to manufacture customized topical gels and creams, ensuring exact dosage and targeted delivery.[18]

III. Applications of 3D printing in pharmaceutical formulations

1) **Personalized Dosage Forms:** Customizing drug doses based on individual patient needs.
2) **Polypills:** Combining multiple active drugs into one tablet with controlled release profiles.
3) **Complex Tablet Geometries:** Producing tablets with intricate shapes for modified release.

4) **Orally Disintegrating Tablets:** Rapidly dissolving tablets for patients with swallowing difficulties.
5) **Controlled-Release Implants:** Implants designed for sustained drug delivery over time.
6) **Oral Thin Films:** Fast-dissolving films with precise drug loading for quick onset.

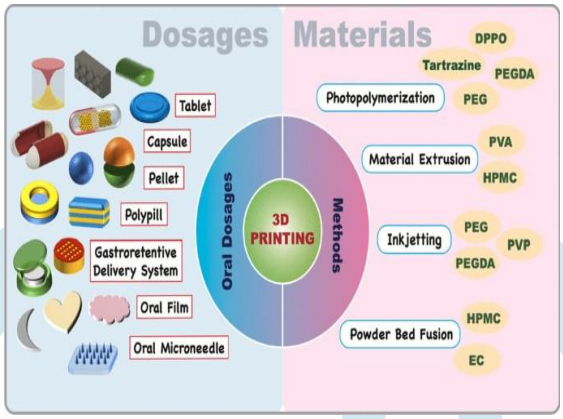

Figure8. *Overview of oral dosage forms and materials used in 3D printing, highlighting different formulation types and printing techniques for personalized drug delivery*

7) **Paediatric Formulations:** Creating child-friendly dosage forms with dose flexibility and taste masking.
8) **Geriatric Formulations:** Designing easy-to-swallow dosage forms for elderly patients.
9) **Topical Gels and Creams:** Producing customized skin applications with specific drug concentrations.
10) **Transdermal Patches:** Tailored patches for controlled drug delivery through the skin.
11) **Veterinary Medicine:** Custom medicines for animals with specific dosing and forms.
12) **ImplantableDrug Delivery Systems:** Localized delivery for cancer or orthopaedic treatments.
13) **Rapid Prototyping:** Accelerating drug formulation development and testing.
14) **On-Demand Manufacturing:** Producing medications as needed, beneficial for remote areas or emergencies.
15) **Multi-layered Dosage Forms:** Layering different drugs or release profiles within a single tablet.
16) **Porous Structures:** Creating tablets with adjustable porosity for controlled dissolution.
17) **Drug-loaded Micro-needles:** Fabricating micro-needle arrays for painless transdermal drug delivery.
18) **Combination Therapy Devices:** Integrating drugs with medical devices (e.g., stents).
19) **Customized Release Kinetics:** Adjusting drug release rates through design and material choice.
20) **Bioactive Scaffolds:** 3D printing scaffolds that deliver drugs for tissue engineering.
21) **Taste-masked Formulations:** Enhancing patient compliance by masking unpleasant tastes.[19]

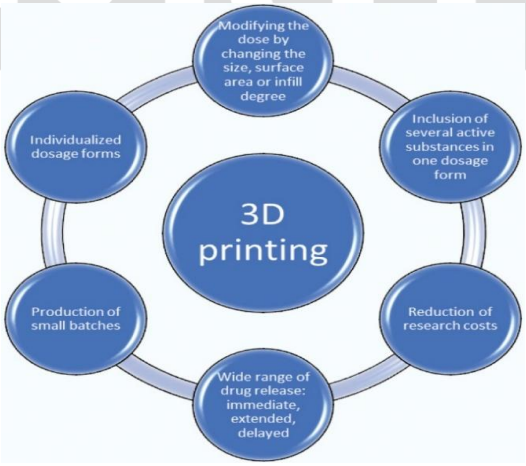

Figure 9*.Key advantages of 3D printing in pharmaceuticals, including personalized dosing, multi-drug combinations, controlled release profiles, rapid prototyping, and small-batch production.*

22) **Multi-drug Layered Capsules:** Capsules with compartmentalized drugs to avoid interaction.
23) **Controlled Porosity Films:** Films designed for sustained or immediate release.
24) **Patient-specific Implants:** Implants tailored to anatomy and drug needs.
25) **Microdosing:** Printing ultra-low doses for precise titration of potent drugs.
26) **4D-Printed Smart Drug Carriers**: Devices that change shape or release profile in response to stimuli like pH or temperature.
27) **Bioinks for Organ-on-Chip Models**: Using 3D printed bioinks to fabricate tissue models for drug testing, reducing animal studies.
28) **Embedded Electronic Drug Delivery Devices**: Integrating sensors or wireless actuation within implants to trigger drug release.
29) **Ultrasound-Directed Scaffold Porosity**: Controlling porosity of biodegradable scaffolds using ultrasound during printing, for tissue regeneration.

30) **Biodegradable Wireless Bioelectronics**: Fully 3D-printed electronic components (sensors, stimulators) that degrade after therapeutic use.
31) **Intracellular Microstructure Printing**: Fabricating micro- or nano-structures inside living cells for intracellular drug targeting or tracking.
32) **Gradient Composition Dosage Forms**: Producing dosage forms where drug or excipient concentration varies spatially within the object.
33) **Triggered/On-Demand Release Implants**: Implants that release drug only when triggered (e.g., via wirelessly controlled mechanisms).
34) **Photocurable 3D Printed Hydrophilic/Hydrophobic Drug Systems**: Using light-based printing to combine different drug-solvent environments in one form.
35) **Nanostructured Scaffolds for Bone Tissue Engineering**: Scaffolds at nano-scale to aid bone repair, with drug delivery incorporated.
36) **Drug-loaded Nanoparticles Incorporated in 3D Structures**: Embedding nanoparticles in printed structures for combined structural and therapeutic functions.
37) **Rapid Customizable Implants for Surgery**: Patient-specific implants for surgical repair (orthopaedics, craniofacial) with incorporated drug release for infection control.[20]

IV. Main Outcomes of 3D Printing Research in Pharmaceutics

1) Advancement in Personalized Medicine

3D printing has significantly enhanced the ability to personalize drug therapy. It allows precise adjustments in dosage strength, shape, and release pattern based on individual patient needs, offering a new frontier in precision medicine.

2) Versatile Printing Technologies Utilized

Multiple 3D printing techniques have been employed in pharmaceutical development, including FDM, SSE, SLA, and Binder Jetting. Each method brings unique advantages depending on the formulation type and desired release characteristics.

3) Complex Dosage Forms and Drug Combinations

One of the major findings is that 3D printing can fabricate complex, multilayered dosage forms and combine multiple active drugs into a single tablet (polypills), improving treatment efficiency and patient adherence.

4) Expanded Applications Across Patient Populations

Customized drug delivery systems developed via 3D printing are particularly beneficial for paediatric, geriatric, and veterinary populations, where flexible dosing and easy-to-administer forms are essential.[21]

5) Flexibility in Drug Release Profiles

The technology supports a wide spectrum of drug release types, including immediate, sustained, and delayed release, by simply modifying design features such as infill, geometry, or material composition.

6) Rapid Prototyping and Batch Production

3D printing enables quick development of prototypes and supports the manufacturing of small, personalized batches, reducing waste and speeding up early-stage formulation testing.

7) Integration with Emerging Fields

Recent innovations include the integration of 3D printing with biosensors, stimuli-responsive materials (4D printing), and regenerative medicine, expanding its role beyond traditional drug delivery.

8) Challenges and Limitations

Despite its advantages, 3D printing in pharma still faces hurdles such as scalability, regulatory approval, material limitations, and the need for standardized quality control.[22]

V. Acknowledgement

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Conclusion

3D printing has emerged as a groundbreaking technology in the pharmaceutical field, offering a highly adaptable platform for fabricating drug delivery systems with unprecedented precision. Its capacity to customize dosage forms based on individual patient needs is revolutionizing traditional manufacturing, especially in the context of personalized medicine. By enabling the

incorporation of multiple drugs into a single dosage form, 3D printing simplifies complex therapeutic regimens and improves patient compliance.

Moreover, the ability to manipulate drug release profiles—ranging from immediate to delayed or extended release—has broadened the scope of pharmaceutical applications. Technologies such as fused deposition model (FDM), semi-solid extrusion (SSE), binder jetting, and stereolithography (SLA) have been effectively utilized to develop a variety of solid and semi-solid dosage forms, including polypills, implants, microneedles, and orally disintegrating films. Beyond clinical benefits, 3D printing also offers economic advantages. It reduces material waste, supports small-batch production, and accelerates drug development through rapid prototyping. These features are particularly valuable in early-phase formulation screening and clinical trials, where agility and cost-efficiency are critical. However, challenges remain—such as regulatory uncertainties, material limitations, scalability issues, and the need for robust quality control standards. Addressing these barriers is essential for widespread adoption. Future research must focus on refining printing technologies, developing biocompatible materials, and establishing clear regulatory pathways.

In conclusion, 3D printing holds immense promise to transform pharmaceutical manufacturing from a "one-size-fits-all" model to a highly personalized, flexible, and efficient process. As the technology continues to mature, it is poised to become a cornerstone of next-generation drug delivery and patient-centric healthcare.

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