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Research Article

3D Printing of Dosage Form and Personalised Medicine in Pharmaceuticals

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Abstract

This article provides information about 3D printing in pharmaceuticals. It provides details about three-dimensional printing is an innovative pharmaceutical technology that enables the development of personalised dosage forms with precise control over drug dose, Geometry, and release characteristics. It supports complex formulation and improves patient compliance, though challenges in regulation, material and scalability remain. This review article contains Methods used for 3D printing, the mechanism of Action of 3D printed drugs, marketed formulations, materials, and Methodology Advantages, Limitation Future scope, etc.

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KEYWORDS: 3D printing; Additive manufacturing; Novel drug delivery system, personalised dosage form, controlled release system. A recent study on 3D printing of dosage forms, Scope.

1. INTRODUCTION

Three-dimensional (3D) printing is an innovative manufacturing technology that employs computer-aided design and programmable systems to fabricate solid objects through a layer-by-layer deposition process. In the pharmaceutical domain, 3D printing has emerged as a transformative approach across the drug development continuum, including preclinical research, clinical evaluation, and patient-centred therapy. This technology facilitates the fabrication of various advanced drug delivery systems, such as controlled-release formulations, fast-dissolving tablets, implants, and multi-drug dosage forms with complex geometries.

Compared to conventional manufacturing techniques, 3D printing offers significant advantages, including precise control over drug dosing, high drug-loading capacity, reduced material wastage, and the ability to process a wide range of active pharmaceutical ingredients, including poorly water-soluble drugs, proteins, and drugs with a narrow therapeutic index. The regulatory approval of the first 3D-printed pharmaceutical product has further accelerated research interest in this field.

Importantly, 3D printing enables the development of personalised medicine by allowing the customisation of drug dosage, combinations, and release profiles according to individual patient requirements. Additionally, its capability for on-demand and prescription-specific manufacturing presents promising opportunities for improving therapeutic outcomes and addressing urgent medical needs.

2. HISTORY

The concept of three-dimensional (3D) printing, also known as additive manufacturing, originated in the early 1980s as a rapid prototyping technology. Initially developed for industrial applications, its potential in healthcare and pharmaceutical sciences gradually became evident, particularly in the field of personalised medicine.

Early Developments (1980s–1990s)

The foundational technologies of 3D printing were established during the 1980s. One of the earliest breakthroughs was the development of binder jet printing, where a liquid binding agent is selectively deposited onto a powder bed to create solid structures layer by layer. This approach laid the groundwork for pharmaceutical applications due to its ability to fabricate porous and precise dosage forms.

In parallel, fused deposition modelling (FDM) was introduced in the late 1980s. This technique involves the extrusion of thermoplastic polymers through a heated nozzle, forming objects in a layer-by-layer manner. Although initially used in engineering, FDM later gained attention in drug delivery research for its adaptability and cost-effectiveness.

During the early 1990s, researchers at academic institutions, particularly the Massachusetts Institute of Technology (MIT), advanced inkjet-based 3D printing technologies. These systems enabled controlled deposition of materials, which became highly relevant for producing pharmaceutical dosage forms with defined geometries and drug distribution.

Transition to Pharmaceutical Applications (2000s)

In the early 2000s, the pharmaceutical industry began exploring 3D printing for drug formulation and delivery. Researchers demonstrated that 3D printing could be used to fabricate tablets with:

- Complex internal structures
- Controlled drug release profiles
- Multiple active pharmaceutical ingredients (APIs) in a single dosage form

These innovations marked a shift toward patient-specific drug design, enabling customisation of dose, shape, and release characteristics.

Regulatory Milestone and Commercialisation (2010s)

A major milestone was achieved in 2015–2016 when the first 3D-printed pharmaceutical product, Spritam® (levetiracetam), was approved by regulatory authorities. Manufactured using a proprietary inkjet-based technology, this formulation exhibited a highly porous structure, allowing rapid disintegration and improved patient compliance, especially for individuals with swallowing difficulties.

This approval validated 3D printing as a viable manufacturing method in pharmaceutics and encouraged further research and development in the field.

Recent Advancements (2020s–Present)

Recent years have witnessed significant advancements in 3D printing technologies for drug delivery, including:

Multi-material printing for combination therapies

Personalised dosage forms tailored to patient-specific needs

Development of on-demand drug manufacturing systems

Integration with digital health technologies for precision medicine

Regulatory agencies have also begun establishing guidelines for 3D-printed medical products, supporting their safe and effective implementation.

3. ROUTES OF ADMINISTRATION

1. Oral Route

The oral route is the most widely used and preferred route for 3D-printed pharmaceuticals due to its convenience, safety, and high patient compliance. 3D printing has significantly advanced oral drug delivery by enabling the fabrication of personalised tablets, capsules, and oro-dispersible formulations with precise control over dose and release characteristics.

Key Features of Oral 3D-Printed Dosage Forms

1. Personalised Dosage and Design

3D printing allows the production of patient-specific oral dosage forms by adjusting drug dose, size, geometry, and composition using computer-aided design (CAD). This eliminates the “one-size-fits-all” limitation of conventional tablets.

2. Controlled and Modified Drug Release
Oral 3D-printed tablets can be engineered with layered or compartmental structures to achieve:
- Immediate release
- Sustained release
- Multi-phase release

This is achieved by modifying porosity, infill density, and internal geometry, which directly influence drug dissolution and absorption.

3. Polypill Concept (Multiple Drugs in One Tablet)
3D printing enables the development of polypills, where multiple drugs are incorporated into a single oral dosage form with different release profiles. This improves treatment of chronic diseases and reduces pill burden.

4. Improved Patient Compliance
Oro-dispersible tablets and fast-dissolving forms are beneficial for pediatric and geriatric patients with swallowing difficulties. Customised shapes, flavours, and doses enhance acceptability and adherence.

5. Enhanced Bioavailability and Therapeutic Effect
3D printing allows precise control over drug release location and timing in the gastrointestinal tract, improving:
- Drug absorption
- Bioavailability
- Therapeutic outcomes

FDA-Approved Example
Spritam® (Levetiracetam)
First FDA-approved 3D-printed oral tablet (2015)
Designed as a highly porous, rapidly disintegrating tablet for epilepsy treatment
Enables easy swallowing and rapid drug release

Types of Oral 3D-Printed Dosage Forms
Tablets (immediate/controlled release)
Capsules
Orodispersible tablets (ODTs)
Polypills
Chewable/gummy formulations
MDPI

2. Transdermal Route
Drugs are delivered through the skin using 3D printed patches or microneedles. 3D printed microneedle arrays for insulin or vaccines. Avoids first-pass metabolism, painless delivery, suitable for controlled release.

3. Parenteral Route (Injectable)
3D printing helps design biodegradable implants or scaffolds that release drugs slowly after injection or implantation. Personalised drug-loaded implants for cancer or hormone therapy. Long-term, targeted drug release reduces dosing frequency.

4. Ophthalmic Route
3D printing can create drug-loaded contact lenses or ocular inserts. Used for treating glaucoma, infections, or dry eye. Sustained release directly to the eye; avoids systemic side effects.

5. Buccal / Sublingual Route
3D printed films or tablets placed under the tongue or against the cheek.Rapid absorption through mucous membranes. Used for Pain relief, heart conditions (e.g., nitroglycerin).

6. Vaginal / Rectal Route
3D printed suppositories or rings for local or systemic effect used for Hormonal therapy, infections, and contraception.

4. MECHANISM OF ACTION

1 Diffusion-Controlled Release
Drugs released from polymer -based dosage forms occur primarily through diffusion, where the active pharmaceutical ingredient gradually migrates from the polymer matrix into the surrounding environment. This mechanism is frequently observed in dosage forms fabricated using techniques such as Fused deposition modelling and stereolithography. The rate of release is significantly influenced by factors including
- matrix porosity
- degradation behaviour of the polymer.

2. Erosion-Controlled Release
The polymer matrix erodes or dissolves gradually in the release medium. The drug is released as the polymer breaks down. Common in biodegradable polymers (e.g., PLA, PCL).
Example:
In tablets printed using PLGA, the polymer slowly degrades → sustained drug release over time.

3. Swelling-Controlled Release
The polymer swells upon contact with fluid, forming a gel layer.The drug diffuses through the swollen gel layer.
Common in hydrophilic polymers (like HPMC, PVP).
Example:
In a 3D printed matrix tablet using HPMC → water absorption → gel formation → controlled drug diffusion.

4. Osmotically-Controlled Release
The printed structure contains osmotic agents. When water enters, osmotic pressure builds up, pushing the drug solution out through a designed orifice or channel. Can be designed by 3DP-controlled geometry.

5. Geometry-Controlled Release (Unique to 3DP)
By modifying shape, infill density, or internal channels, 3D printing allows precise control of drug release.
For example:
High infill density → slower release Hollow or porous design → faster release multi-layer or core–shell design → pulsatile or delayed release.

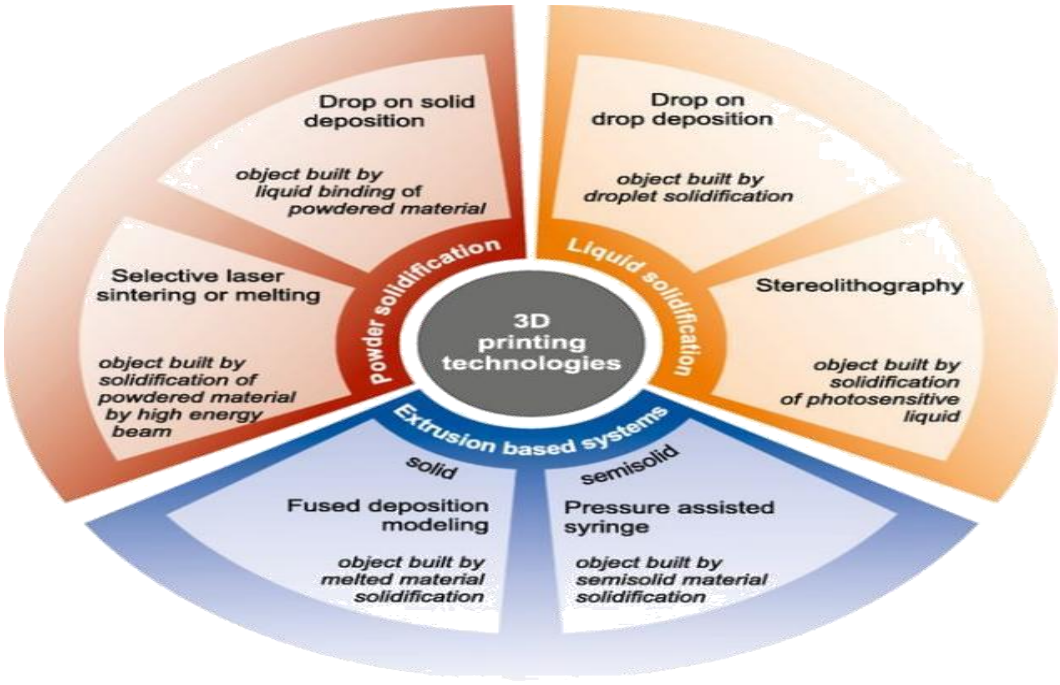

Fig 1: Techniques used in 3D Printing

Thermal Ink-Jet Printing

Thermal inkjet printing is a technique in which heat is applied to an aqueous formulation, causing rapid vapour formation. The resulting expansion creates pressure that ejects tiny droplets of the solution through a fine nozzle. In pharmaceutical applications, this method is used in the development of drug-loaded biodegradable microspheres and liposomes. It is also employed for coating microelectrode arrays and for incorporating drugs into drug-eluting stents. Additionally, this technique is considered suitable for forming thin films of biologically active compounds, as it helps maintain the stability and functionality of sensitive proteins.

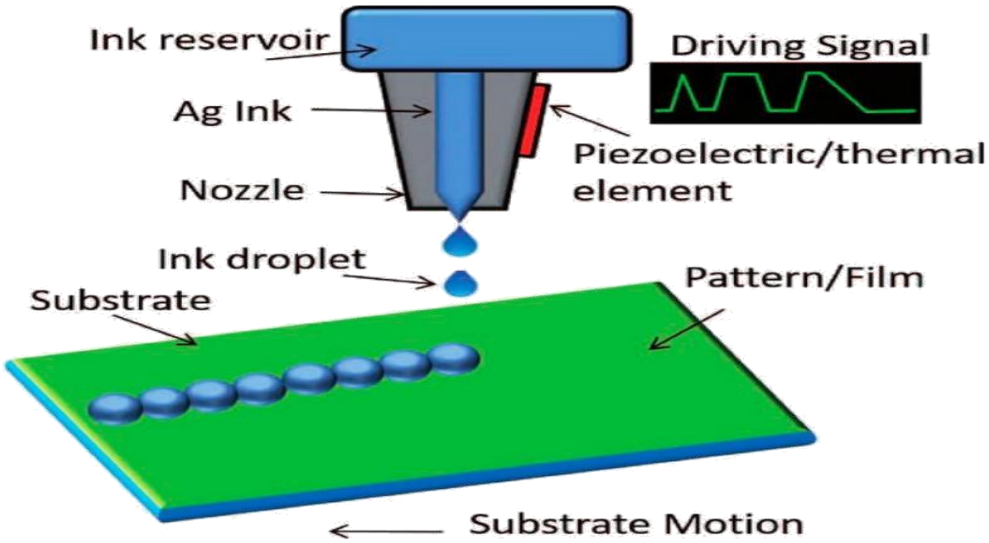

Fig 2: Thermal Inkjet Printing

Ink-jet Printing

Inkjet printing is a maskless technique where structures are formed by controlling the movement of the nozzle or surface. It works by depositing tiny droplets of liquid (ink) onto a substrate either continuously (CJP) or only when needed

(DOD). This method gives high precision, low cost, and minimal material wastage.

In pharmaceutical 3D printing, inkjet technology is used to prepare drug-loaded dosage forms by depositing drug-containing solutions or binders' layer by layer. In binder jetting, a liquid binder is sprayed onto a powder bed to join particles,

While in material jetting, liquid materials are directly deposited and solidified.

There are two main types: Continuous Inkjet Printing (CJP), which produces droplets constantly but may waste material, and Drop-on-Demand (DOD), which releases droplets only when required, giving better control and accuracy.

Different mechanisms, like thermal, piezoelectric, and electrostatic systems, are used to generate droplets. Overall, inkjet printing is a flexible and efficient method widely used in pharmaceutical applications.

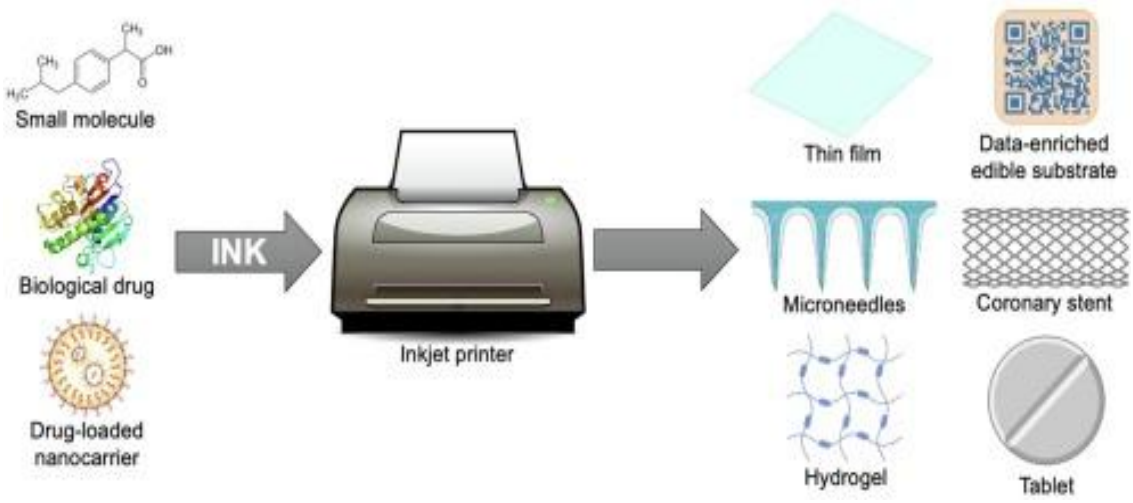

Fig 3: Ink Jet Printing

Fused disposition modelling

Fused Deposition Modelling (FDM) is a widely used 3D printing technique in which materials are heated until they soften or melt and are then deposited layer by layer to form solid objects. In pharmaceutical applications, FDM can be used to prepare delayed-release tablets without the need for an additional enteric coating, and it also supports the development. of personalised doses. However, this method has some limitations. The availability of suitable pharmaceutical-grade polymers is limited, and drug release may be slow or incomplete because the drug can remain trapped within the polymer matrix. In addition, the compatibility of drugs with polymers and other additives is not always fully understood.

Fig. 4: Fused disposition modelling

Extrusion 3D Printing

Uses semisolid materials for fabricating dosa form

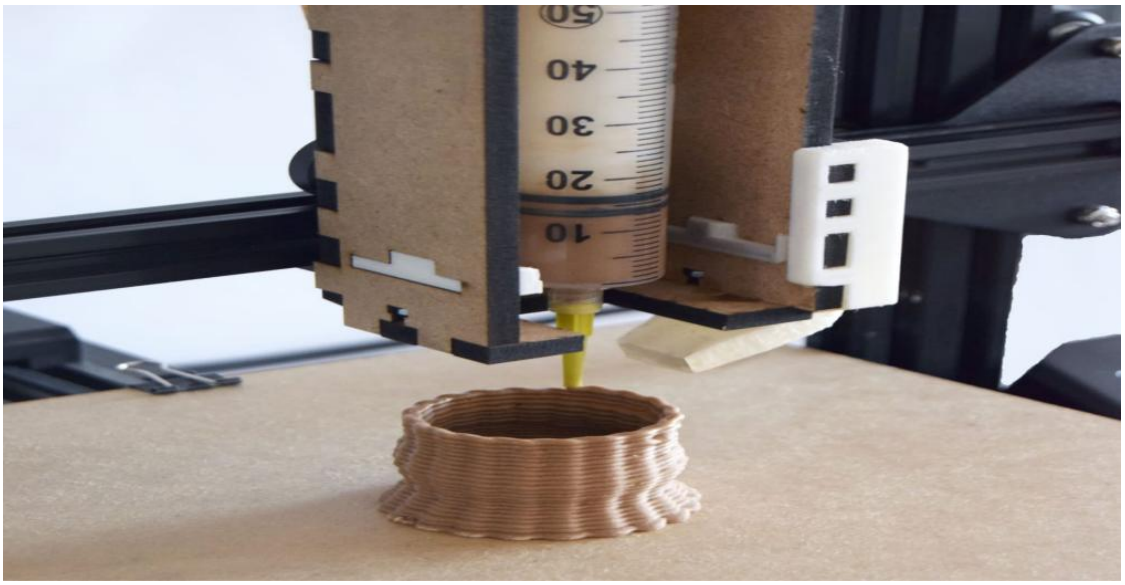

Fig 5: Extrusion 3D printing

Zip dose

ZipDose technology is a proprietary three-dimensional (3D) printing technique developed by Aprecia Pharmaceuticals for the manufacturing of highly porous oral solid dosage forms. This technology is based on a powder bed printing approach, where layers of powder containing the drug and excipients are selectively bound together using a liquid binding agent. The process is repeated layer-by-layer until a complete tablet is formed. One of the key features of ZipDose technology is its ability to produce tablets with a highly porous internal structure. This unique architecture enables rapid disintegration when the tablet comes into contact with a small amount of liquid, making it especially suitable for patients who have difficulty swallowing conventional tablets, such as pediatric and geriatric populations. The working principle of ZipDose involves spreading a thin layer of powder on a build platform, followed by the precise deposition of a binding solution through a printing head. The binder selectively fuses the powder particles in predefined areas according to the digital design. Subsequent layers are added and bonded in the same manner until the final structure is achieved. The unbound powder acts as a support material and is removed after printing.

A major advantage of this method is its capability to incorporate high doses of active pharmaceutical ingredients (APIs) while maintaining rapid disintegration properties. This is often difficult to achieve using traditional tablet compression techniques. Additionally, the digital nature of the process allows for flexibility in modifying dose, shape, and release characteristics without significant changes in the manufacturing setup. ZipDose technology gained significant recognition with the approval of the first 3D-printed drug, Spritam® (levetiracetam), by the U.S. Food and Drug Administration (FDA) in 2015. This formulation is used in the treatment of epilepsy and demonstrates rapid disintegration in the mouth without the need for water, improving patient compliance. Despite its advantages, certain limitations exist. These include the requirement for specialised equipment, limited availability of suitable excipients, and challenges in scaling up for mass production. Regulatory considerations also play a crucial role in the widespread adoption of this technology. Overall, ZipDose technology represents an important advancement in pharmaceutical manufacturing by enabling the development of patient-friendly dosage forms with improved therapeutic outcomes and personalised dosing capabilities.

Fig 6: Zip dose

Hot melt extrusion (HME)

Hot Melt Extrusion (HME) is a widely adopted manufacturing technique in pharmaceutical technology, increasingly integrated with 3D printing for the development of customised drug delivery systems. It is a solvent-free, continuous process in which a mixture of active pharmaceutical ingredients (APIs) and thermoplastic polymers is heated, mixed, and forced through an extruder to produce a uniform product.

In this method, the drug and excipients are first blended and then introduced into an extruder equipped with rotating screws. Inside the barrel, the material is subjected to controlled heat and mechanical shear, which causes the polymer to soften or melt. As a result, the drug is dispersed uniformly within the polymer matrix at a molecular or amorphous level. The molten mass is then pushed through a die to form a continuous extrudate, which can be shaped into filaments, pellets, or directly used in 3D printing processes such as fused deposition modeling (FDM).

One of the most important features of HME is its ability to produce amorphous solid dispersions, where poorly water-soluble drugs are molecularly dispersed within a polymer carrier. This significantly enhances drug solubility, dissolution rate, and bioavailability. Additionally, the absence of organic solvents makes the process environmentally friendly and reduces the risk of residual solvent toxicity.

The working mechanism of HME depends on the combined effect of thermal energy and mechanical mixing. The rotating screws inside the extruder generate shear forces that ensure uniform mixing, while the elevated temperature softens the polymer and facilitates drug incorporation. After extrusion, the material solidifies upon cooling, forming a stable matrix system where the drug is embedded. These matrices can function as drug reservoirs, allowing controlled or sustained drug release depending on the formulation design. HME plays a crucial role in 3D printing, particularly in the preparation of drug-loaded filaments used in FDM printers.

These filaments must possess suitable mechanical strength, flexibility, and thermal stability to ensure smooth printing and accurate dosage form fabrication. By adjusting formulation variables such as polymer type, plasticiser content, and processing conditions, it is possible to tailor drug release profiles, including immediate, sustained, or targeted release systems.

This method is highly versatile and has been successfully used to manufacture a wide range of dosage forms, including tablets, capsules, films, implants, and transdermal systems. It also supports multiple routes of drug administration, such as oral, transdermal, and transmucosal delivery.

Despite its advantages, HME has certain limitations. The process involves elevated temperatures, which may lead to degradation of heat-sensitive drugs. Additionally, the selection of suitable polymers is critical, as they must exhibit appropriate thermal stability and compatibility with the drug. High initial equipment cost and process optimisation requirements may also pose challenges in large-scale production.

Overall, Hot Melt Extrusion is considered a robust and efficient technique for modern pharmaceutical manufacturing. When combined with 3D printing, it offers a powerful platform for developing personalised dosage forms with improved drug performance and patient compliance.

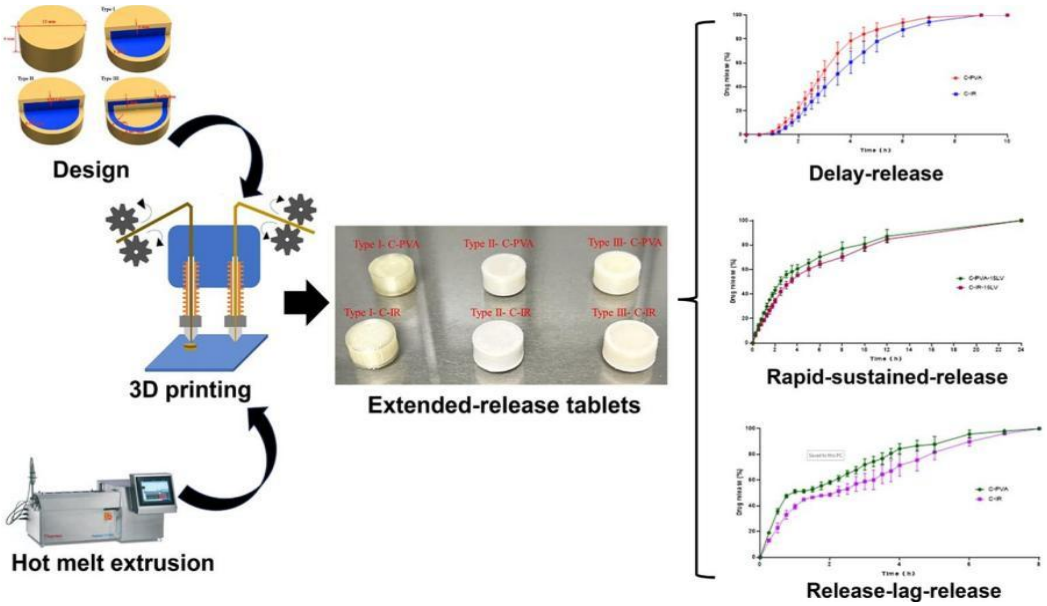

Fig. 7: Hot-Melt Extrusion

Stereolithography

A Stereolithography (SLA) is a light-based 3D printing technique that utilises photopolymerization to fabricate highly precise and complex pharmaceutical dosage forms. It is one of the earliest and most refined additive manufacturing methods, widely recognised for its superior resolution and ability to produce intricate geometries. In pharmaceutical applications, SLA offers a unique advantage by enabling the fabrication of dosage forms under relatively mild thermal conditions, making it suitable for heat-sensitive drugs.

The SLA process involves a liquid photopolymer resin that contains monomers, oligomers, photo-initiators, and, in pharmaceutical applications, the active drug substance. A computer-controlled ultraviolet (UV) laser or light source selectively irradiates the surface of the resin. Upon exposure, the photo-initiator generates reactive species that initiate polymerisation, converting the liquid resin into a solid structure. This process is carried out layer-by-layer, with each newly formed layer adhering to the previous one to build the final three-dimensional object.

One of the key strengths of stereolithography is its exceptional precision and surface finish. The technology allows the fabrication of dosage forms with highly controlled internal structures, including microchannels, porous networks, and layered systems. These structural features play a crucial role in modulating drug release profiles, enabling immediate, sustained, or pulsatile drug delivery depending on the design. Additionally, SLA provides excellent reproducibility, which is essential for ensuring dose uniformity and quality control in pharmaceutical products. Another important advantage of SLA is its compatibility with a wide range of formulation strategies. Drug molecules can be Either dissolved or uniformly dispersed within the photopolymer resin before printing. This enables the formation of homogeneous drug-loaded matrices. Furthermore, since the process does not rely on high temperatures, it minimizes the risk of thermal degradation of sensitive drugs such as proteins, peptides, and certain small molecules.

Stereolithography has been explored for the fabrication of various pharmaceutical dosage forms, including tablets, implants, microneedles, and drug-eluting devices. For example, SLA-printed oral tablets with complex geometries have demonstrated the ability to control drug release by modifying surface area and internal architecture. Similarly, microneedle arrays produced using SLA have shown promise for transdermal drug delivery due to their precise dimensions and mechanical strength.

Despite these advantages, certain limitations are associated with SLA technology. The selection of biocompatible and pharmaceutically acceptable photopolymer resins remains a significant challenge. Additionally, the potential toxicity of residual monomers or photo-initiators must be carefully addressed through post-processing and curing steps. The relatively high cost of equipment and materials may also limit its widespread industrial adoption.

Overall, stereolithography represents a powerful and versatile 3D printing technique in pharmaceutical manufacturing. Its ability to produce highly precise and customizable dosage forms makes it particularly valuable for advancing personalised medicine and innovative drug delivery systems.

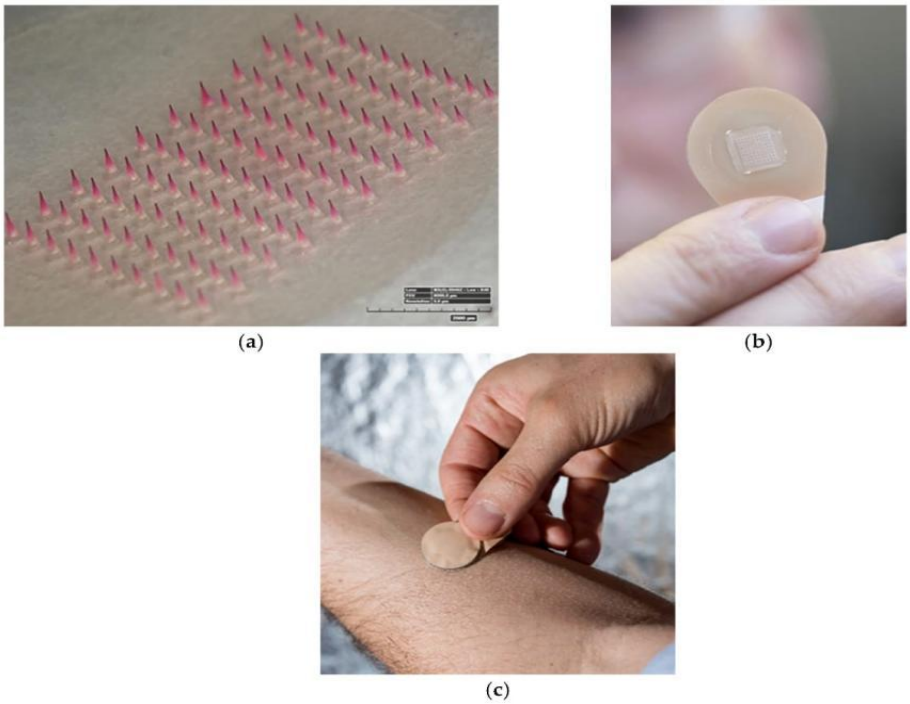

Fig. 8: Transdermal Patches by Using Stereolithography

Powder-Based 3D Printing

Powder-based 3D printing is an important additive manufacturing technique widely used in pharmaceutical applications for the fabrication of solid dosage forms. This method typically operates through a powder bed system, where fine layers of powder containing active pharmaceutical ingredients (APIs) and excipients are selectively bound together using a liquid binder or energy source to create three-dimensional structures.

The process begins with the uniform spreading of a thin layer of powder over a build platform. A printing head then deposits a binding solution in specific regions according to a digital design. The binder causes localised adhesion of powder particles, forming a solid layer. This sequence is repeated layer-by-layer until the complete dosage form is produced. The unbound powder surrounding the structure acts as a natural support and is removed after printing, making the process efficient and minimising the need for additional support materials.

One of the most notable advantages of powder-based 3D printing is its ability to produce highly porous structures. This porosity plays a crucial role in enhancing drug dissolution and disintegration, making the method particularly suitable for fast-dissolving tablets. Additionally, the technique allows for precise control over drug loading, spatial distribution, and internal architecture, which can be tailored to achieve desired drug release profiles. A significant milestone in this field was the development of ZipDose® technology, a powder bed-based printing approach used to manufacture the first FDA-approved. 3D-printed drug, Spritam® (levetiracetam). This formulation demonstrates rapid disintegration and high-dose drug loading, highlighting the clinical potential of powder-based systems.

Powder-based 3D printing is highly versatile and supports the fabrication of various dosage forms, including immediate-release tablets, controlled-release systems, multi-layered structures, and polypills. It is particularly advantageous for developing personalised medicines, where dose and composition can be adjusted according to patient-specific requirements.

The mechanism of drug release in powder-based systems is primarily influenced by the structure's porosity, binder distribution, and particle interactions. Highly porous tablets allow rapid penetration of dissolution media, leading to faster drug release, whereas denser structures can provide sustained release characteristics. By modifying printing parameters such as layer thickness, binder concentration, and powder composition, it is possible to fine-tune these properties.

Despite its advantages, powder-based 3D printing also presents certain challenges. These include limited mechanical strength of printed tablets, potential variability in layer uniformity, and the need for careful optimisation of powder flow properties. Additionally, the selection of suitable binders and excipients is critical to ensure stability, safety, and regulatory compliance. Scaling up the process for large-scale industrial production remains another important consideration. Overall, powder-based 3D printing represents a promising and flexible platform for pharmaceutical manufacturing. Its ability to create complex, porous, and patient-specific dosage forms makes it a key technology in advancing personalised medicine and next-generation drug delivery systems.

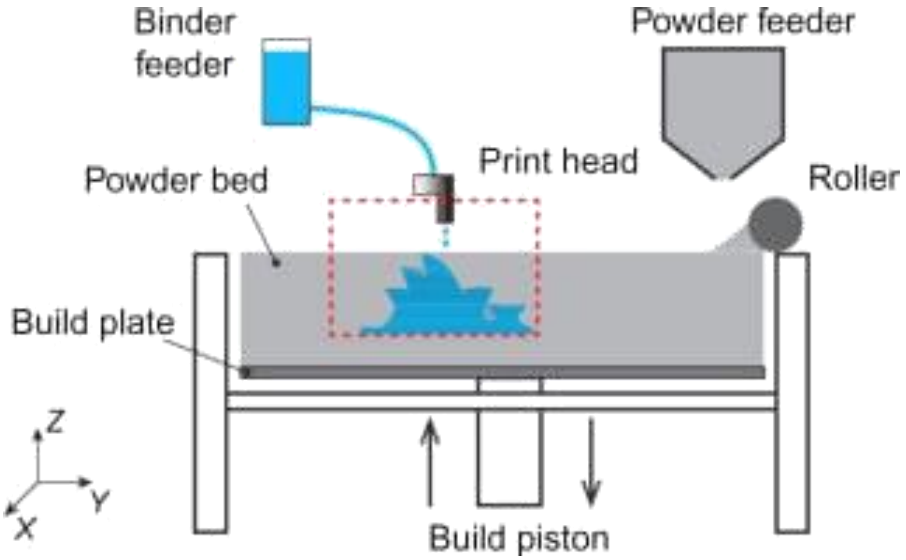

Fig. 9: Powder-Based 3D Printing

MATERIALS USED FOR 3D Printing

The material used for 3D printing of the dosage form is as follows

1 Polymers/ Hydrogels

Examples – Chitosan, polyvinyl alcohol, Alginate, polyvinyl alcohol, ethylene vinyl acetate.

Role of Polymer or Hydrogels

1. Structural Matrix Formation

Polymers or hydrogels act as the main building material of the printed object. They provide mechanical strength, shape retention, and integrity of the dosage form after printing. In Fused Deposition Modelling (FDM) or Stereolithography (SLA), the polymer is the filament or resin that gets printed layer by layer.

2. Drug Encapsulation and Protection

Polymers/hydrogels serve as carriers or encapsulating agents that hold the drug uniformly. They protect the drug from degradation caused by temperature, moisture, or light. Help in maintaining stability and uniformity of the active pharmaceutical ingredient (API) during printing.

3. Controlled and Sustained Drug Release

One of the most important roles of polymers /hydrogels is to control the release rate of the drug. By modifying polymer type, molecular weight, and cross-linking, the release can be tuned to: Immediate release, Sustained release, Pulsatile or targeted release. 3D printing is a process. Polymers must be biocompatible, non-toxic, and pharmaceutically acceptable. Hydrogels like alginate, chitosan, and gelatin are biodegradable, making them.

suitable for oral, transdermal, and implantable dosage forms. **Example:** Gelatin and chitosan are used in printing biocompatible scaffolds for tissue regeneration and drug implants.

5. Rheological and Printing Properties

For successful 3D printing, the polymer/hydrogel must have suitable viscosity, flow, and solidification characteristics. Determines printability, layer adhesion, and resolution. In semi-solid extrusion (SSE) or inkjet printing, hydrogel viscosity is critical.

Example: Sodium alginate + gelatin hydrogels give good flow and solidify quickly by ionic cross-linking with calcium chloride ($CaCl_2$).

6. Personalised and Flexible Dosage Design

Polymers enable flexibility in design, allowing adjustments in:

Drug dose

Geometry (shape)

Porosity

Layer thickness

This supports personalised medicine, where the dosage can be customised for each patient.

Example: PVA-based filaments can be printed into different shapes (cube, ring, pyramid) to modify surface area and release rate.

7. Stimuli-Responsive (Smart) Drug Delivery

Certain advanced hydrogels can respond to pH, temperature, or enzyme changes. Enables site-specific and on-demand release in the gastrointestinal tract or tissues.

Example: pH-sensitive polymers (Eudragit L100) dissolve only in the intestinal pH.

Thermo-sensitive hydrogels (Pluronic F127) release drugs when body temperature triggers gelation.

2.Resin /Photopolymerizable material

Bio- compatible resin used in stereoligraphy prints of micro needle patches. prepolymer with photoinitiator for high fidelity printing.

3.Nanoparticle / Functional additives
Gold nanoparticles are added for photothermal responsiveness or for controlled release.
Graphene oxide nanosheets Used to modulate the release profile of NIR Irradiation.

4. Carbon pyrolytic carbon
1. Introduction
Pyrolytic carbon is a biocompatible carbon material produced by the pyrolysis (thermal decomposition) of hydrocarbons (like methane or acetylene) at high temperatures in the absence of oxygen. It forms a hard, smooth, chemically stable, and wear-resistant coating. PyC is widely used in biomedical applications, especially heart valves, stents, and orthopaedic implants, and is now being explored in 3D printed pharmaceutical and tissue-engineering systems.

2. As a Biocompatible and Inert Material
PyC is chemically inert and biocompatible, making it suitable for contact with biological tissues or drug environments. In 3D printing, it can be used
to coat or reinforce drug-delivery scaffolds or implants that come into contact with tissues or fluids. It doesn't react with the drug or degrade easily, ensuring drug stability and safety.

3. As a Conductive Material for Smart Drug Delivery
PyC is electrically conductive, allowing it to be used in electro-responsive drug delivery systems. When incorporated into a 3D printed matrix, the material can release drugs in response to electrical stimulation (on-demand release). This is being studied for neurological, cancer, and implantable systems.
Example:
Electroconductive carbon composites (carbon nanotubes, graphene, or PyC) in hydrogels enable controlled drug release when voltage is applied.

4. Structural Reinforcement
PyC has excellent mechanical strength and wear resistance. When used as a coating or composite filler in 3D printed dosage forms or implants, it improves mechanical durability.
Prevents deformation during printing or use
Increases thermal stability of the dosage structure
Example:
In implants or microneedles, a thin PyC coating enhances mechanical robustness while maintaining biocompatibility.

5. Surface Modification and Drug Interaction
The surface of PyC can be modified to control drug adsorption, release rate, or cell adhesion. 3D printed dosage forms or scaffolds coated with PyC can be engineered for.
Slow and sustained drug release, improved cell compatibility in tissue engineering, reduced protein adsorption, avoiding an immune reaction

6. Heat and Chemical Resistance during Printing
PyC withstands high temperatures and chemical stress, so it can be combined with polymers that need thermal stabilisation during 3D printing (like FDM or laser sintering). It prevents degradation of sensitive drugs or polymer components by acting as a thermal barrier.

7. Role in Implantable and Transdermal 3D Systems
In implantable drug delivery or 3D printed micro-needle systems, PyC can act as: A coating material for long-term stability in the body. Barrier or diffusion layer to control the rate of drug movement through the Structure. Ensures extended, stable, and safe release over weeks or months.

Materials Used For 3d Printing of Dosage Form

Table 1: Materials used for 3D printing of a dosage form

CATEGORY	MATERIAL (EXAMPLE)	ROLE
POLYMERS (MATRIX POLYMER)	Polyvinyl Alcohol, Poly-lactic Acid, Polycaprolactone, Hydroxypropyl Methylcellulose, Polyvinylpyrrolidone, Ethyl Cellulose, Gelatine, Sodium alginate	Form a structural matrix, control drug release, improve mechanical strength, and ensure biocompatibility and stability.
PLASTICIZER	polyethene glycol, triethyl citrate	Enhance flexibility and printability, reduce brittleness during extrusion and improve layer adhesion.
FILLERS AND BINDER	Lactose, Mannitol, Microcrystalline cellulose	Provide bulk, improve mechanical strength, ensure uniformity and smooth extrusion.
ACTIVE PHARMACEUTICAL INGREDIENT	Paracetamol, Ibuprofen, Captopril, etc.	Delive therapeutic action
SOLVENT	Ethanol, Water, Chloroform, Dichloromethane	Dissolve the polymer or drug in solvent-based 3D printing methods
CROSS-LINKING AGENT	Calcium Chloride, Glutaraldehyde,	Stabilise the hydrogel structure, control porosity and drug release rate through cross-linking
COLORING AND FLAVORING AGENT	Food-grade colourants, sucralose, and sweeteners	Improve appearance, taste and patient compliance for oral dosage form
SUPPORT MATERIALS	Povinyl Alcohol, Hydrogel support	Acts as a temporary scaffold during complex printing, later dissolved or removed.

Categories of drugs formulated using 3D printing

1. **Oral solid dosage forms** — immediate-release tablets (including orodispersible / fast-dissolving)
   - 3D printing (binder-jet, FDM, etc.) can create highly porous or tailored geometries for rapid disintegration or swallowability (example: SPRITAM® levetiracetam).

2. **Oral solid dosage forms** controlled-release / modified-release tablets & complex release profiles
- Layering, internal infill patterns and multi-material printing allow immediate + sustained release from a single printed unit

3. **Polypills (fixed-dose combinations and personalised multi-drug tablets**)
- 3D printing enables spatial separation of actives and individualised dosing in one single printed tablet (useful for polypharmacy/geriatrics).

4. Buccal/sublingual films and oral thin films
- Printing thin geometries and low-temperature deposition supports rapid mucosal delivery and dose personalisation.

5. Transdermal systems & microneedle patches
- 3D printing (stereolithography, two-photon, high-resolution vat polymerisation) is widely used to fabricate microneedle arrays and engineered patches for painless, controlled transdermal delivery.

6. Implants and drug-eluting devices (local release: stents, scaffolds, implants)
- Biodegradable printed implants/scaffolds can be loaded with drugs for long-term local release (orthopaedic, oncologic, contraceptive research)

7. Topical patches, wound-healing dressings and dermal films
- Custom shapes, porosity, and multilayer structures for controlled topical antibiotic/ growth-factor release have been reported

8. Vaginal/rectal dosage forms (suppositories, intravaginal rings)
- Printing allows geometry and release-rate tuning for local therapy (antifungals, contraceptives, long-acting antivirals in research).

9. Parenteral supports/localised injectable depots & hydrogel-based systems
- 3D-printed hydrogel depots and implants for local sustained release of peptides/biologics are being explored (mostly preclinical).

10. Drug-loaded devices, ocular inserts, and niche devices (contact-lens release, implants for ocular delivery)
- Precision printing allows small-device fabrication for specialised delivery routes.

Marketed formulation

1.SPRITAM® (levetiracetam) — First and (so far) only commercially marketed 3D-printed drug
- **Brand name:** SPRITAM®
- **Active ingredient:** Levetiracetam (anticonvulsant used for epilepsy)
- **Manufacturer:** Aprecia Pharmaceuticals
- **Technology:** Printed using **ZipDose®** technology — a binder jetting / layer-by-layer 3D printing method that produces a highly porous tablet which rapidly disintegrates with a small amount of liquid.
- **Significance:** First drug product approved by the U.S. Food and Drug Administration (FDA) based on 3D printing technology (FDA approval in August 2015).

2. **Triastek's 3D-printed drug candidates**
- Several 3D-printed drug products from Triastek, Inc. are in clinical development, and some have received IND approval/clearance in the U.S. (e.g., 3D-printed extended-release formulations).
- These include multi-layer or microstructured tablets designed to control release in targeted regions of the gastrointestinal tract.
- These are being evaluated in clinical trials but have not yet reached full regulatory approval and commercial marketing.

Advantages of 3D Printing in Pharmaceutical Industries
- Enables personalised medicine with patient-specific dosing
- Allows fabrication of complex dosage forms with controlled drug release
- Provides high precision and accuracy in drug distribution
- Supports multiple drug combinations (polypill) in a single dosage form
- Facilitates on-demand drug production
- Improves patient compliance, especially for pediatric and geriatric patients
- Suitable for poorly soluble and potent drugs

Scope of 3D Printing in Pharmaceutical Industries
- Development of personalised drug delivery systems
- Manufacturing of polypills with multiple drugs in one dosage form
- Production of advanced dosage forms like implants, microneedles, and patches
- Use in clinical trials and small-scale production
- Enables on-demand drug manufacturing in hospitals and remote areas
- Supports controlled and targeted drug delivery systems
- Future integration with digital health and smart technologies

Recent studies on the 3D printing of dosage forms

Three-dimensional (3D) printing has gained rapid attention in pharmaceutical research due to its ability to produce customised dosage forms with precise control over drug release and design. In recent years, several studies have focused on improving its applications in personalised medicine and advanced drug delivery systems.

- Wang et al. (2023) provided a comprehensive overview of 3D printing technologies, explaining their mechanisms, advantages, and pharmaceutical applications. The study highlighted that additive manufacturing enables the production of complex dosage forms with improved control over drug release compared to traditional methods.
- Peng et al. (2024) emphasised that 3D printing allows the fabrication of medicines with adjustable dose, size, shape, and release characteristics, making it highly suitable for personalised therapy, especially in pediatric and geriatric patients.
- Majrashi et al. (2024) discussed the growing role of 3D printing in drug delivery systems, highlighting its applications in tablets, capsules, implants, and transdermal systems. The study also pointed out challenges related to material compatibility and large-scale production.
- Recent advancements have also focused on integrating 3D printing with micro- and nanotechnology. A 2024 review reported that combining 3D printing with nano-based systems can enhance drug absorption, stability, and therapeutic effectiveness.
- A 2025 study highlighted that 3D printing enables on-demand production of personalised medicines with tailored drug combinations and release profiles, significantly improving treatment outcomes and patient compliance.
- Furthermore, recent research in 2025–2026 has explored the use of artificial intelligence and advanced materials in 3D printing. These innovations allow better control over dosage form design, improved reproducibility, and the development of smart drug delivery systems.
- Another recent review (2025) emphasised that 3D printing is gradually shifting pharmaceutical manufacturing from a "one-size-fits-all" approach to patient-specific therapy, enabling the production of complex dosage forms with improved bioavailability and therapeutic efficiency.

Overall, recent literature confirms that 3D printing is evolving rapidly with advancements in materials, design strategies, and digital technologies. However, challenges such as regulatory issues, material limitations, and scalability still need to be addressed to ensure its successful implementation in routine pharmaceutical practice.

5. CONCLUSION

Three-dimensional (3D) printing has introduced a new and flexible approach to pharmaceutical dosage form design, enabling the development of personalised medicines with precise control over drug dose and release. Techniques such as powder-based printing, ZipDose, hot melt extrusion, and stereolithography offer unique advantages in improving drug performance and patient compliance.

Although challenges related to materials, cost, and large-scale production remain, ongoing research and technological advancements are expected to overcome these limitations. Overall, 3D printing holds strong potential to play an important role in the future of pharmaceutical manufacturing and personalised healthcare.

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