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The Review on 3-Dimensional Printing in Novel Drug Delivery System for Personalised Drug Delivery

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Abstract: *Three-dimensional (3D) printing has emerged as a transformative technology in the development of novel drug delivery systems and personalized medicines. Unlike conventional manufacturing, which relies on fixed-dose, mass-produced formulations, 3D printing enables dose flexibility, structural customization, and on-demand production tailored to individual patient needs. This review discusses the evolution of 3D printing in pharmaceuticals, explains the underlying principles of additive manufacturing, and provides an in-depth overview of major printing techniques such as fused deposition modeling, stereolithography, selective laser sintering, binder jetting, semi-solid extrusion, and inkjet printing. The materials used—including polymers, excipients, hydrogels, and active pharmaceutical ingredients—are examined with regard to their suitability for different printing processes and their impact on drug release behavior. Key applications such as polypills, controlled-release systems, microneedles, transdermal patches, and implantable devices are highlighted, emphasizing the role of 3D printing in addressing dosage precision and patient-specific therapy. The review further outlines current challenges, including regulatory uncertainty, material limitations, stability concerns, and quality-control issues. Finally, future perspectives are explored, including the integration of artificial intelligence, 4D printing, smart materials, and point-of-care manufacturing. Collectively, this review underscores the potential of 3D printing to reshape modern pharmaceutical practice and advance truly individualized drug delivery..*

Keywords*:* 3D printing , techniques, additive manufacturing , polypill ,novel drug delivery system , personalised drug

I. INTRODUCTION

The Landscape Of Modern Medicine Is Undergoing A Profound Transformation, Driven By The Need To Move Beyond The Limitations Of Traditional, One-Size-Fits-All Pharmaceutical Approaches Toward Therapies That Are As Unique As The Patients They Serve.[1] At The Heart Of This Shift Lies The Concept Of Personalized Drug Delivery, Which Tailors Treatments To Individual Patient Characteristics—Such As Genetic Makeup, Metabolic Rate, Disease Progression, And Even Lifestyle Preferences—To Maximize Therapeutic Efficacy And Minimize Adverse Effects.[2] Complementing This Is The Development Of Novel Drug Delivery Systems (NDDS), Which Leverage Cutting-Edge Technologies To Create Innovative Platforms For Administering Medications In Ways That Enhance Precision, Bioavailability, And Patient Compliance.[3]

Among The Many Advancements Propelling These Fields Forward, 3D Printing, Or Additive Manufacturing, Stands Out As A Revolutionary Tool That Seamlessly Integrates The Principles Of Personalization And Innovation To Redefine How Drugs Are Designed, Produced, And Delivered.[4]

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3D Printing Technologies, Including Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), And Inkjet Printing, Allow For The Creation Of Sophisticated Drug Delivery Platforms Such As Orally Disintegrating Tablets, Implantable Devices, Microneedles, And Transdermal Patches These Systems Can Incorporate Multiple Active Pharmaceutical Ingredients (API) Into A Single Dosage Form, Known As Polypills, Or Feature Complex Geometries That Control Drug Release Kinetics (E.G., Immediate, Sustained, Or Pulsatile Release).[5] For Example, 3D-Printed Tablets Can Be Customized For Precise Dosing In Pediatric Or Geriatric Patients, While Novel Implants Can Deliver Drugs Directly To Targeted Tissues, Minimizing Systemic Side Effects. This Dual Capability Of Personalization And Innovation Makes 3D Printing A Transformative Tool In Pharmaceutical Development.[6]

The Advantages Of 3D Printing In Novel And Personalized DDS Are Significant. It Supports On-Demand Manufacturing, Enabling Rapid Production Of Patient-Specific Medications At The Point Of Care, Which Is Particularly Beneficial In Emergency Settings Or Underserved Regions.The Technology Also Facilitates The Design Of Intricate Microstructures, Such As Porous Scaffolds Or Multi-Layered Tablets, That Optimize Drug Bioavailability, Enhance Therapeutic Outcomes, And Improve Adherence.[7] Furthermore, 3D Printing Allows The Integration Of Advanced Materials, Including Biocompatible Polymers, Hydrogels, And Nanomaterials, To Create Next-Generation DDS With Enhanced Functionality. The FDA's Approval Of Spritam (Levetiracetam) In 2015, The First 3D-Printed Drug, Marked A Pivotal Milestone, Demonstrating The Clinical And Commercial Viability Of This Technology.[8]

However, Challenges Persist In Fully Realizing The Potential Of 3D Printing For Novel And Personalized Drug Delivery. Regulatory Hurdles, Including The Need For Standardized Quality Control And Safety Protocols, Remain A Significant Barrier. Scalability, Material Biocompatibility, And Integration With Digital Health Platforms For Real-Time Personalization Also Require Further Development. Nevertheless, Advancements In Bioprinting, Material Science, And Data-Driven Manufacturing Are Rapidly Addressing These Issues, Opening New Avenues For Precision Medicine And Point-Of-Care Therapeutics.[9]

II. HISTORY

3D Printing: A Technological Evolution Of Revolution

3D-Printing Technology Was Developed At The Massachusetts Institute Of Technology, Boston, USA, By Emanuel Sachs And Co-Researchers During The Late 1980s (US Patent Number 5204055). Initially, 3D Printing Was Performed Using The Principles Of Binder Jet Technology, Which Involves Laying Down A Layer Of Powder And Then Squirting A Liquid Binder On The Areas To Be Solidified.Later, The Science Underlying 3D-Printing Was Significantly Revolutionized With Several Modifications For Developing Objects With High Process Efficiency For Numerous Applications.

Further Innovations Were Made For Improving The Use Of Materials More Efficiently For Flexibility And Producing Objects In A More Precise Manner. In 1986, The 3D-Printing Approach Was Integrated With Computer-Aided Drafting Technology And Programming To Produce 3D Objects By Layering Materials Onto A Substrate.

The Principle Again Involves The Binding Of Material From The Printer To The Solid Surface Onto An X–Y Plane To Create The Base Of The Object. The Printer Then Moves Along The Z-Axis To Print The Complete Object With The Help Of Selected Material Onto The Base Of The Object For The Desired Thickness. With Fine Control Of The Printer Nozzle Geometry And Its Movement, Objects With Customized Shapes And Sizes Can Be Manufactured Using This Layer By Layer Printing Approach. Thus, The Process Of Additive Manufacturing Comprises Three Main Activities: 3D-Printing, Rapid Prototyping, And Scale-Up Application.[10]

III. PRINCIPLE OF 3 PRINTING IN PHARMACEUTICAL

The Concept Of Three-Dimensional (3D) Printing, Also Known As Additive Manufacturing, Is Based On The Simple But Powerful Principle Of Building Objects Layer By Layer From A Digital Design. Unlike Conventional Manufacturing Methods Such As Compression, Molding, Or Milling, Which Usually Subtract Material From A Larger Block Or Rely On Uniform Mass Production, 3D Printing Takes The Opposite Approach. It Adds Material Only Where It Is Needed, Which Provides Remarkable Flexibility In Creating Customized Drug Delivery Systems.[11]

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At The Heart Of This Process Lies The Digital Model, Which Is Designed Using Computer-Aided Design (CAD) Software. The Digital File Contains All The Details Of The Final Dosage Form, Including Its Shape, Internal Structure, Porosity, And Dimensions. Once The Model Is Finalized, It Is Processed By Slicing Software That Converts The Design Into Hundreds Or Thousands Of Thin Horizontal Layers. The Printer Then Deposits Or Solidifies The Material Layer By Layer, Following The Digital Instructions With High Precision, Until The Final Object Is Completed.[12]

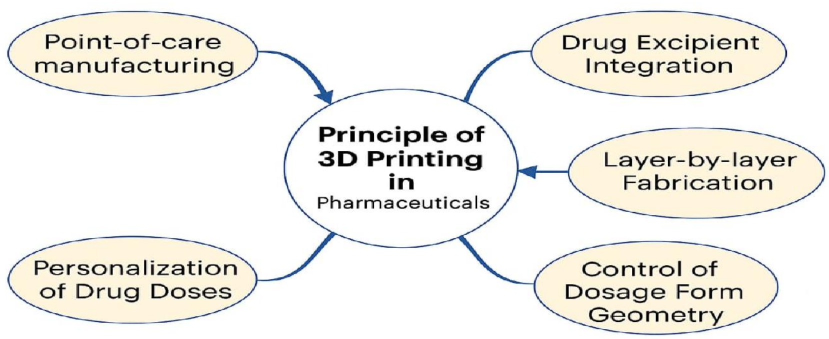

Fig no 1. Principle of 3d printing in pharmaceutical[14]

1. Drug–Excipient Integration

In Pharmaceutical 3D Printing, The Printing Material Is Not Just An Inert Polymer But A Carefully Chosen Formulation Of Active Pharmaceutical Ingredients (Apis) Along With Suitable Excipients Such As Polymers, Binders, And Plasticizers.These Excipients Play A Vital Role In Stabilizing The Drug During Printing, Controlling The Release Rate, And Ensuring Mechanical Strength Of The Final Dosage Form. By Adjusting The Excipient Composition And Drug Loading, Researchers Can Fine-Tune Drug Solubility, Dissolution Rate, And Bioavailability.[16]

2. Layer-By-Layer Fabrication

The Fundamental Principle Of 3D Printing Is The Layer-By-Layer Deposition Or Solidification Of Material. Each Layer Corresponds To A Cross-Section Of The Digital Model. Depending On The Printing Technique, This Can Be Achieved By:Extrusion Of Semi-Solid Or Molten Material Through A Nozzle (e.g. Fused Deposition Modeling)Laser Sintering Or Ultraviolet Curing To Solidify Powders Or Liquid Resins (e.g. SLA, SLS).Droplet-Based Deposition Where Small Amounts Of Drug-Containing Liquid Are Sprayed Onto A Surface (e.g. Inkjet Printing).This Controlled Layering Allows Precise Construction Of Highly Complex Geometries, Which Are Impossible To Achieve With Traditional Pharmaceutical Processes.[17]

3. Control Of Dosage Form Geometry

One Of The Most Significant Principles Of 3D Printing In Drug Delivery Is The Ability To Manipulate The Geometry And Internal Architecture Of The Dosage Form.By Changing The Shape, Surface Area, And Porosity, Researchers Can Directly Influence How Quickly Or Slowly The Drug Is Released. For Instance:A Porous Structure May Promote Rapid Disintegration And Immediate Releas.A Dense Multilayered Design May Enable Sustained Or Pulsatile Release.Complex Internal Channels Can Guide Drug Diffusion In A Controlled Manner.This Geometric Control Provides Unmatched Flexibility In Tailoring Therapies To Patient-Specific Needs.[18]

4. Personalization Of Drug Doses

Another Core Principle Is Dose Personalization. Traditional Manufacturing Requires Large Batches Of Tablets With Fixed Doses, But 3D Printing Enables Adjusting The Drug Content In Each Tablet Or Implant By Simply Modifying The Digital Design.[31] This Is Particularly Beneficial For Pediatric And Geriatric Patients, Where Dosing Requirements Are Highly Variable. It Also Supports The Creation Of Polypills, Which Combine Multiple Drugs Into A Single Unit With Separate Release Profiles.[19]

5. Point-Of-Care Manufacturing

The Principles Of 3D Printing Also Support On-Demand, Decentralized Manufacturing. Since Medicines Can Be Printed Directly At Hospitals, Pharmacies, Or Even Remote Clinics, Patients Could Potentially Receive Customized Treatment Almost Instantly. This Minimizes Storage Requirements, Reduces Wastage, And Ensures That Therapies Are Always Fresh And Tailored To Individual Needs.[20]

IV. TYPES OF 3D PRINTING TECHNIQUES

3D Printing Techniques in Pharmaceutical Drug Delivery

3D printing technologies have revolutionized pharmaceutical sciences by enabling the development of patient-specific dosage forms and advanced drug delivery systems. Among the wide variety of available approaches, six methods are considered the established core techniques—Fused Deposition Modeling (FDM), Binder Jetting (BJ), Stereolithography (SLA), Selective Laser Sintering (SLS), Semi-Solid Extrusion (SSE), and Inkjet Printing (Drop-on-Demand). Alongside these, several emerging methods such as Digital Light Processing (DLP), Pressure-Assisted Microsyringe (PAM), Electrohydrodynamic Jet (E-jet) Printing, and Hybrid/Multi-Material Printing are also attracting attention. Together, these techniques represent the present and future of 3D printing in personalized drug delivery.[21]

1. Fused Deposition Modeling (FDM)

Introduction:

Fused Deposition Modeling (FDM) is one of the earliest and most widely studied 3D printing techniques in pharmaceuticals. Its popularity stems from the relatively low cost of printers, the availability of polymers, and its adaptability to various drug formulations.[22]

Mechanism / Process:

In FDM, a thermoplastic filament—often prepared using hot-melt extrusion—is fed into a heated nozzle, where it is softened and extruded layer by layer onto the build platform. As the extruded filament cools, it solidifies to form the desired dosage form. By modifying design parameters such as infill density, layer thickness, and filament composition, the drug release profile can be finely tuned.[23]

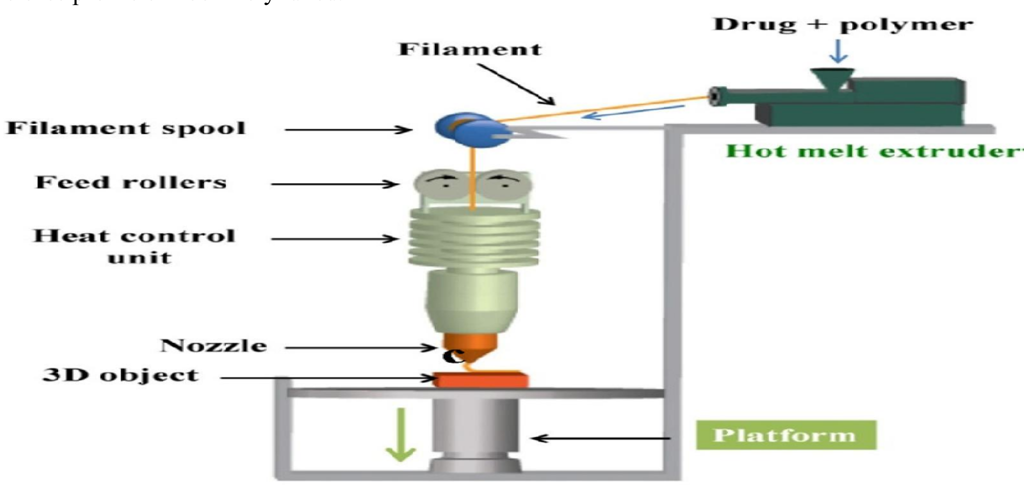

Fig no 2. fused deposition modelling[24]

Advantages:

The method is simple, scalable, and highly flexible. It allows the production of personalized medicines, polypills, and complex geometries that are difficult to achieve using conventional techniques. FDM also provides an opportunity to combine multiple drugs with different release profiles in a single tablet.

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Limitations:

The primary limitation is the requirement for high processing temperatures, which makes FDM unsuitable for thermolabile drugs. Additionally, the need for polymers that can be processed into filaments restricts excipient choices, and the relatively slow printing speed poses challenges for industrial-scale manufacturing.[25]

Applications:

FDM has been applied to fabricate extended-release tablets, gastroretentive systems, and implantable devices. Several studies have demonstrated the successful use of drug–polymer filaments for improving solubility and bioavailability of poorly soluble drugs.[26]

Recent Developments:

Advances in filament formulation, such as the incorporation of plasticizers and novel polymer blends, are helping to expand the use of FDM. Research is also focusing on combining FDM with hot-melt extrusion to improve mechanical strength and drug stability, thereby overcoming some of its limitations.[27]

2. Binder Jetting (BJ)

Introduction:

Binder Jetting (BJ) is a powder-based 3D printing technique that has received attention in pharmaceuticals for its ability to print without exposing drugs to heat. It represents one of the few technologies that has already reached commercial success.

Mechanism / Process:

In BJ, a thin layer of powder is spread over the build platform, and a liquid binder is selectively deposited to fuse particles together. This process is repeated until the entire object is formed, after which post-processing steps such as drying or curing are performed.[28]

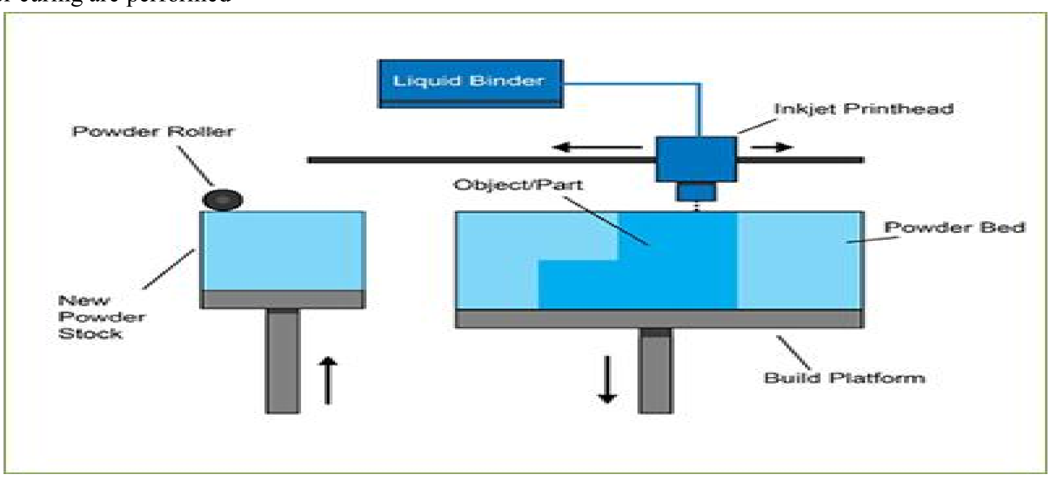

Fig no 3. binder jetting[29]

Advantages:

BJ is particularly suitable for thermolabile drugs since it operates at ambient temperature. It also enables the production of highly porous tablets, which enhances disintegration and dissolution. The process is relatively fast and allows high drug loading.

Limitations:

The main drawback is the poor mechanical strength of the printed tablets, which can lead to friability. The choice of suitable binders and powders is also limited, which restricts formulation flexibility. Moreover, drying and post-processing steps may add complexity.[30]

Applications:
The most notable example of BJ in pharmaceuticals is **Spritam® (levetiracetam)**, which became the first FDA-approved 3D printed drug.[48] It is manufactured using BJ and demonstrates rapid disintegration due to its porous structure. Beyond Spritam®, BJ has been explored for fast-dissolving oral dosage forms and high-dose formulations.[31]

Recent Developments:
Ongoing research focuses on improving binder formulations to enhance mechanical strength and expanding the range of excipients compatible with BJ. Emerging studies also explore combining BJ with coating technologies to produce tablets with dual-release profiles.[32]

3. Stereolithography (SLA)
Introduction:
Stereolithography (SLA) is a resin-based 3D printing technique that uses light to cure photopolymerizable materials. It is widely known for its ability to produce high-resolution and highly accurate structures.[33]
Mechanism / Process:
A vat of liquid resin containing drug molecules or excipients is selectively exposed to a laser or UV light source. The light initiates polymerization, solidifying the resin in a layer-by-layer manner until the desired object is formed.[34]

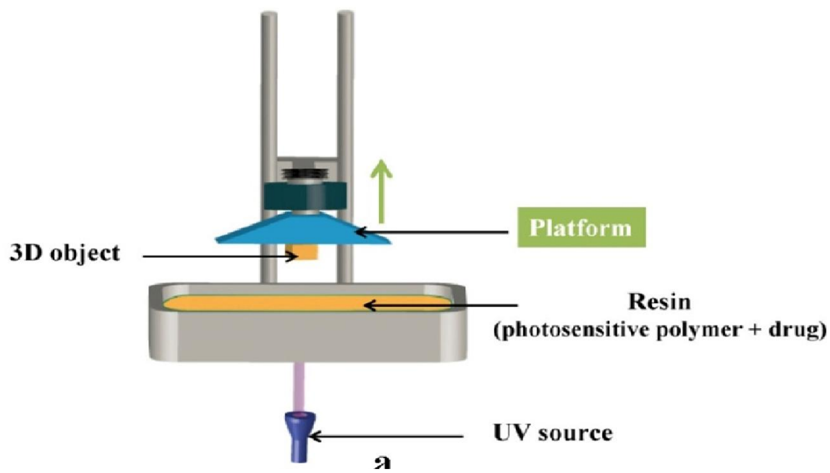

Fig no 4. Stereolithography[35]

Advantages:
The main advantage of SLA is its exceptional precision, allowing fabrication of miniaturized or intricate drug delivery devices. SLA also offers design freedom, enabling customization of geometry to influence drug release kinetics.
Limitations:
The method requires photopolymerizable resins, many of which pose toxicity concerns. Biocompatible resins are limited, and drug loading capacity is lower compared to extrusion-based techniques. Moreover, post-processing steps, such as washing and curing, are necessary to ensure product safety.[36]
Applications:
SLA has been investigated for the production of implants, microneedles, and transdermal systems. For instance, microneedle arrays fabricated by SLA have shown potential for delivering vaccines and biomolecules in a minimally invasive manner.[37]
Recent Developments:
Research is focusing on the design of novel photopolymers with improved biocompatibility and drug-loading potential. SLA is also being combined with drug-eluting coatings to expand its applications in controlled drug delivery.[38]

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4. Selective Laser Sintering (SLS)

Introduction:

Selective Laser Sintering (SLS) is another powder-based printing method, but unlike BJ, it does not use a liquid binder. Instead, high-energy laser beams selectively fuse drug–polymer powder particles.[39]

Mechanism / Process:

During the process, a thin layer of powder is spread onto the build platform, and a laser selectively sinters the desired regions. This process is repeated until the final dosage form is produced. The absence of binders reduces the need for post-processing.[40]

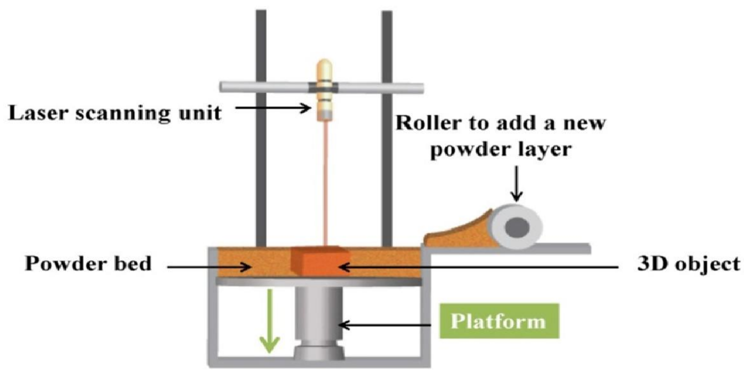

Fig no 5. Selective laser sintering[41]

Advantages:

SLS can produce strong structures with good mechanical stability. It allows control of porosity, which can be exploited to design both immediate- and sustained-release formulations. Additionally, the method enables fabrication of complex dosage forms without the need for solvents.

Limitations:

The requirement for high laser energy restricts its use to thermostable drugs. Equipment costs are high, and surface roughness of the final product may influence drug release. Regulatory acceptance of the method in pharmaceuticals is still in early stages.[43]

Applications:

SLS has been applied in fabricating tablets with tailored release profiles and drug-loaded scaffolds for implants. Studies have demonstrated its utility in producing porous structures suitable for fast drug release.[44]

Recent Developments:

Hybrid approaches combining SLS with polymer coating and surface engineering techniques are being explored to improve drug release control and expand material compatibility.[45]

5. Semi-Solid Extrusion (SSE)

Introduction:

Semi-Solid Extrusion (SSE) represents a versatile approach in which paste, gel, or semi-solid formulations are extruded through a nozzle to build 3D structures. Unlike FDM, SSE does not require high heat, making it more suitable for fragile molecules.

Mechanism / Process:

Formulations are loaded into a syringe-like system and extruded under pneumatic or mechanical pressure. The deposited layers are subsequently solidified by cooling, drying, or chemical cross-linking. The rheological properties of the formulation play a key role in ensuring printability.[46]

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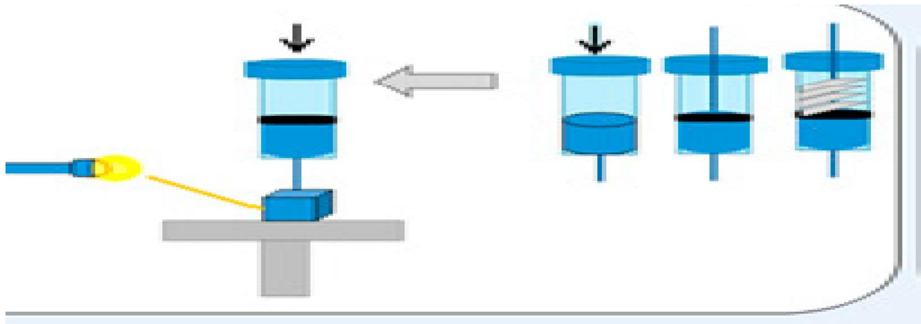

Fig no 6.semi solid extrusion[47]

Advantages:
SSE is highly suitable for thermolabile drugs, proteins, and biologics. It supports the use of hydrogels and natural polymers, offering high drug-loading potential and the possibility of sustained release. The process also enables incorporation of living cells in the context of bioprinting.

Limitations:
The technique has relatively low resolution compared to SLA and Inkjet printing. The semi-solid formulations may suffer from stability issues, and printing speed is slower than powder-based techniques.

Applications:
SSE has been applied in producing ophthalmic gels, peptide-loaded implants, and bioactive scaffolds. It has also been explored in regenerative medicine, where hydrogel matrices are loaded with drugs or cells.

Recent Developments:
Recent innovations focus on optimizing rheological properties of semi-solid formulations and combining SSE with cross-linking chemistries to improve stability. Research into personalized hydrogel implants for localized drug delivery is expanding rapidly.[48]

6. Inkjet Printing (Drop-on-Demand)

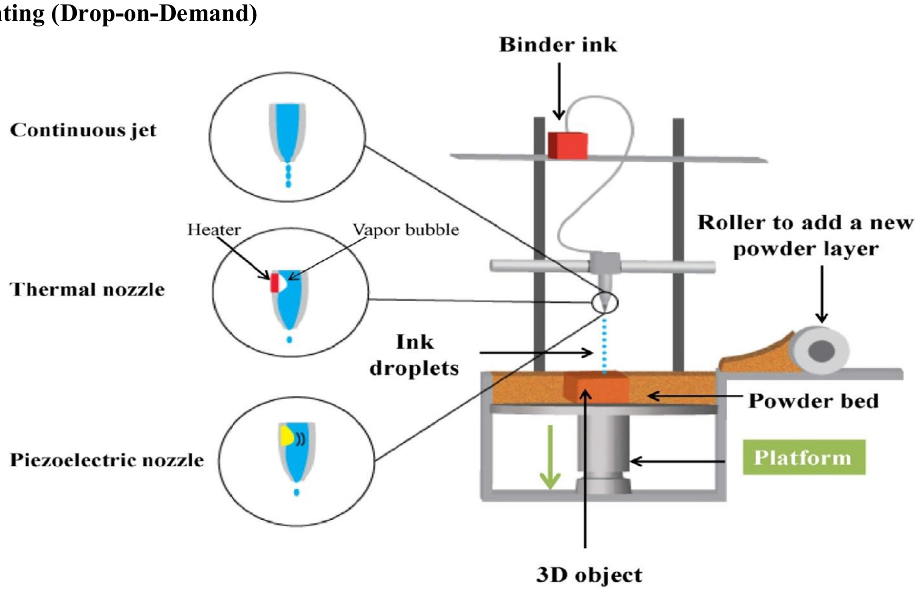

Fig no7.inject printing[50]

Introduction:
Inkjet Printing, or Drop-on-Demand (DoD) printing, is a liquid-based technology where small droplets of drug

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solutions or suspensions are ejected with high precision onto a substrate. This technique is highly regarded for its accuracy and potential for individualized dosing.

Mechanism / Process:

A print head releases micro-droplets in a controlled manner, with the deposition pattern determining the final dosage form. By adjusting the number and size of droplets, precise dosing from micrograms to milligrams can be achieved[49]

Advantages:

Inkjet printing allows accurate drug placement and is ideal for low-dose formulations. It can accommodate multiple drugs in layered formats, enabling combination therapies. It also operates at room temperature, making it suitable for thermolabile molecules.

Limitations:

The method is limited to low-viscosity solutions and cannot accommodate formulations with high drug loads. Drug stability in liquid form may also present challenges. Additionally, nozzle clogging is a common issue.

Applications:

Inkjet printing has been widely explored for pediatric formulations, thin-film dosage forms, and vaccines. Its ability to deliver very low doses makes it suitable for highly potent drugs. Hospitals may eventually adopt it for on-demand preparation of individualized medicines.[51]

Recent Developments:

Current research explores the use of inkjet printing for vaccine microdosing and production of personalized strips for chronic diseases. Its integration with smart digital technologies is expected to make real-time personalized drug manufacturing possible in clinical settings[52]

4.2. Emerging 3D Printing Methods

While the six established methods dominate pharmaceutical research, several emerging technologies are gaining importance. These methods are still under development but demonstrate unique advantages and potential future applications

1. DIGITAL LIGHT PROCESSING (DLP)

Introduction:

Digital Light Processing (DLP) is a photopolymerization-based 3D printing technique similar to Stereolithography (SLA). However, instead of using a laser to cure single points, DLP projects an entire image of a layer using a digital micromirror device, which allows faster and more accurate printing.

Mechanism / Process:

A digital projector emits light patterns onto a photosensitive resin. Each projected layer hardens through polymerization, and the process continues layer by layer until the complete structure is formed.[53]

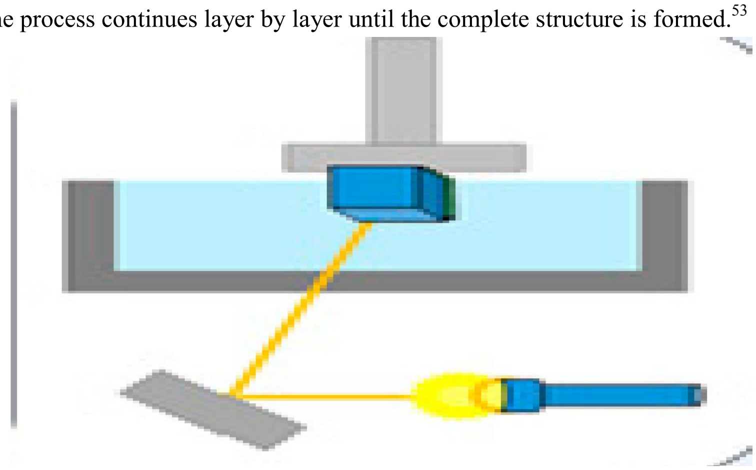

Fig no 8.digital light processing[54]

Advantages:
DLP provides faster printing compared to point-by-point laser methods and offers excellent accuracy and smooth surface quality. It is highly suitable for small, complex drug delivery devices where precision is critical.

Limitations:
The main limitation of DLP is the limited number of biocompatible photopolymer resins available for pharmaceutical use. Post-curing is also required to ensure safety and stability.

Applications:
DLP is used to create microneedle patches, customized oral dosage forms, and implantable drug delivery systems that require fine detail and surface precision.[55]

Recent Developments:
Recent research focuses on developing safer biocompatible resins and improving curing speed. These updates have increased printing accuracy and made DLP more suitable for producing personalized implants and dosage forms.[56]

2. PRESSURE-ASSISTED MICROSYRINGE (PAM)

Introduction:
Pressure-Assisted Microsyringe (PAM) printing is an advanced extrusion-based method similar to Semi-Solid Extrusion (SSE). It provides better control over material flow and is especially useful for printing gels, pastes, and viscous biomaterials under mild conditions.

Mechanism / Process:
A controlled pneumatic pressure pushes semi-solid formulations through a fine nozzle. The nozzle moves layer by layer to form a 3D structure with uniform thickness and accuracy.[57]

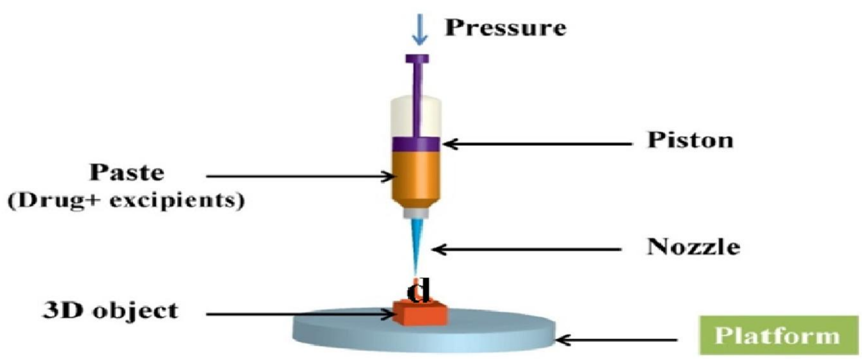

Fig no 9. Pressure assisted microsyringe[58]

Advantages:
PAM allows precise printing without high temperature, making it suitable for sensitive materials like proteins and peptides. It supports the use of hydrogels and can create complex designs with consistent drug distribution.

Limitations:
The process is relatively slow, and controlling uniform pressure can be difficult. Scaling up for industrial production also remains a challenge.

Applications:
PAM is used in printing tissue scaffolds, biodegradable implants, and hydrogel-based drug delivery systems for regenerative medicine.[59]

Recent Developments:
Recent studies have improved the pressure control system and introduced new hydrogel formulations. PAM is now being used to print multi-drug implants and customized scaffolds for localized drug delivery.[60]

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4.3.COMPARISION OF 3 PRINTING TECHNIUES

Technique	Mechanism	Suitable Materials	Drug Stability	Advantages	Limitation	Applications
Inkjet Printing	Drop-on-demand microdroplet ejection	Drug solutions or suspensions	Suitable for thermolabile drugs	Accurate dosing, good for potent drugs	Low viscosity only, nozzle clogging	Thin films, pediatric doses, vaccines
Binder jetting	Powder bed fused by liquid binder	Powders with liquid binders	Suitable for thermolabile drugs	Fast, porous tablets, high drug load	Weak mechanical strength, needs post-processing	Spritam®, fast-dissolving tablets
Selective Laser Sintering	Laser selectively sinters polymer powder	Drug-polymer powders	Requires thermostable drugs	Strong, solvent-free, porous structures	High energy cost, surface roughness	Tailored-release tablets, scaffolds
Stereolith-ography	Laser/UV cures liquid resin layer by layer	Photopolymer resins	Limited by resin compatibility	High resolution, intricate designs	Toxicity of resins, low drug load	Microneedles, implants
Digital Light Processing	Digital micromirror projects light to cure resin	Photopolymers	Limited by resin safety	Fast, high resolution	Few safe resins, needs post-processing	Microneedles, oral forms
Semi-solid Extrusion	Extrusion of paste/gel through syringe nozzle	Hydrogels, gels, pastes	Suitable for thermolabile & biologics	Good for proteins/peptides, bioprinting	Low resolution, slow speed	Implants, hydrogels, tissue engineering
Fused deposition Modelling	Extrusion of melted polymer filament layer by layer	Thermoplastic polymers (PLA, PVA, HPMC)	Only thermostable drugs	Simple, scalable, good for polypills	High temp unsuitable for thermolabile drugs	Oral tablets, implants
Pressure Assisted microsyri-nge	Pressure-assisted extrusion of viscous material	Hydrogels, viscous pastes	Biologics & thermolabile drugs	Mild processing, suitable for proteins	Slow, difficult to scale	Tissue scaffolds, implants

Table no 1.comparision of 3d printing techniques in pharmaceuticals[61]

V. MATERIAL USED IN 3D PRINTING

The Selection Of Suitable Materials Is One Of The Most Critical Aspects In The Development Of 3D Printed Drug Delivery Systems. The Material Not Only Determines The Printability And Stability Of The Final Product But Also

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Directly Affects The Drug Release Profile, Biocompatibility, Patient Safety, And Therapeutic Efficacy. Materials For Pharmaceutical 3D Printing Must Meet Stringent Requirements, Including Being Non-Toxic, Pharmaceutically Acceptable, And Capable Of Processing Under Mild Conditions That Do Not Degrade The Active Pharmaceutical Ingredient (API) Broadly, The Materials Can Be Classified Into Polymers, Excipients, Hydrogels, And Active Pharmaceutical Ingredients.[62]

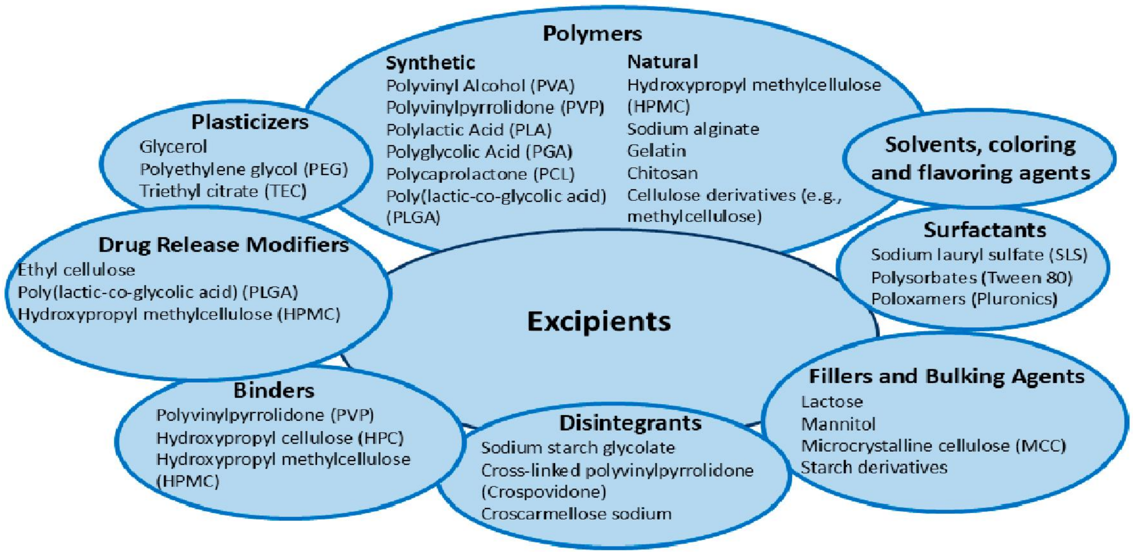

Fig no 10.The main excipient used in 3d printing [63]

1. Polymers

Polymers Are The Most Widely Used Materials In Pharmaceutical 3D Printing Due To Their Versatility, Biocompatibility, And Tunable Physicochemical Properties. They Act As The Backbone Of The Dosage Form, Providing Structural Integrity, Controlling Drug Release, And Enhancing Mechanical Strength.

Biodegradable Polymers: Polylactic Acid (PLA), Polycaprolactone (PCL), And Polyglycolic Acid (PGA) Are Commonly Used Biodegradable Polymers. They Degrade In The Body Into Non-Toxic By-Products And Are Especially Useful For Implants And Controlled-Release Systems. PLA Is Widely Used In Fused Deposition Modeling (FDM) Because Of Its Good Thermal Stability And Ease Of Printing.

Water-Soluble Polymers: Polyvinyl Alcohol (PVA), Hydroxypropyl Methylcellulose (HPMC), And Polyethylene Glycol (PEG) Are Used When Rapid Dissolution Or Drug Release Is Desired. These Polymers Are Also Favored For Orodispersible Formulations, Pediatric Medicines, And Personalized Fast-Release Tablets

Functional Polymers: Polymers Such As Eudragit® Can Be Tailored To Provide Ph-Dependent Release, Protecting Drugs From Gastric Degradation Or Enabling Targeted Delivery To The Intestine Or Colon.[64]

2. Pharmaceutical Excipients

Excipients Are Added To Improve Processability, Stability, And Drug Release Characteristics. In 3D Printing, Excipients Play An Important Role In Ensuring Smooth Extrusion Or Jetting And In Preventing Clogging Or Deformation Of The Printed Product.

Plasticizers : Reduce Brittleness Of Polymers And Improve Flexibility During Extrusion- Based Printing.(eg; Glycerol, Triethyl Citrate):

Fillers : Enhance Mechanical Strength And Bulk Density. (E.G., Lactose, Mannitol, Microcrystalline Cellulose):

Binders : Provide Adhesion Between Layers In Binder Jetting Or Powder Bed Printing.
(eg: Povidone)

Lubricants : Reduce Friction And Prevent Sticking During Printing . The Choice Of Excipient Depends On The Printing Technology. For Example, In Inkjet Printing, Solvents And Viscosity-Modifying Agents Are Necessary To

Control Droplet Formation, While In FDM, Plasticizers And Stabilizers Are Crucial For Filament Flexibility (eg. Magnesium Stearate, Talc)[65]

3. Hydrogels And Biomaterials

Hydrogels Are 3D Networks Of Hydrophilic Polymers That Can Absorb Large Amounts Of Water. They Are Gaining Increasing Attention In 3D Printing Due To Their Biocompatibility And Ability To Mimic Biological Tissues.

Natural Hydrogels: Alginate, Gelatin, And Chitosan Are Biopolymers Widely Used In Bioprinting Applications. They Are Suitable For Encapsulating Cells Or Fragile Biomolecules Such As Proteins And Peptides.

Synthetic Hydrogels: Polyethylene Glycol Diacrylate (PEGDA) And Polyacrylamide Are Used When More Controlled Mechanical Strength And Degradation Rates Are Required.[116]

Applications: Hydrogels Are Useful In Creating Controlled-Release Matrices, Wound-Healing Patches, Tissue Scaffolds, And Implantable Drug Devices. They Also Allow For Localized And Sustained Drug Delivery, Which Is Essential In Cancer Therapy And Regenerative Medicine[67]

4. Active Pharmaceutical Ingredients (Apis)

The Integration Of Apis Into The Printing Material Is The Most Important Step In Fabricating Functional Drug Delivery Systems. Apis Can Be Incorporated In Different Forms Such As Powders, Solutions, Or Dispersions Depending On The Printing Technique.

Heat-Stable Drugs: Apis Such As Levetiracetam, Caffeine, And Paracetamol Can Be Successfully Processed Through High-Temperature Methods Like FDM.Heat-Sensitive Drugs: Proteins, Peptides, And Biological Molecules Require Milder Conditions Such As Inkjet Printing Or Semi-Solid Extrusion, Since These Techniques Avoid High Thermal Degradation.

Poorly Soluble Drugs: Amorphous Solid Dispersions With Polymers Like PVA Or PEG Can Be Used To Improve Solubility And Bioavailability.The Concentration Of The API Must Be Optimized To Avoid Crystallization, Ensure Uniform Distribution, And Maintain Reproducibility Between Batches[68]

5. Material-Property Relationship

The Choice Of Material Influences:

Mechanical Properties: Hardness, Brittleness, And Flexibility Of The Dosage Form.

Drug Release Profile: Immediate, Sustained, Delayed, Or Pulsatile Release.

Biocompatibility: Safety And Tolerability Inside The Human Body.

Stability: Resistance To Moisture, Light, And Temperature.[69]

6. Emerging Trends In Material Development

With The Rapid Advancement Of 3D Printing, Researchers Are Developing Smart Materials That Respond To Stimuli Such As Ph, Temperature, Or Enzymes. These Materials Allow For Dynamic And Targeted Drug Release. Nanocomposite Polymers And Bio-Inks Containing Nanoparticles Are Also Being Investigated To Enhance Solubility, Improve Mechanical Properties, And Enable Multifunctional Drug Delivery Systems.[70]

VI. PERSONALISATION IN 3 PRINTING DRUG DELIVERY

Personalized Medicine Is Rapidly Emerging As A Cornerstone Of Modern Healthcare, And 3D Printing Has Become One Of The Most Promising Technologies To Bring This Concept Into Reality. Traditional Pharmaceutical Manufacturing Is Largely Based On Mass Production, Which Means Drugs Are Produced In Fixed Doses And Standard Forms. While This Approach Works For The Majority Of Patients, It Does Not Account For Individual Differences Such As Age, Weight, Metabolism, Genetics, Or The Presence Of Multiple Diseases. This Gap Often Results In Under-Dosing, Overdosing, Or Poor Patient Compliance.By Contrast, 3D Printing Introduces A New Level Of Flexibility, Allowing The Design And Fabrication Of Medicines Tailored To Each Patient’s Unique Requirements. This Shift From

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A "One-Size-Fits-All" Model To Patient-Specific Formulations Has The Potential To Improve Treatment Outcomes, Reduce Side Effects, And Enhance Adherence To Therapy.[71]

1. Dose Customization

One Of The Most Straightforward Applications Of 3D Printing In Personalization Is The Ability To Adjust Drug Dose With High Precision. Instead Of Relying On Standard Tablet Strengths (For Example, 5 Mg Or 10 Mg), 3D Printing Enables A Doctor To Prescribe Exactly The Dose Needed — Such As 7.5 Mg Or 12 Mg — And Have It Fabricated On Demand. This Is Especially Useful In Pediatrics And Geriatrics, Where Dosing Flexibility Is Crucial. The Ability To Fine-Tune Dose Levels Also Benefits Patients With Chronic Conditions Like Epilepsy Or Cancer, Where Therapy Often Requires Frequent Adjustments.[72]

2. Multi-Drug Polypills

Another Exciting Possibility Is The Development Of Polypills. Patients With Chronic Diseases Such As Diabetes Or Cardiovascular Disorders Are Often Prescribed Multiple Medications, Leading To "Pill Burden" And Poor Compliance. With 3D Printing, Several Drugs Can Be Incorporated Into A Single Tablet, Each With A Programmed Release Profile.For Instance, One Drug Can Be Released Immediately To Provide Rapid Action, While Another Is Released Slowly To Maintain Therapeutic Effect Over Many Hours. This Reduces The Number Of Tablets A Patient Must Take Daily, Simplifies Treatment, And Lowers The Chances Of Missing Doses.[73]

3. Age-Specific And Patient-Friendly Formulations

Children And Older Adults Often Struggle With Standard Tablets, Either Because They Are Too Large, Unpalatable, Or Difficult To Swallow. 3D Printing Allows The Creation Of Age-Specific Dosage Forms. For Children, Medicines Can Be Printed In Smaller Sizes, In Appealing Shapes, And Even In Flavors That Make Them Easier To Take. For The Elderly, Orodispersible Tablets That Dissolve Quickly In The Mouth Can Be Designed, Addressing The Problem Of Swallowing Difficulties. Such Patient-Friendly Designs Go A Long Way In Improving Adherence And Acceptance Of Therapy.[74]

4. Tailored Release Profiles

Personalization Is Not Limited To Dose Or Size — It Extends To How The Drug Is Released Inside The Body. Using 3D Printing, Tablets Can Be Engineered With Sophisticated Geometries And Multiple Layers To Provide Customized Release Patterns:

Immediate Release For Fast Relief In Conditions Like Pain.

Sustained Release For Chronic Illnesses Such As Hypertension.

Delayed Or Pulsatile Release For Drugs That Must Act At A Specific Time Of Day, Such As Those Aligned With Circadian Rhythms.

This Level Of Control Ensures That The Medicine Acts Exactly When And Where It Is Needed, Improving Both Safety And Effectiveness.[75]

5. On-Demand Production At Point-Of-Care

A Further Advantage Of 3D Printing Is The Possibility Of Manufacturing Drugs Directly At Hospitals, Clinics, Or Pharmacies. Instead Of Relying On Large Factories, A Healthcare Provider Could Print A Personalized Drug Formulation On-Site, Tailored To The Patient's Needs Immediately After Diagnosis. This "Point-Of-Care Manufacturing" Is Particularly Valuable In Cases Where Treatments Require Frequent Dose Modifications, Such As In Cancer Therapy, Where Doses Are Adjusted According To Patient Response And Tolerance.[76]

6. Special Populations And Rare Diseases

Patients With Rare Diseases Or Very Specific Medical Conditions Often Face Difficulties In Accessing Suitable Drugs, Since Pharmaceutical Companies Rarely Produce Formulations For Small Patient Populations. 3D Printing Can Bridge This Gap By Enabling Small-Scale Or Single-Patient Production. Similarly, Transplant Patients Or Individuals On Complex Drug Regimens Can Receive Personalized Formulations That Simplify Therapy And Reduce The Risk Of Errors.[77]

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VII. APPLICATIONS OF 3D PRINTING IN NOVEL DRUG DELIVERY SYSTEMS

1 Controlled And Sustained Release Systems

One Of The Most Promising Applications Of 3D Printing In Drug Delivery Is The Development Of Controlled And Sustained Release Dosage Forms. Traditional Oral Tablets Often Release Drugs Rapidly, Which Can Cause Fluctuations In Plasma Concentration And Lead To Side Effects Or Reduced Efficacy. 3D Printing Enables Researchers To Design Dosage Forms With Complex Geometries, Multilayer Structures, Or Porous Matrices That Allow The Drug To Be Released Gradually Over A Specific Period Of Time.

For Example, Hydrophilic And Hydrophobic Polymers Can Be Incorporated Into The Design To Regulate Dissolution And Diffusion Rates. By Altering Internal Structures, Such As Honeycomb-Like Pores Or Layered Drug Reservoirs, The Release Profile Can Be Tailored Precisely For Different Therapeutic Needs. This Ensures Steady Drug Levels, Minimizes Dosing Frequency, And Enhances Patient Compliance, Particularly In Chronic Diseases Like Hypertension, Epilepsy, Or Diabetes Where Long-Term Therapy Is Required.[78]

2. Targeted Drug Delivery

3D Printing Provides A Unique Opportunity To Create Dosage Forms That Deliver Drugs Specifically To Certain Regions Of The Body, Such As The Stomach, Small Intestine, Or Colon. This Site-Specific Delivery Improves Therapeutic Efficiency And Reduces Systemic Side Effects. For Instance, Colon-Targeted Systems Are Valuable In Treating Inflammatory Bowel Disease (IBD) Or Colon Cancer, Where Drugs Need To Act Locally Without Being Degraded In The Upper Gastrointestinal Tract.

By Combining Ph-Sensitive Polymers, Time-Delay Coatings, Or Layer-By-Layer Printed Structures, The Drug Can Be Protected During Transit And Only Released At The Target Site. Such Precision Is Difficult To Achieve With Conventional Manufacturing Techniques. Moreover, Targeted Systems Also Allow For Lower Drug Doses, As The Medication Is Concentrated At The Site Of Action Rather Than Distributed Throughout The Entire Body.[79]

3. Multi-Drug Loading (Polypills)

Patients Suffering From Chronic Conditions Such As Cardiovascular Disease, Diabetes, Or HIV Often Require Multiple Medications Daily. This Polypharmacy Can Reduce Adherence And Increase The Chances Of Errors. 3D Printing Addresses This Challenge By Enabling The Design Of "Polypills," Which Integrate Several Active Pharmaceutical Ingredients (Apis) Into A Single Dosage Form.

Each Drug Can Be Compartmentalized In Separate Layers Or Regions Within The Pill, With Different Release Profiles—Some Immediate, Others Sustained. This Not Only Reduces The Pill Burden But Also Simplifies Therapy And Improves Adherence. A Classic Example Is Aprecia's FDA-Approved Spritam®, A 3D-Printed Epilepsy Medication That Demonstrates How High-Dose Drugs Can Be Efficiently Produced And Administered Using This Technology.[80]

4. Pediatric And Geriatric Friendly Dosage Forms

Children And Elderly Patients Often Face Difficulties In Swallowing Conventional Solid Dosage Forms. For These Populations, Palatability, Safety, And Precise Dosing Are Especially Important. 3D Printing Offers The Ability To Design Chewable Tablets, Fast-Dissolving Films, Or Even Candy-Like Formulations In Various Shapes, Sizes, And Flavors That Are More Acceptable To Pediatric And Geriatric Patients.

Furthermore, The Dose Can Be Personalized Based On Body Weight, Age, Or Metabolic Needs. For Example, A Child May Require A Much Smaller Dose Than An Adult, And 3D Printing Allows Accurate Fabrication Of The Exact Amount Required. This Reduces The Risks Of Overdosing Or Underdosing While Making The Treatment Experience More Patient-Friendly.[81]

5. Implantable Drug Delivery Devices

Implants Are A Vital Component Of Novel Drug Delivery Systems, And 3D Printing Allows Their Customization According To Patient Anatomy And Therapeutic Needs. Biodegradable Polymeric Implants Can Be Fabricated To Release Drugs Steadily Over Weeks Or Even Months. These Are Particularly Valuable In Areas Such As Oncology, Where Localized And Sustained Drug Delivery Is Required, Or In Hormone Therapy, Where A Constant Release Profile Ensures Therapeutic Efficacy Additionally, The Ability To Personalize Implants To Match The Shape And Size Of The Implantation Site Improves Comfort And Compatibility. By Loading The Implant With Multiple Drugs Or

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Adjusting Release Kinetics, Treatment Outcomes Can Be Optimized For Complex Conditions, Reducing The Need For Repeated Surgeries Or Frequent Dosing.[82]

6. Transdermal And Microneedle Patches

Another Innovative Application Of 3D Printing In Novel Drug Delivery Systems Is The Fabrication Of Microneedle Arrays And Transdermal Patches. These Systems Provide A Painless Alternative To Injections While Improving Patient Compliance. Drugs Such As Insulin, Vaccines, Or Pain Medications Can Be Delivered Directly Through The Skin, Bypassing The Gastrointestinal Tract And First-Pass Metabolism.3D Printing Allows Precise Control Over The Length, Density, And Sharpness Of Microneedles, Which Determines Penetration Depth And Drug Release Profile. Furthermore, Patches Can Be Designed To Release Drugs Immediately Or Over A Prolonged Period, Depending On Therapeutic Needs. This Approach Holds Great Promise For Self-Administration And Mass Vaccination Programs.[83]

VIII. ADVANTAGES OF 3D PRINTING IN PERSONALIZED MEDICINES

1 Patient-Specific Dosing

One Of The Biggest Strengths Of 3D Printing Is The Ability To Prepare Dosage Forms

According To Individual Patient Requirements. Unlike Conventional Dosage Forms That Are Manufactured In Fixed Doses, 3D Printing Allows Fine-Tuning Of The Drug Amount.

For Example, In Pediatric Patients, Even Small Variations In Body Weight May Require Dosage Adjustments That Standard Commercial Formulations Cannot Provide. Similarly, Elderly Patients With Altered Metabolism And Organ Function Benefit From Exact Doses.

Personalized Dosing Reduces Adverse Drug Reactions And Improves Therapeutic Efficacy, Which Is A Key Goal Of Precision Medicine.[83]

2. Complex Drug-Release Profiles

Traditional Tablets Often Follow Immediate Release Or Simple Sustained Release Patterns. In Contrast, 3D Printing Makes It Possible To Design Internal Architectures Of Tablets (Like Porous Structures, Multilayers, Or Core-Shell Systems) That Control How The Drug Is Released.

A Single 3D Printed Tablet Can Provide A Combination Of Immediate Release (For Fast Action) And Sustained Release (For Long-Term Effect), Improving Patient Convenience And Treatment Outcomes.This Flexibility Is Particularly Valuable In Diseases Like Epilepsy, Cancer, Or Cardiovascular Conditions Where Timing Of Drug Release Is Crucial.[84]

3. Multi-Drug Polypills

Patients With Chronic Diseases Often Need To Take Multiple Medications Daily. 3D Printing Enables The Fabrication Of "Polypills" – Single Tablets That Contain Multiple Drugs With Different Release Characteristics.

For Instance, A Diabetic Patient Who Also Suffers From Hypertension And Hyperlipidemia May Receive A Single Pill Containing All Necessary Medications, Reducing Pill Burden.This Not Only Improves Compliance But Also Decreases The Risk Of Medication Errors, Which Is A Common Problem In Polypharmacy.[85]

4. On-Demand Manufacturing Of Medicines

3D Printing Eliminates The Need For Bulk Storage And Mass Manufacturing. Hospitals And Pharmacies Can Print Drugs On-Site According To Patient Demand.This Approach Is Highly Useful In Emergency Situations, Rare Diseases, Or Remote Areas Where Conventional Supply Chains Are Difficult To Maintain.On-Demand Printing Also Reduces Drug Wastage And Helps In Managing Short Shelf-Life Medications.[86]

5. Flexibility In Research And Development

3D Printing Provides Scientists With A Flexible Tool To Modify Formulations Quickly. They Can Adjust Drug Release, Shape, Or Composition Without Going Through Long Industrial Processes.For Example, During Clinical Trials, Different Dose Strengths Can Be Produced Rapidly, Saving Time And Cost.This Accelerates The Process Of Drug Development, Making It Easier To Test Multiple Designs In A Short Duration.[87]

6. Customization For Special Populations

Pediatric And Geriatric Populations Face Difficulties In Swallowing Conventional Tablets. 3D Printing Allows Creation Of Chewable, Dispersible, Or Rapidly Dissolving Tablets That Improve Acceptability.Patients With

Swallowing Disorders (Dysphagia) Can Benefit From Unique Dosage Forms Designed For Ease Of Administration.Similarly, Veterinary Medicine Can Also Benefit, As Animals Often Require Specifically Flavored Or Dosed Medications.[88]

IX. LIMITATIONS AND CHALLENGES OF 3D PRINTING IN DRUG DELIVERY

1. Regulatory Hurdles And Approval Challenges

Regulatory Authorities Such As FDA And EMA Require Strict Evidence Of Safety, Quality, And Reproducibility.Currently, Only One 3D-Printed Drug (Spritam®) Has FDA Approval. The Pathway For Approval Of New Products Remains Unclear, Creating Hesitation Among Pharmaceutical Companies.Establishing Universal Regulatory Frameworks For 3D Printing In Pharmacy Is Still A Work In Progress.[89]

2. Scalability And Production Speed Issues

While 3D Printing Is Effective For Small-Batch And Customized Therapy, It Is Relatively Slow Compared To Conventional Mass Production Methods Such As Tablet Compression.For Large-Scale Industrial Use, This Limitation Makes 3D Printing Less Practical.Printing Each Dosage Unit Individually Is Time-Consuming, Which Restricts Its Widespread Commercial Application.[90]

3. Stability Concerns Of Active Pharmaceutical Ingredients (Apis)

Many 3D Printing Methods, Such As Fused Deposition Modeling (FDM), Require High Temperatures That Can Degrade Heat-Sensitive Drugs.Similarly, Stereolithography (SLA) Uses UV Light, Which May Cause Photodegradation Of Some Apis.These Stability Challenges Restrict The Choice Of Drugs That Can Be Formulated Using 3D Printing.[91]

4. High Cost Of Technology And Implementation

Although The Cost Of 3D Printers Is Gradually Decreasing, Pharmaceutical-Grade 3D Printing Still Requires High Initial Investment.Specialized Excipients, Polymers, And Validation Methods Add To The Overall Cost, Making It Less Accessible In Resource-Limited Countries.Training Of Personnel And Maintenance Of High-Quality Standards Also Contribute To Expenses.[92]

5. Quality Control And Reproducibility Difficulties

Ensuring Uniformity Of Drug Content In Each Printed Dosage Unit Is Challenging. Small Variations In Printer Calibration Or Material Flow Can Lead To Inconsistencies.

Mechanical Properties Such As Hardness, Friability, And Dissolution Rate Must Be Tested For Each Batch, Which Is Resource-Intensive.Unlike Conventional Tablet Manufacturing, Standardized Methods For Quality Assurance In 3D Printed Drugs Are Still Lacking.[93]

6. Ethical, Legal, And Safety Concerns

Intellectual Property Rights Become Complicated When Dosage Forms Can Be Digitally Designed And Shared.Liability Issues Arise If A Wrong Dose Is Printed Or If Errors Occur Outside Regulated Environments.The Possibility Of Misuse (E.G., Printing Of Controlled Substances) Raises Additional Concerns About Safety And Monitoring.[94]

X. FUTURE PERSPECTIVES OF 3D PRINTING IN NOVEL DRUG DELIVERY SYSTEMS

1. Integration With Precision Medicine And AI

The Future Of Drug Delivery Lies In Precision Medicine, Where Treatments Are Customized According To A Patient's Genetic Makeup, Disease Profile, And Metabolism.3D Printing, When Combined With Artificial Intelligence (AI) And Big Data Analytics, Can Design Drug Formulations Optimized For Each Patient.For Example, AI Can Analyze Patient Data And Suggest A Drug Formulation, Which Can Then Be Printed Immediately In A Hospital Setting.[95]

2. 4D Printing – The Next Revolution

While 3D Printing Creates Static Dosage Forms, 4D Printing Introduces Materials That Change Their Structure Over Time In Response To Stimuli Such As Ph, Temperature, Or Enzymes.In Drug Delivery, This Means Creating Tablets Or Implants That Adjust Their Release Rate Depending On The Patient's Physiological Condition.For Instance, A 4D-

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Printed Implant Could Release Drugs Faster When Inflammation Is Detected And Slower When The Condition Stabilizes.[96]

3. Smart Drug Delivery Systems

Future Advancements May Integrate 3D Printing With Nanotechnology, Biosensors, And Internet Of Things (Iot).

This Could Lead To Smart Pills Capable Of Monitoring Physiological Conditions (Like Glucose Levels) And Releasing Drugs Accordingly.

Such Innovations Would Significantly Improve Disease Management In Chronic Conditions Like Diabetes Or Epilepsy.[97]

4. Decentralized Manufacturing And Hospital Pharmacies

Instead Of Relying On Large Pharmaceutical Factories, 3D Printers Can Be Placed In Hospitals, Clinics, And Even Community Pharmacies, Allowing Point-Of-Care Production.Doctors May Prescribe Not Only The Drug But Also The Digital File Of The Drug Design, Which Can Then Be Printed On-Site.This Vision Could Drastically Reduce Delays In Treatment And Improve Patient-Centered Care.[98]

5. Expansion To New Drug Delivery Routes

Current Research Mainly Focuses On Oral Dosage Forms, But Future Applications Will Expand To:

Transdermal Patches With Controlled Release.

Implants And Prosthetics Capable Of Long-Term Drug Delivery.

Inhalable Formulations For Respiratory Conditions.

Injectable Microspheres Or Scaffolds For Tissue Regeneration And Targeted Therapy.[99]

6. Wider Material Development

Future Research Will Focus On Developing Novel Printable Biomaterials That Are Safe, Biodegradable, And Compatible With Sensitive Drugs Such As Proteins, Peptides, And Vaccines.This Will Expand The Range Of Drugs That Can Be Manufactured Using 3D Printing, Overcoming Current Limitations.[100]

7. Global Accessibility And Cost Reduction

With Advancements In Technology, The Cost Of 3D Printers And Materials Will Decrease. This Will Make 3D Printing More Accessible In Low- And Middle-Income Countries.Wider Adoption Could Help In Reducing The Global Drug Shortage Problem And Improve Healthcare Equality.[101]

8. Regulatory Evolution And International Collaboration

In The Future, Regulatory Bodies Are Expected To Develop Specific Guidelines For 3D-Printed Pharmaceuticals, Making The Approval Process More Transparent.International Collaboration Between Regulatory Agencies, Industry, And Academia Will Be Essential For Harmonizing Standards And Ensuring Global Safety.[102]

XI. CONCLUSION

Three-dimensional (3D) printing has emerged as one of the most innovative and transformative technologies in modern pharmaceutical science. By allowing the fabrication of complex, customized dosage forms, it bridges the gap between conventional drug delivery and truly personalized medicine. Through various techniques such as fused deposition modeling, stereolithography, selective laser sintering, and inkjet printing, researchers can now design dosage forms with controlled release profiles, multi-drug combinations, and patient-specific doses—all tailored to individual therapeutic needs.The technology offers significant advantages, including on-demand manufacturing, dose flexibility, and the potential to simplify polypharmacy through polypills. It also supports the creation of novel delivery systems such as implants, microneedles, and transdermal patches, enhancing patient comfort and compliance. Despite these remarkable benefits, several challenges remain, particularly concerning regulatory approval, scalability, material safety, and quality control.

Future progress in 3D pharmaceutical printing will depend on the development of biocompatible materials, improved printer precision, and clearer regulatory frameworks. The integration of artificial intelligence, data-driven design, and even emerging 4D printing technologies promises to further advance this field, enabling dynamic, responsive, and intelligent drug delivery systems.In conclusion, 3D printing represents a paradigm shift from mass production to patient-centric therapy. With continued research, technological refinement, and interdisciplinary collaboration, it holds the potential to revolutionize personalized drug delivery and redefine the future of modern healthcare.

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