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# Revolutionizing Drug Delivery Through Additive Manufacturing: A Critical Review Of Progress, Technological Barriers, And Future Prospects In 3d-Printed Dosage Forms

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***Abstract :*** Three-dimensional (3D) printing, a quickly developing technology that allows the creation of personalised dosage forms with exact control over drug release and geometry, has completely changed the evolution of pharmaceutical manufacturing. Recent developments, materials, methods, and regulatory issues in the field of pharmaceutical dosage form additive manufacturing are highlighted in this study. Several 3D printing technologies, including selective laser sintering (SLS), inkjet printing, stereolithography (SLA), and fused deposition modelling (FDM), have shown promise in creating patient-specific implants, transdermal patches, oral tablets, and orodispersible films. Polyvinyl alcohol (PVA), hydroxypropyl methylcellulose (HPMC), and polyethylene glycol (PEG) are examples of polymeric carriers that provide versatility in creating formulations with specific mechanical and dissolving characteristics.

Personalised medicine is further supported by 3D printing, which makes it possible to combine several medications, modify dosages, and achieve controlled-release kinetics in a single unit. Notwithstanding these developments, issues with scalability, material compatibility, print quality, and regulatory compliance still exist. The first 3D-printed tablet, Spritam®, was approved by the US FDA, which is a major milestone. However, process validation and standardised criteria are needed for wider implementation. To maximise this new technology, future studies should concentrate on combining artificial intelligence, quality-by-design concepts, and sustainable materials. All things considered, 3D printing is a revolutionary method for

developing dosage forms, providing fresh avenues for customised treatment, enhanced patient adherence, and creative pharmaceutical product design.

**Keywords:** 3D printing, additive manufacturing, personalized medicine, dosage form development, fused deposition modeling, Spritam®, controlled release.

## 1. Introduction

A crucial area of pharmaceutical science that affects medication therapy's safety, effectiveness, and patient compliance is dosage form creation. It entails converting an active pharmaceutical ingredient (API) into a form that is appropriate for precisely and steadily delivering the desired therapeutic effect (1). Techniques like granulation, compression, coating, and encapsulation have long been used in conventional dosage form design; however, these approaches frequently lack the flexibility needed for complex release profiles and dose personalisation (2).

Additive manufacturing (AM), commonly referred to as three-dimensional (3D) printing, has transformed the pharmaceutical industry in recent years. Using computer-aided design (CAD) models, 3D printing creates dosage forms with customised shapes, porosity, and release properties based on the layer-by-layer deposition principle (3). The production of customised medications, multi-drug combinations, and complicated geometries that are not possible with conventional techniques is made possible by this technology's fine control over microstructure (4).

Precision pharmaceutics has undergone a paradigm change with the transition from conventional batch manufacturing to digital fabrication. In contrast to traditional methods, 3D printing supports decentralised manufacturing, such as printing in hospitals or pharmacies, reduces material waste, and enables on-demand production (5,6). Furthermore, the first 3D-printed tablet, Spritam® (levetiracetam), was approved by the U.S. Food and Drug Administration, confirming the usefulness of additive manufacturing in the creation of commercial pharmaceuticals (7).

With an emphasis on printing methods, material selection, formulation issues, and regulatory considerations, this review attempts to provide an overview of the most recent developments in the 3D printing of pharmaceutical dosage forms. Future thoughts on how additive manufacturing can transform next-generation medication delivery systems and personalised medicine are also examined (8).

**2.Selecting the Subject:** Justification and Pertinence ,Because of its revolutionary potential in dosage form design and personalised medicine, 3D printing, also known as additive manufacturing, has been chosen as a focus topic in pharmaceutical research. Even though they are well-established, traditional pharmaceutical production techniques frequently lack the adaptability to create complex release systems or customised doses, particularly when treating patients with chronic diseases, paediatrics, or geriatrics (1). On the other hand, 3D printing makes it possible to precisely manage the drug's dosage, shape, and release properties, which makes it possible to create customised formulations that are intended to satisfy specific therapeutic requirements (4).

3D printing has emerged as a major pharmaceutics research topic due to the growing need for patient-centric dose forms. It improves patient adherence and therapeutic success by enabling complex internal structures, multi-drug combinations, and spatial drug distribution inside a single dosage unit (3,5). Furthermore, this technology facilitates on-demand manufacturing and rapid prototyping, which cut down on production time and material waste (8).

The U.S. FDA's approval of Spritam® (levetiracetam) opened new market adoption pathways and proved the commercial viability of 3D printed medications from an industrial and regulatory standpoint (7). Significant obstacles still exist in spite of these developments, such as those related to scalability, reproducibility, quality control, and the absence of standardised regulatory frameworks (9). These discrepancies show that more study is required to determine reliable validation procedures, assess excipient compatibility, and optimise printing parameters (10).

As a result, the purpose of this review is to examine the latest developments in materials, printing methods, applications, and regulatory trends that will influence additive manufacturing in the pharmaceutical industry going forward, with a focus on how it could revolutionise industrial manufacturing and personalised medicine (11).

**3. Formulating the Research Question and Objective** :-This review's main objective is to objectively assess the contribution of 3D printing technologies to the development of contemporary dosage forms, with an emphasis on current developments, obstacles, and prospects for the future. One important concern that emerges as pharmaceutical sciences shift towards patient-specific and precision-based medicines is how additive manufacturing can maximise formulation design, guarantee quality control, and facilitate the scalable production of customised dosage forms. (3,4).

**Table 1: Comparison of 3D Printing Techniques**

| Technique | Principle | Advantages | Limitations | Common Applications |
|---|---|---|---|---|
| FDM | Extrudes thermoplastic filaments | Easy, low-cost, multilayer tablets | Heat-sensitive APIs, slower | Controlled-release tablets, multi-drug tablets |
| Inkjet Printing | Droplet deposition | High precision, low-dose films | Nozzle clogging, limited viscosity | Orodispersible films, personalized dosing |
| SLA | UV polymerization | High resolution, complex geometry | Resin toxicity, cost | Implants, complex tablets |
| SLS | Laser fusion of powders | Porous structures, fast dissolution | High energy, cost | Fast-dissolving tablets, implants |

The growing demand for adaptable, adaptable, and effective drug delivery systems—which conventional manufacturing techniques find difficult to satisfy—is the root cause of the research problem (5). The transition from laboratory to large-scale manufacture is still limited, even though multiple studies have shown the potential of 3D printing for oral, transdermal, and implantable formulations (7,12). A thorough grasp of printing settings, excipient compatibility, and post-processing methods that impact product performance and regulatory approval is necessary to close this gap (10).

**This review aims to:**

1. Provide an overview of the various 3D printing methods utilised in pharmaceutics, such as fused deposition modelling, inkjet, and stereolithography.
2. Examine excipients and materials appropriate for printable compositions.
3. Talk about uses in personalised medicine and different dosage forms.
4. Determine the obstacles and legal issues preventing scalability.
5. Examine potential future paths, such as integrating AI and using quality-by-design (QbD) frameworks (8,11).

The review aims to offer a comprehensive understanding of how 3D printing may transform industrial manufacturing efficiency, patient compliance, and dosage form innovation by addressing these goals (9).

**4. Synopsis of 3D Printing Methods for Developing Dosage Forms** :-.A new paradigm in dosage form design has been brought about by the use of 3D printing technology in pharmaceutics, which allow for exact spatial control of drug distribution and release profiles (4). Depending on the formulation type, material compatibility, and intended therapeutic results, each printing method has unique benefits. The most often investigated techniques are Selective Laser Sintering (SLS), Stereolithography (SLA), Inkjet Printing, and Fused Deposition Modelling (FDM) (3,9).

The most popular 3D printing method for pharmaceuticals is fused deposition modelling, or FDM. To create the required geometry, a thermoplastic polymer filament is extruded via a heated nozzle, depositing material layer by layer (7). As carriers, polymers including hydroxypropyl methylcellulose (HPMC), polyvinyl alcohol (PVA), and polylactic acid (PLA) are frequently employed (13). FDM enables the manufacture of sustained-release, pulsatile, and multi-drug dosage forms, while thermal degradation of heat-sensitive medicines remains a restriction (14). Drug and excipient solution droplets are precisely deposited onto substrates using the non-contact technique of inkjet printing (15). It is perfect for low-dose formulations or orodispersible films and permits excellent dosing precision; however, it has drawbacks such as nozzle clogging and a narrow viscosity range (8).

In order to create high-resolution structures appropriate for complex oral or implantable devices, stereolithography (SLA) polymerises photosensitive resins layer by layer using a UV laser (16). Similarly, to create porous, quickly-dissolving tablets, Selective Laser Sintering (SLS) uses a laser to fuse powdered materials without the need for binding agents (17).

When taken as a whole, these technologies show how additive printing might transform the design of dosage forms by providing flexibility in shape, release control, and medication personalisation while cutting down on production time and material waste (11).

**5. Materials and Excipients for Dosage Form 3D Printing** :-.Because it affects printability, mechanical strength, drug release behaviour, and biocompatibility, the choice of materials and excipients is crucial to the success of pharmaceutical items that are 3D printed (3). The right rheological characteristics, thermal stability, and compatibility with the drug and printing process are essential for materials used in additive manufacturing (4).

**5.1. Polymers** :-The structural matrix of dosage forms that are 3D printed is made up of polymers. Because of their high mechanical strength and capacity to form filaments, thermoplastic polymers like ethylene-vinyl acetate (EVA), polylactic acid (PLA), polycaprolactone (PCL), and polyvinyl alcohol (PVA) are frequently utilised in fused deposition modelling (FDM) (13,17). To provide controlled or sustained drug release, hydrophilic polymers such as polyethylene glycol (PEG), carbopol, and hydroxypropyl methylcellulose (HPMC) are employed (7). Implantable or targeted delivery systems can be designed using biodegradable polymers, such as poly(lactic-co-glycolic acid) (PLGA) and Eudragit® derivatives (16).

**5.2 Fillers and Plasticisers :-** By reducing the glass transition temperature of polymeric filaments, plasticisers such triethyl citrate, glycerol, and polyethylene glycol (PEG 400) are added to increase their flexibility and printability (14). In Selective Laser Sintering (SLS) and Binder Jetting processes, fillers and flow enhancers such as mannitol and microcrystalline cellulose (MCC) increase particle flow characteristics and structural homogeneity (18).

**Table 2: Common Polymers and Excipients in 3D Printing**

| Material Type | Example | Role in 3D Printing | Dosage Form Example |
|---|---|---|---|
| Polymers | PLA, PVA, HPMC, PLGA | Structural matrix, controlled release | Tablets, implants |
| Plasticizers | Glycerol, triethyl citrate | Improve flexibility, filament formation | Films, tablets |
| Fillers | MCC, lactose | Flowability, stability | SLS and Binder Jetting tablets |
| APIs | Levetiracetam, Budesonide | Therapeutic effect | Tablets, patches, films |
| Biopolymers / Resins | PEGDA, GelMA | SLA/Inkjet printing, biodegradable | Implants, hydrogels |

**5.3 A Pharmaceutical Active Ingredients (APIs) :-**Therapeutic performance is directly impacted by the drug's distribution and loading capacity within the printed matrix. 3D printing APIs need to be compatible with the selected polymer and stable during printing (19). Paracetamol, ibuprofen, nifedipine, and prednisolone have all been successfully printed in studies, resulting in complicated dose geometries and adjustable release profiles (20). Combination treatments for chronic illnesses are made possible by multi-drug printing, which has major benefits for personalised medicine (11).

**5.4. New Materials :-** For use in stereolithography (SLA) and inkjet printing, recent studies investigate photo-curable resins, nanocomposites, and biopolymers made from cellulose and chitosan (21,22). Precision, bioadhesion, and biodegradability are improved by these materials, signalling a move towards patient-centered and sustainable formulations.

Overall, the integration of 3D printing in dosage form creation is advanced by the careful selection of functional excipients, which are essential for maximising mechanical integrity, release kinetics, and biocompatibility (9).

**6. 3D Printing Applications in the Development of Dosage Forms :-** Beyond conventional oral dosage forms, 3D printing (3DP) is being used in pharmaceuticals to provide a variety of innovative drug delivery systems, including transdermal patches, implants, orodispersible films, and personalised multi-drug packages (4). Complex geometries, accurate spatial medication distribution, and customised dosages based on patient-specific therapeutic requirements are all made possible by additive manufacturing's adaptability (3).

**6.1. Tablets and Capsules as Oral Solid Dosage Forms :-** The most researched use of 3DP in pharmaceutics is in oral tablets. Spritam® (levetiracetam), the first FDA-approved 3D-printed medication, showed that powder bed inkjet printing could be used to create quickly dissolving tablets (23). Controlled-release,

pulsatile, and multi-layered tablets have been created in later research utilising Fused Deposition Modelling (FDM) and Selective Laser Sintering (SLS) (7). Drug release kinetics can be better controlled by altering tablet geometry (e.g., hollow cores, gyroid lattices) (17).

**6.2. Cutaneous and Transdermal Systems :-** Customised transdermal patches with accurate medication loading and adjustable surface patterns to control skin penetration can be produced using 3D printing (13). Flexible and sticky patches containing medications like lidocaine and diclofenac have been created using methods including inkjet and extrusion-based printing (24). A minimally invasive platform for systemic medication delivery and transdermal vaccination is offered by the use of microneedle arrays made of biodegradable polymers (25).

**6.3. Buccal and Orodispersible Films :-** Orodispersible films (ODFs) made by additive manufacturing provide benefits for treating swallowing issues in children and the elderly. For quick disintegration and absorption, inkjet printing enables the exact deposition of microdoses onto polymeric films (15). For medications undergoing considerable first-pass metabolism, these technologies enable customised dosage and enhanced bioavailability (8).

**6.4. Biomedical Devices and Implants :-** Localised and sustained medication distribution at target areas is made possible by 3D-printed biodegradable implants made of polymers such as polycaprolactone (PCL) and polylactic acid (PLA) (16). These implants are intended for use in orthopaedic, contraceptive, and oncological settings where mechanical stability and long-term release are essential (22). For creating porous or hybrid implants that combine drug reservoirs and sensors, stereolithography (SLA) and SLS offer superior resolution (11).

**6.5. Complex Formulations and Personalised Polypharmacy :-** Poly-drug formulations, in which several active pharmaceutical ingredients (APIs) with different release kinetics are co-printed in a single tablet, represent one of the most revolutionary uses of 3DP (26). These developments greatly increase patient adherence and therapeutic efficacy by enabling chronotherapeutic administration and fixed-dose combinations (19). All things considered, 3D printing provides a flexible platform that makes precision medicine possible by providing patient-tailored dosages, controlled release, and innovative dosage form geometries that were previously impossible to achieve through traditional manufacturing (9).

**7. Difficulties and Restrictions with 3D-Printed Dosing Forms :-** Although 3D printing (3DP) has the potential to revolutionise the production of pharmaceutical dosage forms, its broad use in clinical and industrial contexts is constrained by a number of practical, legal, and technical issues (3,4). Comprehending these constraints is crucial for directing forthcoming investigations and enhancing the viability of additive manufacturing in the pharmaceutical industry.

**7.1. Manufacturing Efficiency and Scalability :-** Scaling laboratory accomplishments to industrial production is one of the main problems facing 3D printing. Time-consuming methods like inkjet printing and fused deposition modelling (FDM) might not be able to meet the throughput requirements of large-scale manufacturing (9). Commercial viability is further constrained by expensive equipment and slow printing (7).

**7.2. Restrictions on Materials :-** The selection of excipients and polymers is still limited. Due to inadequate filament formation, inappropriate rheological characteristics, or thermal instability, many pharmaceutical-grade materials are incompatible with printing techniques (6). This restricts the variety of medications that can be created, especially biologics or APIs that are heat-sensitive (14).

7.3. Quality Control and Reproducibility :- For dosage formulations, reproducibility and homogeneity are essential. Variability in drug content, mechanical strength, and dissolution characteristics is introduced by layer-by-layer deposition (8). Batch-to-batch inconsistencies are more likely when there are no standard procedures for post-processing, validation, and in-process monitoring (11).

**7.4: Difficulties with Regulation and Compliance :-** Pharmaceutical regulations pertaining to 3D printing are continually developing. Although the FDA has issued preliminary recommendations, there are still many unanswered questions regarding quality control, approval processes, and long-term stability (27). International acceptance requires global harmonisation (26).

7.5. Shelf-Life and Stability :- While porous or complicated geometries can influence moisture uptake and degradation, thermal and mechanical stressors during printing may jeopardise the stability of APIs (19). The long-term preservation and packaging needs of 3D-printed dosage forms have not been thoroughly studied.

**7.6. Price and Availability :-** Production costs are higher than in traditional manufacturing due to the high investment in printers, materials, and a skilled workforce (1). Although technology shows promise for personalised medicine, hospital or pharmacy-based decentralised printing necessitates substantial infrastructure and training. Notwithstanding these difficulties, the use of 3D printing in pharmaceutical development is becoming more widespread as a result of continuous research into novel polymers, process optimisation, real-time monitoring, and regulatory guidance (5,28).

**8. Regulatory Considerations and Future Prospects:-** Regulatory bodies have created standards addressing the quality, safety, and effectiveness of additively generated drug products as a result of the incorporation of 3D printing (3DP) into pharmaceutical manufacturing (3,4). In 2017, the FDA released its initial guidance on additive manufacturing, emphasising product testing, process validation, and device design (27). To guarantee batch-to-batch reproducibility and patient safety, the European Medicines Agency (EMA) and other international organisations have also underlined the necessity of standardised quality control procedures (29).

Material characterisation, drug-excipient compatibility, process monitoring, and post-processing validation are important regulatory factors. The special characteristics of 3D-printed dosage forms, such as intricate geometries, customised dosage, and on-demand manufacture, must be taken into account by regulatory

frameworks (9,5). An important milestone was reached with the approval of Spritam® (levetiracetam), proving that 3D-printed oral solids might be accepted by the government (23). In the pharmaceutical industry, 3D printing has bright future prospects. Predictive quality assurance, dosage personalisation, and precise control over drug release are made possible by innovations such as multi-material printing, AI-assisted design, and machine learning for process optimisation (8,11). Customised therapeutic interventions and real-time patient adherence monitoring may be made possible by integration with digital health technologies (19).

**Table 3: Challenges and Limitations of 3D Printing**

| Challenge | Description |
|---|---|
| Scalability | Low throughput, slow printing speed |
| Material Limitations | Heat sensitivity, poor rheology |
| Reproducibility | Variability in content, mechanical properties |
| Regulatory Issues | Lack of standardized guidelines |
| Stability | Moisture absorption, thermal degradation |
| Cost | High equipment and training requirements |

Scalability, cost-effectiveness, and international regulatory harmonisation continue to be obstacles that call for cooperation between business, academia, and regulatory bodies (6). The potential for 3D printing to revolutionise the pharmaceutical industry by providing customised, on-demand, and precision medications is being further explored through ongoing research in biodegradable polymers, nanocomposites, and combination therapies (26,14). In conclusion, the adoption of 3D printing will be accelerated by regulatory guidance and technological innovation, providing hitherto unheard-of possibilities for personalised medicine, enhanced patient compliance, and effective drug development pipelines (28).

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