JOURNAL OF PHARMA INSIGHTS AND RESEARCH ISSN NO. 3048-5428

REVIEW ARTICLE

Innovations in Three-Dimensional Printing for Personalized Drug Delivery Systems

Sai Krishna B*[1], Parimala Vudikala[2]

[1]*UG Scholar, Department of Pharmaceutics, Joginpally BR Pharmacy College, Moinabad, Telangana, India*
[2]*Assistant Professor, Department of Pharmaceutics, Joginpally BR Pharmacy College, Moinabad, Telangana, India*

Publication history: Received on 12th Jan 2025; Revised on 21st Jan 2025; Accepted on 22nd Jan 2025

Article DOI: 10.69613/pd300p92

Abstract: Three-dimensional (3D) printing represents a transformative approach in pharmaceutical manufacturing, offering unprecedented possibilities in drug delivery system development. The technology enables precise control over dosage forms, complex geometries, and personalized medication production. Various 3D printing methodologies, including Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Inkjet Printing, have demonstrated significant potential in pharmaceutical applications. The FDA approval of Spritam®, the first 3D-printed medication, marked a pivotal milestone in the field. Recent advances encompass the development of patient-specific dosing systems, drug-eluting implants, and innovative transdermal delivery platforms. While the technology presents remarkable opportunities for personalized medicine and on-demand drug production, several challenges persist, including regulatory compliance, material limitations, and quality control considerations. Integration with digital health technologies and bioprinting advances suggest promising future directions. The convergence of 3D printing with continuous manufacturing processes could revolutionize pharmaceutical production methods.

Keywords: Three-dimensional printing; Pharmaceutical manufacturing; Personalized medicine; Drug delivery systems; Additive manufacturing.

1. Introduction

Three-dimensional (3D) printing, or additive manufacturing, has fundamentally transformed manufacturing processes across numerous industries, with its impact particularly evident in pharmaceutical development and production [1]. The technology's capacity to generate intricate geometries and structures with high precision has opened new avenues in drug delivery system design and manufacturing [2]. The pharmaceutical sector has traditionally relied on conventional manufacturing methods that primarily focus on large-scale production of standardized dosage forms. However, these approaches often fall short in addressing individual patient needs, particularly in cases requiring precise dosing adjustments or unique drug release profiles [3]. The integration of 3D printing technologies in pharmaceutical manufacturing presents opportunities to overcome these limitations by enabling the production of customized medications with specific therapeutic requirements [4].

The evolution of 3D printing in pharmaceuticals has been marked by significant technological advances, from basic prototype development to the creation of FDA-approved medications [5]. The technology's ability to precisely control spatial distribution of active pharmaceutical ingredients (APIs) and excipients has enabled the development of complex drug delivery systems that were previously unattainable through conventional manufacturing methods [6]. Currently, pharmaceutical 3D printing encompasses various technological approaches, each offering distinct advantages in drug formulation and delivery. These technologies have demonstrated potential in creating oral dosage forms, implants, and transdermal delivery systems, among others [7]. The ability to modify drug release profiles through geometric design and material selection has particularly enhanced the potential for therapeutic optimization [8].

Recent developments in materials science and printing technologies have further expanded the scope of 3D printing in pharmaceutical applications. The emergence of biocompatible materials and advanced printing techniques has facilitated the creation of sophisticated drug delivery systems with enhanced therapeutic efficacy [9]. Additionally, the integration of digital design tools has enabled precise control over critical formulation parameters, leading to improved product quality and consistency [10]. The pharmaceutical industry's growing interest in personalized medicine has positioned 3D printing as a key enabling technology. The ability to produce patient-specific dosage forms based on individual therapeutic requirements represents a significant advancement

* Corresponding author: Sai Krishna B

in healthcare delivery [11]. This approach not only enhances treatment efficacy but also potentially reduces adverse effects through precise dose optimization [12, 13]. The aim of this review is to describe about current 3D printing technologies in pharmaceutical manufacturing, recent technological advances, and future directions in the field.

2. 3D Printing in Pharmaceutical Manufacturing

The application of 3D printing in pharmaceutical manufacturing encompasses several distinct technological approaches, each offering unique advantages and capabilities in drug formulation and delivery. The selection of appropriate printing technology depends on various factors, including the physicochemical properties of the active ingredients, desired release profiles, and specific therapeutic requirements [14].

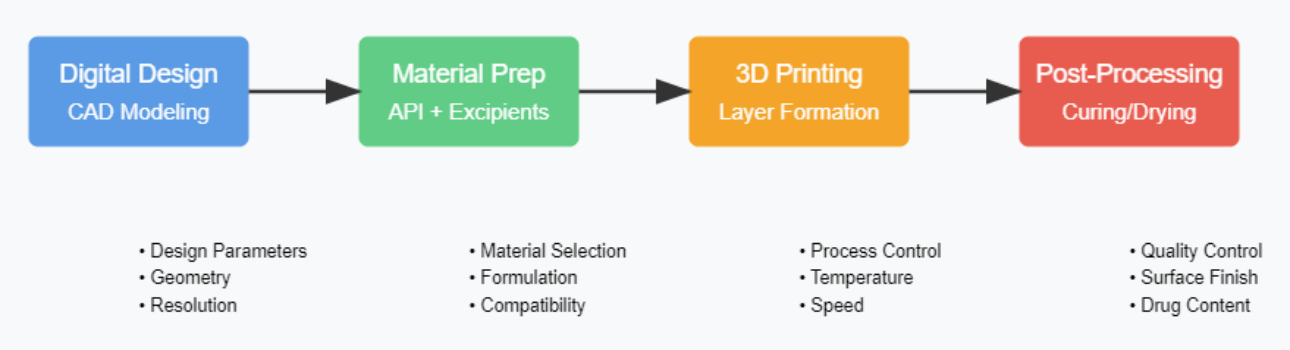

Figure 1. Pharmaceutical 3D printing process showing key stages and critical parameters

2.1. Fused Deposition Modeling (FDM)

FDM technology represents a prominent approach in pharmaceutical 3D printing, operating through the thermal extrusion of drug-loaded polymeric filaments. The process involves heating the filament above its glass transition temperature, followed by precise layer-by-layer deposition to create the desired dosage form [15]. The technology offers significant advantages in terms of cost-effectiveness and operational simplicity.

The critical parameters in FDM printing include: extrusion temperature control, print bed temperature optimization, layer height and infill density adjustment and printing speed modulation. These parameters significantly influence the final product characteristics, including drug content uniformity, dissolution properties, and mechanical strength [16]. The selection of appropriate polymeric carriers plays a crucial role in ensuring API stability during the thermal processing and achieving desired release characteristics [17].

2.2. Stereolithography (SLA)

SLA technology utilizes photopolymerization reactions to generate solid structures from liquid resins containing pharmaceutical ingredients. The process employs directed laser energy to initiate crosslinking reactions in photosensitive materials, enabling the creation of complex geometric structures with high resolution [18].

The technology demonstrates particular advantages in:

- Production of high-precision dosage forms
- Development of controlled-release matrices
- Creation of complex internal structures
- Manufacturing of drug-loaded hydrogels

The photopolymerization process requires careful consideration of:

- Photoinitiator selection
- Light exposure parameters
- Resin viscosity control
- Post-curing requirements

2.3. Selective Laser Sintering (SLS)

SLS technology employs laser energy to sinter powdered materials into cohesive structures. The process involves selective fusion of powder particles through precise thermal energy delivery, enabling the creation of complex pharmaceutical formulations [19]. This technology has demonstrated particular utility in developing orally disintegrating tablets, controlled-release matrices, drug-loaded implants and porous drug delivery systems

Critical process parameters in SLS include:

- Laser power optimization
- Scanning speed control
- Powder bed temperature
- Layer thickness adjustment

2.4. Inkjet Printing

Inkjet printing technology in pharmaceutical manufacturing involves the precise deposition of drug-containing solutions or suspensions onto suitable substrates. The technology offers exceptional control over dose accuracy and enables the creation of complex multi-drug combinations [20].

The main advantages include:

- High precision in drug deposition
- Flexibility in formulation design
- Capability for multi-drug printing
- Minimal drug waste

Table 1 provides details of various 3D printing technologies, highlighting their specific advantages, limitations, and typical applications in pharmaceutical manufacturing.

Table 1. Comparison of Different 3D Printing Technologies in Pharmaceutical Manufacturing

Technology	Resolution Range	Material Requirements	Process Temperature	Applications	Process Limitations
FDM	100-300 µm	Thermoplastic polymers, Drug-loaded filaments	150-250°C	Extended-release tablets, Multi-layer devices	Thermal degradation risk, Limited material choice
SLA	25-100 µm	Photocurable resins, Biocompatible polymers	Room temperature	Hydrogels, Microneedles, Complex geometries	High material cost, Post-curing required
SLS	75-150 µm	Fine powder materials, Thermoplastic polymers	80-200°C	Orally disintegrating tablets, Porous structures	High equipment cost, Powder handling complexity
Inkjet	10-50 µm	Drug solutions, Binders, Low-viscosity materials	Room temperature	Immediate-release formulations, Combination products	Limited drug loading capacity, Substrate requirement

3. Advantages of 3D Printed Medications

3.1. Patient-Centric Drug Design

3.1.1. Personalized Dosing

The implementation of 3D printing technologies enables precise control over medication dosing based on individual patient characteristics. Factors such as age, body weight, genetic polymorphisms, and metabolic variations can be incorporated into the drug design process [21]. This level of customization allows healthcare providers to optimize therapeutic outcomes while minimizing adverse effects through precise dose adjustments.

3.1.2. Multi-Drug Integration

3D printing facilitates the development of polypills, incorporating multiple active pharmaceutical ingredients within a single dosage form. This approach addresses complex medication regimens by combining different drugs with specific release profiles, potentially improving patient adherence to prescribed treatments [22]. The spatial arrangement of different APIs within the printed structure can be precisely controlled to optimize therapeutic efficacy and minimize drug-drug interactions.

3.2. Advanced Formulation

3.2.1. Geometric Complexity

The technology enables the creation of intricate internal structures and complex geometries that are virtually impossible to achieve through conventional manufacturing methods. These sophisticated designs can modulate drug release kinetics through controlled diffusion pathways and erosion patterns [23]. The ability to manipulate internal architecture allows for the development of advanced controlled-release systems with predetermined dissolution profiles.

3.2.2. Modification of Release Profile

Through careful design of structural parameters and material selection, 3D printing enables the creation of dosage forms with tailored release characteristics. Various release profiles, including immediate release, sustained release, and pulsatile release, can be achieved through modifications in printing parameters and formulation composition [24].

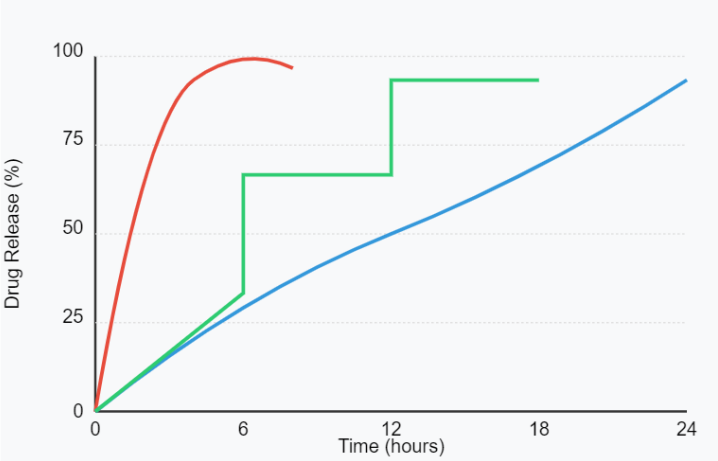

Figure 2. Drug release profiles achievable through different 3D printing designs and formulation strategies, showing immediate (red), sustained (blue), and pulsatile (green) release patterns over 24 hours

3.3. Manufacturing Advantages

3.3.1. On-Demand Production

The flexibility of 3D printing technology allows for rapid response to patient needs through on-site medication production. This capability is particularly valuable in clinical settings requiring immediate dosing adjustments or in regions with limited access to conventional pharmaceutical supply chains [25]. The approach minimizes inventory requirements and reduces medication waste through precise production quantities.

3.3.2. Process Efficiency

3D printing streamlines the manufacturing process by eliminating multiple production steps typically required in conventional pharmaceutical manufacturing. The technology offers reduced setup times, minimal material waste, and enhanced process control through digital design implementation [26]. These advantages contribute to improved production efficiency and reduced manufacturing costs.

3.4. Quality Enhancement

3.4.1. Content Uniformity

The precise nature of 3D printing processes enables superior control over drug content uniformity compared to traditional manufacturing methods. Digital control of material deposition ensures consistent distribution of active ingredients throughout the dosage form [27].

3.4.2. Reproducibility

Advanced process control mechanisms in 3D printing systems ensure high reproducibility in pharmaceutical production. Digital design templates and automated manufacturing processes minimize variations between production batches, contributing to enhanced product quality [28].

Table 2. Impact of 3D Printing on Pharmaceutical Manufacturing Parameters

Manufacturing Parameter	Traditional Methods	3D Printing Approach	Impact Assessment
Production Flexibility	Fixed batch sizes, Limited customization	On-demand production, High customization	Enhanced patient-specific manufacturing
Process Complexity	Multiple unit operations	Single-step fabrication	Reduced processing steps and time
Material Efficiency	20-40% material waste	5-10% material waste	Improved material utilization
Quality Control	Batch-based testing	Real-time monitoring capability	Enhanced process control
Scale-up Requirements	Large facility needs	Modular expansion possible	Reduced infrastructure requirements
Time to Market	12-24 months typical	3-6 months potential	Accelerated development cycle

4. Recent Trends

4.1. Commercial applications

4.1.1. Spritam® Development and Approval

The introduction of Spritam® (levetiracetam) marked a significant milestone as the first FDA-approved 3D printed pharmaceutical product. The medication, manufactured using ZipDose® technology, demonstrates rapid disintegration properties while maintaining high drug loading capacity [29]. The manufacturing process employs a layer-by-layer powder deposition technique, resulting in a highly porous structure that facilitates rapid dissolution upon oral administration [30].

4.1.2. Performance Characteristics

Clinical evaluations of Spritam® have demonstrated superior disintegration properties compared to conventional formulations, with complete dissolution occurring within seconds of oral administration. The enhanced dissolution characteristics are particularly beneficial for patients experiencing difficulty swallowing conventional tablets [31].

4.1.3. Personalized Dosing Systems

Recent developments in pediatric drug delivery have focused on creating precise dosage forms for treating rare metabolic disorders. The application of 3D printing in manufacturing isoleucine formulations for maple syrup urine disease represents a significant advancement in pediatric medicine [32]. Studies have demonstrated successful production of chewable tablets with dosage accuracy within ±5% of target concentrations.

4.1.4. Enhancement of Palatability

Advanced 3D printing techniques have enabled the incorporation of taste-masking elements and child-friendly designs in pediatric formulations. These developments have shown improved acceptance rates among pediatric patients while maintaining therapeutic efficacy [33].

4.2. Implantable Drug Delivery Systems

4.2.1. Biodegradable Implants

Recent innovations include the development of 3D printed biodegradable scaffolds incorporating controlled-release drug delivery mechanisms. Studies utilizing polycaprolactone-based structures have demonstrated sustained drug release profiles extending over several weeks, with applications in tissue engineering and local drug delivery [34].

4.2.2. Tissue-Specific Applications

Advanced implant designs have been developed for specific therapeutic applications, including bone tissue engineering and localized cancer treatment. These systems demonstrate controlled drug release kinetics while promoting tissue regeneration through optimized scaffold architecture [35].

Table 3. Clinical Outcomes of 3D Printed Drug Delivery Systems

Product Type	Clinical Application	Main Findings	Patient Benefits	Reference
Spritam®	Epilepsy treatment	Rapid disintegration (<10 seconds), High dose loading	Improved patient compliance	[29]
Pediatric formulations	Metabolic disorders	Dose accuracy ±5%, Enhanced palatability	Better acceptance rates	[32]
Implantable devices	Local drug delivery	Sustained release over 4-6 weeks, Controlled degradation	Reduced systemic exposure	[34]
Transdermal systems	Pain management	Enhanced skin penetration, Controlled release profiles	Non-invasive administration	[36]

4.3. Drug Delivery Systems

4.3.1. Transdermal Systems

Innovations in microneedle array fabrication using 3D printing have advanced transdermal drug delivery capabilities. These systems demonstrate enhanced skin penetration properties while maintaining drug stability and providing controlled release profiles [36]. The technology enables precise control over microneedle geometry and drug loading capacity.

4.3.2. Modified Release Systems

Recent developments include the creation of complex modified release systems through multi-material 3D printing. These systems incorporate varying polymer compositions and architectural designs to achieve predetermined release profiles for enhanced therapeutic effectiveness [37].

4.3.3. Smart Materials

The incorporation of stimuli-responsive materials in 3D printed pharmaceuticals has enabled the development of environment-sensitive drug delivery systems. These advanced formulations respond to specific physiological conditions, optimizing drug release based on environmental triggers [38].

4.3.4. Biocompatible Polymers

Significant advances have been made in developing new biocompatible polymers specifically designed for pharmaceutical 3D printing applications. These materials demonstrate improved processing characteristics while maintaining drug stability and desired release properties [39].

5. Pharmaceutical Challenges

5.1. Regulatory compliancee

The implementation of 3D printing in pharmaceutical production presents unique challenges in establishing appropriate manufacturing standards. Current Good Manufacturing Practice (cGMP) guidelines require adaptation to accommodate the specific characteristics of 3D printing processes [40]. The definition of batch consistency, process validation parameters, and in-process controls necessitates careful consideration within the context of additive manufacturing.

The development of standardized quality control metrics specific to 3D printed pharmaceuticals remains a significant challenge. Critical quality attributes must address both traditional pharmaceutical parameters and unique aspects of 3D printing processes, including geometric accuracy, layer adhesion, and internal structure consistency [41].

5.2. Materials

5.2.1. Pharmaceutical Grade Materials

The limited availability of pharmaceutical-grade materials suitable for 3D printing applications presents a significant constraint. Materials must demonstrate appropriate thermal stability, processing characteristics, and compatibility with active pharmaceutical ingredients while meeting regulatory requirements for drug product manufacturing [42].

5.2.2. Stability

The impact of thermal processing and mechanical stress during 3D printing on drug stability requires comprehensive evaluation. Studies indicate potential degradation of thermolabile compounds during processing, necessitating careful selection of processing parameters and excipients [43].

Table 4. Critical Material Parameters for Pharmaceutical 3D Printing

Parameter Category	Requirements	Testing Methods	Acceptance Criteria
Thermal Properties	Glass transition temperature, Melting point, Thermal stability	DSC, TGA	Stability up to processing temperature
Mechanical Properties	Tensile strength, Elasticity, Hardness	Material testing, Texture analysis	Meet pharmacopoeial requirements
Processing Properties	Viscosity, Flow behavior, Printability	Rheometry, Process verification	Consistent extrusion/deposition
Stability Parameters	Chemical stability, Physical stability	HPLC, XRD, Stability studies	24-month stability at specified conditions

5.3. Technical Limitations

5.3.1. Process Parameters

The optimization of printing parameters presents significant challenges in ensuring consistent product quality. Variables such as printing temperature, speed, and environmental conditions must be precisely controlled to maintain product specifications [44]. The interaction between these parameters and their impact on final product characteristics requires extensive characterization.

5.3.2. Scale-up Considerations

The transition from laboratory-scale production to commercial manufacturing presents significant technical challenges. Issues related to process speed, equipment capacity, and maintenance of quality attributes during scale-up require careful consideration [45].

5.4. Economic factors

5.4.1. Production Costs

The economic viability of 3D printed pharmaceuticals requires careful evaluation of production costs, including equipment investment, material costs, and operational expenses. Current analysis indicates higher unit costs compared to traditional manufacturing methods, particularly for large-scale production [46].

5.4.2. Infrastructure Requirements

The implementation of pharmaceutical 3D printing requires significant investment in specialized equipment, facilities, and training. The development of appropriate infrastructure for quality control, material handling, and process monitoring represents substantial economic considerations [47].

5.5. Quality Control

5.5.1. Analytical Methods

The development and validation of appropriate analytical methods for 3D printed pharmaceuticals presents unique challenges. Traditional pharmaceutical testing methods require adaptation to address specific characteristics of 3D printed products, including geometric accuracy and internal structure analysis [48].

5.5.2. Process Monitoring

Real-time monitoring of critical process parameters during 3D printing requires sophisticated analytical tools and control systems. The development of appropriate in-process controls and feedback mechanisms remains an active area of investigation [49].

Table 5. Quality Control Parameters for 3D Printed Pharmaceuticals

Parameter	Test Method	Specification	Monitoring Frequency
Content Uniformity	HPLC/UV Spectroscopy	95-105% label claim	Every batch
Geometric Accuracy	3D Scanning, Image Analysis	±5% target dimensions	Continuous monitoring
Layer Adhesion	Mechanical Testing	>2 MPa bond strength	Batch sampling
Dissolution Profile	USP Apparatus	Q-value meets specification	Batch release testing
Internal Structure	Micro-CT Analysis	Porosity within ±10% target	Process validation
Product Identity	NIR/Raman Spectroscopy	Spectral matching >95%	Real-time monitoring

6. Conclusion

The integration of 3D printing technology in pharmaceutical manufacturing represents a significant advancement in drug delivery system development and personalized medicine. This comprehensive review demonstrates the transformative potential of additive manufacturing in addressing current limitations of conventional pharmaceutical production methods. The technology's ability to create complex geometries, enable precise dosing, and facilitate on-demand production positions it as a crucial tool in the future of pharmaceutical manufacturing. Despite notable achievements, including the successful commercialization of products like Spritam®, several challenges remain to be addressed. These include regulatory considerations, material limitations, and economic feasibility of large-scale production. The resolution of these challenges will require continued collaboration between industry stakeholders, regulatory authorities, and research institutions.

References

[1] Norman J, Madurawe RD, Moore CM, Khan MA, Khairuzzaman A. A new chapter in pharmaceutical manufacturing: 3D-printed drug products. Adv Drug Deliv Rev. 2017;108:39-50.

[2] Alhnan MA, Okwuosa TC, Sadia M, Wan KW, Ahmed W, Arafat B. Emergence of 3D printed dosage forms: opportunities and challenges. Pharm Res. 2016;33(8):1817-32.

[3] Trenfield SJ, Awad A, Goyanes A, Gaisford S, Basit AW. 3D printing pharmaceuticals: drug development to frontline care. Trends Pharmacol Sci. 2018;39(5):440-51.

[4] Jamróz W, Szafraniec J, Kurek M, Jachowicz R. 3D printing in pharmaceutical and medical applications. Pharm Res. 2018;35(9):176.

[5] Capel AJ, Rimington RP, Lewis MP, Christie SDR. 3D printing for chemical, pharmaceutical and biological applications. Nat Rev Chem. 2018;2:422-36

[6] Goole J, Amighi K. 3D printing in pharmaceutics: A new tool for designing customized drug delivery systems. Int J Pharm. 2016;499(1-2):376-94.

[7] Prasad LK, Smyth H. 3D Printing technologies for drug delivery: a review. Drug Dev Ind Pharm. 2016;42(7):1019-31.

[8] Zhang J, Feng X, Patil H, Tiwari RV, Repka MA. Coupling 3D printing with hot-melt extrusion to produce controlled-release tablets. Int J Pharm. 2017;519(1-2):186-97.

[9] Khaled SA, Burley JC, Alexander MR, Roberts CJ. Desktop 3D printing of controlled release pharmaceutical bilayer tablets. Int J Pharm. 2014;461(1-2):105-11.

[10] Goyanes A, Det-Amornrat U, Wang J, Basit AW, Gaisford S. 3D scanning and 3D printing as innovative technologies for fabricating personalized topical drug delivery systems. J Control Release. 2016;234:41-8.

[11] Ventola CL. Medical applications for 3D printing: current and projected uses. P T. 2014;39(10):704-11.

[12] Awad A, Trenfield SJ, Goyanes A, Gaisford S, Basit AW. Reshaping drug development using 3D printing. Drug Discov Today. 2018;23(8):1547-55.

[13] Liang K, Brambilla D, Leroux JC. Is 3D printing of pharmaceuticals a disruptor or enabler? Adv Mater. 2019;31(5):1805680.

[14] Reddy S, Madhusudhan A, Ramesh K, Venkateswarlu V. 3D printing technologies in drug delivery formulation: recent developments and future prospects. Drug Dev Ind Pharm. 2020;46(8):1227-44.

[15] Melocchi A, Parietti F, Loreti G, Maroni A, Gazzaniga A, Zema L. 3D printing by fused deposition modeling of single- and multi-compartment hollow systems for oral delivery. Int J Pharm. 2015;494(2):395-407.

[16] Verstraete G, Samaro A, Grymonpré W, Vanhoorne V, Van Snick B, Boone MN, et al. 3D printing of high drug loaded dosage forms using thermoplastic polyurethanes. Int J Pharm. 2018;536(1):318-25.

[17] Kollamaram G, Croker DM, Walker GM, Goyanes A, Basit AW, Gaisford S. Low temperature fused deposition modeling (FDM) 3D printing of thermolabile drugs. Int J Pharm. 2018;545(1-2):144-52.

[18] Wang J, Goyanes A, Gaisford S, Basit AW. Stereolithographic (SLA) 3D printing of oral modified-release dosage forms. Int J Pharm. 2016;503(1-2):207-12.

[19] Fina F, Goyanes A, Gaisford S, Basit AW. Selective laser sintering (SLS) 3D printing of medicines. Int J Pharm. 2017;529(1-2):285-93.

[20] Scoutaris N, Ross S, Douroumis D. Current trends on medical and pharmaceutical applications of inkjet printing technology. Pharm Res. 2016;33(8):1799-816.

[21] Sandler N, Preis M. Printed Drug-Delivery Systems for Improved Patient Treatment. Trends Pharmacol Sci. 2016;37(12):1070-80.

[22] Sarella PN, Vendi VK, Vipparthi AK, Valluri S, Vegi S. Advances in Proniosomes: Harnessing Nanotechnology for Enhanced Drug Delivery. Asian Journal of Research in Pharmaceutical Sciences. 2024 Sep 19;14(3):279-86.

[23] Sun Y, Soh S. Printing tablets with fully customizable release profiles for personalized medicine. Adv Mater. 2015;27(47):7847-53.

[24] Chai X, Chai H, Wang X, Yang J, Li J, Zhao Y, et al. Fused deposition modeling (FDM) 3D printed tablets for intragastric floating delivery of domperidone. Sci Rep. 2017;7(1):2829.

[25] Khaled SA, Burley JC, Alexander MR, Yang J, Roberts CJ. 3D printing of five-in-one dose combination polypill with defined immediate and sustained release profiles. J Control Release. 2015;217:308-14.

[26] Hsiao WK, Lorber B, Reitsamer H, Khinast J. 3D printing of oral drugs: a new reality or hype? Expert Opin Drug Deliv. 2018;15(1):1-4.

[27] Fanous M, Gold S, Muehlenfeld C, Schaefer S, Ziemer F, Kleinebudde P. Simplification of fused deposition modeling 3D-printing paradigm: Feasibility of 1-step direct powder printing for immediate release dosage form production. Int J Pharm. 2020;578:119124.

[28] Karakurt I, Lin L, Koike Y, Troczynski T, Turkmen N. 3D printing pharmaceuticals and drug delivery devices. J Pharm Sci. 2020;109(12):3535-50.

[29] Skowyra J, Pietrzak K, Alhnan MA. Fabrication of extended-release patient-tailored prednisolone tablets via fused deposition modelling (FDM) 3D printing. Eur J Pharm Sci. 2015;68:11-7.

[30] Zhang J, Yang W, Vo AQ, Feng X, Ye X, Kim DW, et al. Hydroxypropyl methylcellulose-based controlled release dosage by melt extrusion and 3D printing: Structure and drug release correlation. Carbohydr Polym. 2017;177:49-57.

[31] Arji SR, Eranki SS, Pecchetty S, Sarella PN. Unconventional stationary phases: Nanomaterials, nanoparticles and the future of liquid chromatography. World Journal of Advanced Research and Reviews. 2023;18(2):492-501.

[32] Kadry H, Wadnap S, Xu C, Ahsan F. Digital light processing (DLP) 3D-printing technology and photoreactive polymers in fabrication of modified-release tablets. Eur J Pharm Sci. 2019;135:60-7.

[33] Tan DK, Maniruzzaman M, Nokhodchi A. Advanced pharmaceutical applications of hot-melt extrusion coupled with fused deposition modelling (FDM) 3D printing for personalised drug delivery. Pharmaceutics. 2018;10(4):203.

[34] Economidou SN, Lamprou DA, Douroumis D. 3D printing applications for transdermal drug delivery. Int J Pharm. 2018;544(2):415-24.

[35] Trenfield SJ, Xian Tan H, Awad A, Buanz A, Gaisford S, Basit AW, et al. Track-and-trace: Novel anti-counterfeit measures for 3D printed personalized drug products using smart material inks. Int J Pharm. 2019;567:118443.

[36] Lim SH, Kathuria H, Tan JJY, Kang L. 3D printed drug delivery and testing systems - a passing fad or the future? Adv Drug Deliv Rev. 2018;132:139-68.

[37] Long J, Gholizadeh H, Lu J, Bunt C, Seyfoddin A. Application of fused deposition modelling (FDM) method of 3D printing in drug delivery. Curr Pharm Des. 2017;23(3):433-9.

[38] Okwuosa TC, Stefaniak D, Arafat B, Isreb A, Wan KW, Alhnan MA. A lower temperature FDM 3D printing for the manufacture of patient-specific immediate release tablets. Pharm Res. 2016;33(11):2704-12.

[39] Araújo MRP, Sa-Barreto LL, Gratieri T, Gelfuso GM, Cunha-Filho M. The digital pharmacies era: How 3D printing technology using fused deposition modeling can become a reality. Pharmaceutics. 2019;11(3):128.

[40] Sarella PN, Godavari LR. The Expanding Scope of Emulgels: Formulation, Evaluation and Medical Uses. Int J Curr Sci Res Rev. 2023;6(5):3030-41.

[41] Içten E, Giridhar A, Taylor LS, Nagy ZK, Reklaitis GV. Dropwise additive manufacturing of pharmaceutical products for melt-based dosage forms. J Pharm Sci. 2015;104(5):1641-9.

[42] Goyanes A, Buanz AB, Basit AW, Gaisford S. Fused-filament 3D printing (3DP) for fabrication of tablets. Int J Pharm. 2014;476(1-2):88-92.

[43] Solanki NG, Tahsin M, Shah AV, Serajuddin AT. Formulation of 3D printed tablet for rapid drug release by fused deposition modeling: screening polymers for drug release, drug-polymer miscibility and printability. J Pharm Sci. 2018;107(1):390-401.

[44] Xu X, Zhao J, Wang M, Wang L, Yang J. 3D printed polyvinyl alcohol tablets with multiple release profiles. Sci Rep. 2019;9(1):12487.

[45] Pietrzak K, Isreb A, Alhnan MA. A flexible-dose dispenser for immediate and extended release 3D printed tablets. Eur J Pharm Biopharm. 2015;96:380-7.

[46] Gioumouxouzis CI, Katsamenis OL, Bouropoulos N, Fatouros DG. 3D printed oral solid dosage forms containing hydrochlorothiazide for controlled drug delivery. J Drug Deliv Sci Technol. 2017;40:164-71.

[47] Rahman Z, Barakh Ali SF, Ozkan T, Charoo NA, Reddy IK, Khan MA. Additive manufacturing with 3D printing: Progress from bench to bedside. AAPS J. 2018;20(6):101.

[48] Yu DG, Zheng Y, Yang Y, Xu X, Wang Q, Shen C. Influence of process parameters on quality of 3D printed tablets. Bioengineering. 2019;6(4):96.

[49] Kempin W, Domsta V, Grießmann K, Thoma I, Weitschies W, Seidlitz A. Immediate release 3D-printed tablets produced via fused deposition modeling of a thermo-sensitive drug. Pharm Res. 2018;35(6):124.