Advancement in 3D Printing for Personalized Drug Delivery and Modern Pharmaceutics

Dr. Shivalika 1, Priya 2, Prikshit Thakur 3, Priyanka koundal 4
Associate professor 1, Student 2, Student 3, Student 4
B. Pharmacy
Abhilashi College of Pharmacy, nerchowk, India

Abstract: Three-dimensional (3D) printing, also known as additive manufacturing, has changed the game in modern pharmaceuticals, especially when it comes to personalized drug delivery. This technology has many advantages over traditional manufacturing methods because it lets you make complex dosage forms layer by layer using digital design models. 3D printing has come a long way since its early days as a way to quickly make prototypes. Now it can be used to make medicines that are tailored to each patient's needs, which improves patient compliance and therapeutic outcomes. A lot of research has been done on a number of 3D printing methods, such as fused deposition modelling (FDM), stereolithography (SLA), selective laser sintering (SLS), and binder jet printing, for making solid dosage forms like polypills with controlled drug release profiles. Adding new materials like polymers, hydrogels, and photopolymers to printed drug delivery systems makes them work even better. Digital Light Processing (DLP) and smart biomaterials have made 3D printing more useful in biomedical and pharmaceutical fields, such as tissue engineering and drug screening. 3D printing is used to make drugs, but it also helps make biological models in vitro and makes prototypes quickly, which saves time and money. It allows for cheap small-batch production, decentralized production, and less waste of materials. Despite its numerous advantages, challenges related to scalability, material limitations, and regulatory constraints persist. In the end, 3D printing could change the way drugs are made in a big way by making personalized medicine possible, improving drug delivery methods, and creating new medical technologies.

Keywords: 3d printing, drug delivery system, control drug release, pharmaceutical models, 3d technology

INTRODUCTION:

In terms of material development and innovative processing techniques, traditional manufacturing techniques like foam injection molding and extrusion foaming have been thoroughly examined. The emergence of three-dimensional (3D) printing, also known as additive manufacturing, has revolutionized several industries, including the pharmaceutical sector. In general, "Omics" represents totality and, when added as a suffix to any particular scientific field, offers a more comprehensive perspective. Rapid prototyping and the creation of objects with intricate geometries are typical advantages of additive manufacturing. Since near net shaping, machining, and integration are technical obstacles to their widespread use, the latter is particularly crucial for ceramic materials. The design, production, and use of medications could undergo a radical change as a result of three-dimensional printing (3DP). For centuries, civilization has undergone sporadic, drastic changes that are frequently referred to as "industrial revolutions." The first industrial revolution became evident with the introduction of steam engines, the textile industry, and mechanized factories. Stereolithography technology, which was first described in 1980as the process of bonding materials layer by layer to create objects from a virtual 3D model. 3D is also known as rapid manufacturing or rapid prototyping printing process, The aforementioned issues have been extensively addressed through the use of 3D printing technology in conjunction with pH-responsive release techniques. Because of their highvolume response to environmental pH changes, pH-responsive hydrogels are the most popular of the numerous 3D printable biomaterials. They can be used to control the release of drugs at particular points in human bodies. One of the biggest challenges in engineering interfaces between biological tissues is establishing a secure integration between mechanically dissimilar materials. The cartilage-to-bone boundary is one example of how hard, mineralized materials are naturally incorporated with soft tissues in musculoskeletal tissues. 3D printing is an additive manufacturing technology in which an object is constructed using computer-aided design software, sliced, and transferred to a printer where the product is constructed layer by layer using the principle of layered manufacturing. The perfect should have a porous structure for vascularization, an appropriate surface for cell attachment, and an appropriate mechanical support. A number of technologies, including gas foaming, electrospinning, and rapid prototyping manufacturing (RPM), have been reported for the production of scaffolds with controlled pore size and structure.

Additive manufacturing, sometimes referred to as 3D printing, physically replicates parallel slices of arbitrary design files by first breaking down the object's shape into a number of parallel slices. Using computer-aided design (CAD) models, 3D objects by layer-by-layer adding material. The ability of peptides to self-assemble into different molecular forms makes them valuable in biomedicine. Particular attention has been paid to USPs, which contain fewer than eight amino acids. A relatively short chain makes manipulation easier, which can change the peptide's actual characteristics. The amino acid sequence can be changed to modify mechanical properties like strength, stiffness, and elasticity. A considerable and growing amount of plastic waste generated by 3D. Economic projections indicate that by 2024, the global 3D printing market will grow to a value of USD 7.7 billion. Utilizing a distributed plastic recycling technique that involves upcycling plastic waste into 3-D printing filament using a recycle is one way to get around these financial obstacles. the recycle bot process revealed a 90% reduction in the embodied energy of the filament from the acquisition, processing, and synthesis of natural resources.

1.Evolution of 3d Printing Technology Used in Pharmaceuticals:

Additive manufacturing, another name for three-dimensional printing (3DP), has developed from a tool for quick prototyping to a game-changing technology in the pharmaceutical industry. With 3DP at the forefront of the fourth industrial revolution, which integrates digitization, automation, and customization in medicine design and manufacturing, its development is parallel to the larger industrial revolutions.

1.1Early Development and Industrial Context:

In the 1980s, the idea of additive manufacturing was developed as a fast proto typing technique. Originally used in the consumer goods, automotive, and aerospace industries, 3D printing allowed complex objects to be made directly from computer-aided design (CAD) models, layer by layer.

1.2. Emergence in Drug Development:

Because of its potential to speed up drug discovery and development, 3DP was adopted early in the pharmaceutical industry. Drug development is costly, time-consuming, and has a high early failure rate. Rapid screening and testing were made possible by 3DP's efficient and economical production of small, customized batches of formulations.

1.3. Transition to Solid Dosage Form Fabrication:

The creation of 3D printed solid oral dosage forms, commonly referred to as "print lets," marked the most important turning point in the evolution of pharmaceutical 3DP. Tablets with intricate geometries, programmable porosity, and customized release profiles were made possible by technologies like stereolithography, binder jet printing, selective laser sintering, and fused deposition modelling (FDM).

1.4. Integration with Personalized Medicine:

3DP has emerged as a key enabling technology as personalized medicine becomes more and more prominent in global healthcare systems. Individualized treatment approaches were given priority in initiatives like the UK healthcare strategies and the US Precision Medicine Initiative (2015).

2.Manufacturing Process of 3d printing:

Additive manufacturing (AM), also referred to as 3D printing, is the process of joining materials layer by layer using digital 3D model data as opposed to traditional subtractive or formative manufacturing techniques.

2.1. Digital Design and Pre-Processing:

Using Computer-Aided Design (CAD) software, a digital 3D model is created to start the manufacturing process. After that, the model is transformed into a Standard Tessellation Language (STL) file format, which uses triangular facets to approximate the surface geometry.

2.2. Material Selection and Preparation:

In the manufacturing process of 3D printing, material selection is crucial. Materials can be classified as filaments, powders, liquid resins, pastes, or sheets based on AM.

2.3. Layer-by-Layer Fabrication Technologies:

In the core manufacturing stage, fabrication is done layer by layer. Binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat polymerization are the seven main categories into which ISO/ASTM divides AM processes.

- Material Extrusion (FDM/FFF)
- Powder Bed Fusion (SLS)
- Vat Polymerization (SLA)

2.4. Post-Processing:

Parts frequently need post-processing procedures like heat treatment, surface finishing, curing, sintering, removal of support structures, and polishing after printing.

2.5. Advantages and Limitations in Manufacturing:

3D printing has a number of benefits over traditional manufacturing techniques. Freedom of geometric design Efficiency of materials with less waste Rapid prototyping and personalization shortened supply chain due to regional manufacturing Integration with digital manufacturing systems and Industry 4.0.

3.3D Printing to Support Drug Discovery

Rapid prototyping, sometimes referred to as additive manufacturing (AM) or three-dimensional (3D) printing, has become a game-changing technology in the pharmaceutical sciences. 3D printing, which was first developed from stereolithography in the 1980s, makes it possible to create objects layer by layer from a digital model.

3.1. Role of 3D Printing in Drug Discovery:

Target identification, formulation development, preclinical testing, and drug delivery system optimization are all part of the intricate and expensive process of drug discovery. Conventional manufacturing techniques frequently necessitate large production batches, restrict flexibility, and lengthen development times. These issues are resolved by 3D printing, which permits small-scale, customized manufacturing with exact control over drug distribution, composition, and geometry.

3.2. Rapid Prototyping of Drug Delivery Systems:

One major benefit of 3D printing technology is its ability to facilitate rapid prototyping. It makes it possible to fabricate intricate drug delivery systems without requiring costly molds or tools.

- Inkjet Printing (Binder Jetting)
- Fused Deposition Modelling (FDM)
- Semi-Solid Extrusion (SSE)
- Laser-Based Systems (SLA and SLS)

3.3. 3D Bioprinting and Advanced Models:

3D printing is being used more and more to produce biological models for drug testing in addition to solid dosage forms. The ability to create scaffolds that resemble tissue facilitates toxicity and drug screening in vitro. This improves prediction accuracy in the early phases of drug development and lessens dependency on animal models

3.4. Advantages in Drug Discovery:

There are various benefits to using 3D printing in drug discovery. Quick formulation creation and screening Customized dosage for clinical studies Drug release studies that are targeted and controlled creation of multilayer systems and intricate geometries Lower production costs and less material waste.

4.Revolutionizing Drug Manufacturing using 3D Printing

In the field of pharmaceutical sciences, additive manufacturing (AM), commonly referred to as three-dimensional (3D) printing, has become a game-changing technology. In the 1980s, stereolithography was used to conceptualize 3D printing, which ASTM later defined as the process of creating objects layer by layer from a digital model.

4.1. Shift from Conventional to Digital Manufacturing:

Conventional pharmaceutical production uses mass production methods like granulation, molding, and compression. These techniques are frequently rigid when dose modifications or customized treatments are needed, and they are made for large, homogeneous batches. However, the need for individualized drug therapy has arisen due to growing interindividual variability in pharmacokinetics, pharmacogenetics, age, weight, and comorbidities.

4.2. Key 3D Printing Technologies in Drug Manufacturing:

- Inkjet Printing (Binder Jetting)
- Fused Deposition Modelling (FDM)
- Semi-Solid Extrusion (SSE)
- Laser-Based Systems (SLA and SLS)

4.3. Personalized Medicine and Polypills:

The potential of 3D printing to create customized medications is among its most innovative features. Customized dosage cannot be readily accommodated by traditional mass production, particularly for patients who are poly medicated, elderly, or pediatric.

4.4. Advanced Drug Delivery and Controlled Release:

The potential for targeted and regulated drug delivery has increased with the combination of 3D printing and material science. Hydrogels that respond to pH, like sodium alginate, swell in alkaline environments and shrink in acidic ones.

4.5. Advantages Over Conventional Manufacturing:

3D printing has several benefits. Individualized treatment and dosage Decentralized and on-demand production Decreased waste of materials creation of intricate geometries Quick formulation optimization and prototyping Improved adherence to treatment.

5.Fundamentals of DLP 3D Printing:

A vat photopolymerization-based additive manufacturing method called Digital Light Processing (DLP) 3D printing uses projected light to selectively cure liquid photopolymer resins into solid three-dimensional structures. Because of its high resolution, quick fabrication speed, and superior surface finish, it has become increasingly important in biomedical engineering, materials science, and pharmaceutical applications.

5.1. Basic Working Principle of DLP:

DLP works by exposing a liquid resin that contains monomers, oligomers, and photo initiators to patterned ultraviolet (UV) or visible light. This process is known as photopolymerization. An entire layer image is projected onto the resin surface by a digital micromirror device (DMD), which simultaneously cures the resin. DLP cures an entire layer at once, which is substantially faster than stereolithography (SLA), which uses a laser to scan each point individually.

5.2. Resin Composition and Material Design:

The formulation of the resin has a significant impact on DLP printing performance. Typical components of a DLP resin include: Monomers or oligomers that are photopolymerizable Initiators of photosynthesis Cross-linkers Additives (colorants, fillers, stabilizers) The mechanical and biological properties of hydrogels and polymeric networks can be adjusted, which makes them widely used.

5.3. Photopolymerization Mechanism:

Three main steps are involved in the photopolymerization process in DLP: Initiation: Reactive species (free radicals or cations) are produced when the photo initiator absorbs light. Propagation: By adding monomers, reactive species start the growth of polymer chains. Termination: Recombination or disproportionation reactions cause the chain to stop growing. Light intensity, exposure duration, photo initiator concentration, and resin optical characteristics all affect the curing depth and resolution.

a.Process Parameters Affecting DLP Printing:

- Light Intensity and Exposure Time
- Layer Thickness
- Resin Viscosity

6.Material Innovation in DLP 3D Printing:

Digital Light Processing (DLP) 3D printing is a vat-photopolymerization method that uses projected light to cure photosensitive resins layer by layer to create three-dimensional structures. Although photopolymerization is the basic mechanism of DLP, new developments in material science have greatly increased its uses in flexible electronics, pharmaceuticals, biomedical engineering, and advanced functional devices.

6.1. Advanced Photopolymer Resins:

The pH sensitivity, superior biocompatibility, and adjustable crosslinking density of PAA-based hydrogels make them especially promising. Researchers have established a material design window appropriate for 3D fabrication by meticulously regulating the concentration of monomers, the amount of covalent crosslinker, and the dynamic crosslinker ratio.

6.2. Self-Healing and Smart Hydrogels:

The creation of self-healing hydrogels is among the most important material advancements in DLP printing.

6.3. Polyurethane-Based and Hybrid Materials:

Novel polyurethane–urea (WBPUU) systems have been investigated for additive manufacturing because of their environmental friendliness, elasticity, and flexibility. By removing volatile organic compounds (VOCs), waterborne polyurethane-based inks become more environmentally friendly and appropriate for use in biomedical applications.

a.Nano composites and Functional Additives:

The mechanical strength, conductivity, and biological performance of polymer matrices have been altered by the incorporation of additives like cellulose nanocrystals (CNC), graphene, and plant-based extracts.

b. Biomedical and Pharmaceutical Implications:

Pharmaceutical and Biomedical Consequences DLP is now a potent instrument in healthcare applications thanks to material innovation. Biodegradable polymers and sophisticated hydrogels allow for the creation of: Scaffolds loaded with drugs Customized dosage forms E-skin devices and synthetic skin Tissue engineering structures Systems that use microfluidics.

7. Types of 3d Printing Technologies used in pharmaceuticals:

Additive manufacturing, another name for three-dimensional (3D) printing, is a new technology that uses computer-aided design (CAD) to create pharmaceutical dosage forms layer by layer. Complex drug delivery systems with patient-specific dosages and controlled release characteristics can be produced thanks to this technology. Because it allows for personalized medicine, quick prototyping, and the creation of intricate dosage forms that are challenging to produce using traditional methods, it has drawn a lot of attention in pharmaceutical research.

7.1. Binder Jet Printing (Powder Bed Printing):

One of the first and most popular 3D printing methods in the pharmaceutical industry is binder jet printing. This process involves covering a build platform with a thin layer of powder that contains the drug and excipients. Layer by layer, the procedure is repeated until the finished dosage form is produced.

Binder-jet printed tablets' high porosity enables quick dissolution and enhanced bioavailability. Furthermore, complex structures like multilayer tablets and polypills with several active pharmaceutical ingredients (APIs) can be created using binder jet printing.

7.2. Fused Deposition Modeling (FDM):

Another popular 3D printing technique in the pharmaceutical industry is fused deposition modelling (FDM). This method involves heating a thermoplastic polymer filament containing the medication until it melts, after which it is extruded through a nozzle to create layers that solidify when cooled.

Additionally, FDM makes it possible to create customized medications with unique release profiles and dosages. Researchers can regulate tablet strength and drug release kinetics by modifying printing parameters like infill density and layer thickness.

7.3. Inkjet Printing:

Another significant 3D printing technology utilized in pharmaceutical applications is inkjet printing. It entails the controlled deposition of droplets of drug-containing suspensions or solutions onto a substrate. This method falls into two categories: drop-on-demand inkjet printing and continuous inkjet printing.

8.Economical and Logistical Benefits of 3d Printing Pharmaceuticals:

The pharmaceutical industry is increasingly investigating three-dimensional (3D) printing, also referred to as additive manufacturing (AM), because of its potential to boost supply-chain management, lower costs, and increase manufacturing efficiency. In contrast to traditional pharmaceutical manufacturing techniques like injection, molding, or compression, 3D printing creates products directly from digital designs, layer by layer . This novel strategy offers a number of logistical and financial benefits that could revolutionize the manufacturing and distribution of pharmaceuticals.

The decrease in manufacturing costs for customized and small-scale production is one of 3D printing's biggest economic benefits. Due to high setup costs, specialised equipment, and intricate manufacturing procedures, traditional pharmaceutical manufacturing typically needs large-scale batch production to remain economically viable. On the other hand, costly moulds and equipment are not required when using additive manufacturing. This makes it economically possible to produce customised or small-batch medications. Research has demonstrated that, when compared to traditional moulding and assembly techniques, additive manufacturing can drastically cut costs and production time, especially when creating customised goods or short production runs.

The decrease in material waste during the manufacturing process is another significant financial advantage. When working with costly pharmaceutical ingredients or speciality polymers used in drug delivery systems, the ability to optimise material usage is especially helpful.

Additionally, 3D printing encourages the use of economical and sustainable materials. For instance, because of their advantageous processing properties and reduced energy requirements during fabrication, materials like the biodegradable polymer polylactic acid (PLA) are being used more frequently in additive manufacturing.

In addition to lowering energy use, the use of such materials supports environmentally friendly production methods. Furthermore, recycled polymer blends can be used in additive manufacturing to print functional components, indicating the possibility of resource conservation and cost reduction in production systems.

9.Materials Used For 3d Printing Technology in Manufacturing Industry:

Additive manufacturing (AM), another name for three-dimensional (3D) printing, has emerged as a key technology in contemporary manufacturing sectors. Depending on the application, printing process, and mechanical needs of the finished product, a variety of materials, including polymers, metals, ceramics, composites, and photopolymers, are used in various 3D printing techniques. These materials make it possible to create intricate structures with better functionality and customisation in sectors like electronics, automotive, aerospace, and healthcare.

9.1. Polymer Materials:

Due to their affordability, ease of processing, and compatibility with numerous additive manufacturing techniques, polymers are the most commonly used materials in 3D printing. Thermoplastic polymers are frequently utilised as filaments in procedures like fused deposition modelling (FDM). Layer-by-layer construction is made possible by these materials, which melt at certain temperatures and solidify after cooling.

9.2. Metal Materials:

In industrial 3D printing applications that demand high strength, durability, and thermal resistance, metal materials are frequently utilised. In powder-bed fusion techniques like selective laser sintering (SLS) and electron beam melting (EBM), metal powders like stainless steel, titanium, aluminium, and nickel-based alloys are frequently utilised.

9.3. Composite Materials:

Because of their improved mechanical and functional qualities, composite materials are becoming more and more popular in 3D printing. These materials are made by mixing reinforcing fibres or particles with a base material, like a polymer. Strength, stiffness, electrical conductivity, and thermal performance are all improved by the addition of reinforcements.

a.Photopolymer and Resin Materials:

Stereolithography (SLA) and material jetting (MJ) are two additive manufacturing processes that use photopolymers and liquid resins. These procedures use ultraviolet (UV) light to solidify liquid resin materials that have been deposited in thin layers. With the use of this technology, highly accurate and detailed objects with smooth surface finishes can be produced.

10.The Applications of 3d printing in Manufacturing Technology:

Additive manufacturing (AM), commonly referred to as three-dimensional (3D) printing, has emerged as a game-changing technology in contemporary manufacturing sectors. By layering materials, it makes it possible to create intricate three-dimensional objects straight from digital designs. In contrast to traditional manufacturing methods like casting, machining, or injection moulding, additive manufacturing constructs parts one after the other, enabling greater design flexibility, less material waste, and quicker product development cycles. These benefits have led to the widespread use of 3D printing in a number of industries, including consumer goods manufacturing, aerospace, automotive, healthcare, and construction.

10.1. Rapid Prototyping and Product Development:

Rapid prototyping is one of the first and most popular uses of 3D printing in manufacturing. During the design stage, manufacturers use 3D printing to swiftly create prototype models of new products. This enables engineers and designers to test a product's performance, shape, and functionality prior to starting full-scale production. Because design changes can be made quickly without interfering with conventional manufacturing processes, rapid prototyping dramatically lowers the time and expense of product development. As a result, through qick testing and iteration, businesses can continuously enhance and optimise product designs.

10.2. Aerospace and Automotive Manufacturing:

The need for lightweight, high-performance components has led to a widespread adoption of 3D printing in the automotive and aerospace industries. Complex parts with optimised internal structures that minimise weight without sacrificing strength can be produced thanks to additive manufacturing. These qualities are particularly crucial in the production of aircraft and spacecraft, as weight reduction improves performance and fuel efficiency.

10.3. Medical and Healthcare Applications:

The medical and healthcare industry is another important area where 3D printing is being used in manufacturing technology. The technology makes it possible to create prosthetics, implants, and medical devices that are customised to each patient's unique anatomical needs. To improve surgical accuracy and patient outcomes, for example, surgeons can plan complex surgical procedures using 3D-printed models of organs or bones.

11. 3d Printing Process and Techniques:

Additive manufacturing (AM), another name for three-dimensional (3D) printing, is a manufacturing process that creates objects layer by layer from a digital design. Since its initial introduction in the 1980s, this technology has developed into a significant manufacturing technique utilised in sectors including healthcare, engineering, architecture, automotive, and pharmaceuticals. In contrast to traditional manufacturing techniques like injection moulding or machining, 3D printing enables the creation of intricate geometries with less material waste and production time.

a.3D Printing Process:

When customised medical products are needed, the digital design can also be produced using medical imaging methods like CT or MRI scans. These digital models enable accurate product customisation for particular uses.

The chosen material, such as liquid resins, powders, or thermoplastic polymers, is applied layer by layer during printing. The final structure is gradually constructed by solidifying each layer before applying the subsequent layer. To create successive layers, the platform moves in the Z direction while the printing head moves in the X–Y direction.

b. Techniques of 3d Printing: Depending on the kind of material and intended use, 3D printing employs a variety of methods. Fused deposition modelling (FDM), hot-melt extrusion (HME) assisted printing, and other additive manufacturing techniques are among the most popular methods.

11.1. Fused Deposition Modeling (FDM):

One of the most popular methods for 3D printing is fused deposition modelling, or FDM. This process involves feeding thermoplastic filaments into a heated nozzle, where the material melts and is layer-by-layer extruded onto a build platform. The molten substance solidifies and creates the intended three-dimensional object as it cools.

11.2. Hot-Melt Extrusion (HME) Assisted 3D Printing:

One crucial method that is frequently used in conjunction with FDM 3D printing is hot-melt extrusion (HME). In order to create filaments, polymers and active pharmaceutical ingredients are combined and melted under carefully regulated heat and pressure. FDM printers then use these filaments as their printing material.

12. Methods of 3d Printing:

Additive manufacturing (AM), another name for three-dimensional (3D) printing, is a manufacturing process that builds objects layer by layer from a digital model. Since the invention of stereolithography in the 1980s, the technology has grown to include several printing techniques utilised in the manufacturing, engineering, and medical sectors. 3D printing allows for quick prototyping, intricate geometries, and customised production with little material waste, in contrast to conventional manufacturing techniques like casting or injection moulding.

12.1. Fused Deposition Modelling (FDM):

One of the most popular and easily accessible 3D printing techniques is fused deposition modelling (FDM), sometimes referred to as fused filament fabrication (FFF). Using instructions produced from a computer-aided design (CAD) model, a thermoplastic filament is fed into a heated nozzle, where it is melted and deposited layer by layer onto a build platform. The final structure is formed by the material cooling and solidifying after deposition.

12.2. Stereolithography (SLA):

One of the first methods of 3D printing was stereolithography (SLA). It uses ultraviolet (UV) light to selectively cure a liquid photopolymer resin. By tracing the object's cross-section on the resin surface, a laser beam solidifies the material layer by layer until the entire object is formed.

12.3. Selective Laser Sintering (SLS):

Another popular additive manufacturing technique is selective laser sintering (SLS). Using this method, powdered materials like polymers, metals, or ceramics are selectively fused by a laser beam. Particles are sintered together to create a solid layer as the laser scans the powder bed in accordance with the digital model's cross-section. A fresh layer of powder is applied to the surface after each layer is finished, and the procedure is repeated.

12.4. Laminated Object Manufacturing (LOM):

The process of joining layers of material sheets to create a three-dimensional object is known as laminated object manufacturing, or LOM. This technique involves laminating or adhering sheets of paper, plastic, or metal, then using a laser or blade to cut them into the required shape. Until the object is finished, the layers are stacked one after the other.

Conclusion:

Three-dimensional (3D) printing has emerged as a transformative technology in the pharmaceutical and manufacturing industries by enabling the development of personalized, efficient, and advanced drug delivery systems. Unlike conventional manufacturing techniques, 3D printing offers precise control over dosage form design, drug release profiles, geometry, and material composition, making it highly suitable for patient-specific therapies. Technologies such as fused deposition modelling (FDM), stereolithography (SLA), selective laser sintering (SLS), binder jet printing, and digital light processing (DLP) have significantly expanded the possibilities for fabricating complex pharmaceutical formulations, including polypills, controlled-release tablets, and implantable drug delivery systems.

The integration of advanced biomaterials, smart hydrogels, photopolymers, and biodegradable polymers has further enhanced the functionality and biomedical applicability of 3D-printed products. In addition to pharmaceutical manufacturing, 3D printing plays an important role in rapid prototyping, tissue engineering, drug screening, and the development of customized medical devices. The technology also supports decentralized and on-demand production, reduces material waste, shortens manufacturing time, and improves supply-chain flexibility, thereby contributing to sustainable healthcare systems.

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