



**International Journal of Biology, Pharmacy
and Allied Sciences (IJBPAS)**

'A Bridge Between Laboratory and Reader'

www.ijbpas.com

3D PRINTED DOSAGE FORMS INTEGRATED WITH NANOPARTICLE DRUG DELIVERY: CURRENT ADVANCES, EVALUATION AND FUTURE PERSPECTIVES

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Received 16th April 2026; Revised 19th May 2026; Accepted 1st Aug, 2026; Available online 1st Nov. 2026

<https://doi.org/10.31032/IJBPAS/2026/15.11.10619>

ABSTRACT

Because it makes it possible to create customized medications, intricate geometries, and programmed drug release systems, three-dimensional (3D) printing has become a game-changing technology in the pharmaceutical sciences. Customized pharmacokinetics and patient-specific dosing are frequently not possible with conventional dose forms. A synergistic platform that combines precise manufacturing with increased solubility, targeting, controlled release, and bioavailability is provided by the combination of 3D printed dosage forms and nanoparticle-based drug delivery. Tablets, films, microneedles, implants, and scaffolds made by additive manufacturing can incorporate nanoparticles such as polymeric nanoparticles, liposomes, solid lipid nanoparticles, nanostructured lipid carriers, nanoemulsions, and metallic nanoparticles. The foundations of pharmaceutical 3D printing technologies, the function of nanoparticles in sophisticated formulations, comparative examples of medications created using printed systems loaded with nanoparticles, evaluation techniques, therapeutic applications, benefits, drawbacks, and future prospects are all summarized in this review. The integration of nanotechnology and 3D printing is a significant step toward next-generation smart dosage forms, on-demand production, and precision medicine.

Keywords: 3D Printing, Nanoparticles, Drug Delivery System, Personalized Medicine, Controlled Release, Novel Dosage Forms, Printlets, Nanotechnology

INTRODUCTION

The pharmaceutical industry has historically relied on "one-size-fits-all" mass production of tablets, capsules, injections, and topical preparations. The age, body weight, metabolism, severity of the disease, and therapeutic requirements of patient populations vary greatly, though. Customized medication delivery methods become more in demand as a result [1].

Additive manufacturing, another name for 3D printing, creates objects layer by layer from a digital design [2]. In the pharmaceutical industry, it enables single-unit control over dose, shape, porosity, release kinetics, and combination therapy. Pharmaceutical printing

has been increasingly popular since the FDA authorized Spritam® (levetiracetam), the first 3D printed tablet [3, 4].

Nanoparticles are submicron colloidal systems (typically 1–1000 nm) that improve drug delivery by [5] enhancing solubility of poorly water-soluble drugs, Protecting unstable drugs, Improving permeability, Providing sustained/ targeted release, Reducing toxicity, Enabling intracellular delivery. A hybrid system that blends macroscale customized fabrication with nanoscale drug engineering is created when nanoparticles are included into 3D printed dosage forms.

Table 1: Need for Integration of 3D Printing with Nanoparticles [6, 7].

Dosage Forms	Role of Nanoparticles	Role of 3D Printing
Fixed dose strength	Improve loading efficiency	Personalized dosing
Poor solubility	Nano-size improves dissolution	Complex release architecture
Frequent dosing	Sustained release carriers	Controlled geometry
Lack of targeting	Ligand-functionalized nanoparticles	Patient-specific devices
Multiple medications	Separate nanoparticle compartments	Polypills / multi-drug tablets

This integration is especially useful in oncology, pediatrics, neurology, dermatology, and chronic disease management [8, 9].

Types of 3D Printing Technologies Used in Pharmaceutics

Pharmaceutics uses a variety of 3D printing technologies based on drug characteristics and formulation requirements [10, 11]. One of the most popular methods is fused deposition modeling (FDM), which uses polymers like

PLA, PVA, and HPMC to create tablets, implants, and gastroretentive devices by melting a drug-loaded polymer filament through a nozzle and depositing it layer by layer [12, 13]. High precision and appropriateness for microneedles, scaffolds, and implants are provided by stereolithography (SLA), which uses ultraviolet light to cure photopolymer resin in successive layers. Inkjet printing is excellent

for thin films and low-dose medications because it deposits tiny droplets of ink or drug solution onto a substrate [14-16].

Without the use of solvents, Selective Laser Sintering (SLS) fuses powder particles into solid structures using laser energy. Paste or gel-like materials are extruded using semi-solid extrusion (SSE), which is especially useful for heat-sensitive medications and gels containing nanoparticles [17, 18].

Types of Nanoparticles Used in Printed Dosage Forms

Because of their special qualities and therapeutic benefits, many kinds of nanoparticles are frequently utilized in sophisticated drug delivery systems. For targeted distribution and prolonged drug release, polymeric nanoparticles made of PLGA, chitosan, and alginate are frequently utilized [19, 20]. The solid lipid core of solid lipid nanoparticles (SLN) improves medication stability and offers controlled release. A combination of liquid and solid lipids is used to create Nanostructured Lipid Carriers (NLC), which function better than SLN and have a larger drug loading capacity. Liposomes are phospholipid vesicles that are extremely adaptable carriers since they can encapsulate both hydrophilic and lipophilic medications [21-23]. Oil-in-water or water-in-oil nanosystems known as nanoemulsions

enhance topical and oral medication absorption. Silver, gold, and zinc oxide nanoparticles are examples of metallic nanoparticles that are mostly used for theranostic and antibacterial purposes [24, 25].

Novel 3D Printed Dosage Forms with Nanoparticles

By combining nanoparticles with 3D printing technology, a number of innovative dosage forms have been created to improve patient compliance and therapeutic efficacy. In addition to being manufactured as multi-compartment tablets for combination therapy, nanoparticle-loaded tablets can be made for immediate, sustained, or pulsatile drug release [26]. Orodispersible films are thin films that dissolve quickly and contain nanocarriers for convenient administration and quick drug release. For painless transdermal medication delivery, dissolving microneedles filled with nanoparticles make up microneedle patches [27, 28]. Nanoreservoir-containing long-acting printed implants are helpful for long-term therapy. Antimicrobial nanoparticle-loaded scaffolds are being investigated extensively for use in tissue engineering and bone regeneration. Low-density printed tablets with nanoparticles that stay buoyant in the stomach to extend gastric residence duration and enhance drug absorption are known as floating gastroretentive devices [29, 30].

Table 2: Comparative Data of Different Drugs in 3D Printed Nanoparticle Systems [30]

Drug	Nanoparticle Type	Printed Dosage Form	Therapeutic Benefit
Curcumin	Polymeric NP	Tablet / Film	Improved solubility
Paclitaxel	Liposomes / PLGA NP	Implant / Scaffold	Targeted anticancer action
Ibuprofen	SLN	Tablet	Sustained release
Levetiracetam	Nano-dispersion	Fast disintegrating tablet	Personalized dose
Dexamethasone	Polymeric NP	Pediatric chewable printlet	Taste masking + custom dose
Ciprofloxacin	Silver NP composite	Wound scaffold	Antibacterial action
Insulin	Chitosan NP	Microneedle patch	Non-invasive delivery
Amphotericin B	Lipid NP	Implant	Reduced toxicity
Metformin	NLC	Gastroretentive tablet	Extended release
Diclofenac	Nanoemulsion	Topical printed patch	Better skin permeation

Evaluation Parameters

Preformulation Evaluation

An essential stage in the creation of medication delivery systems based on nanoparticles is preformulation evaluation. It aids in comprehending the physicochemical characteristics of nanoparticles prior to their integration into the finished dosage form. Stability, repeatability, and the intended treatment outcome are guaranteed by accurate evaluation [31, 32].

Particle Size

Because it directly impacts drug release, solubility, bioavailability, cellular uptake, and stability, particle size is one of the most important factors. The typical size range of nanoparticles is 1–1000 nm. Smaller particles have more surface area, which improves the absorption and solubility of medications that are less soluble [33, 34]. Electron microscopy, laser diffraction, and dynamic light scattering (DLS) are frequently used to quantify particle size. For instance, compared to pure curcumin powder, curcumin nanoparticles with an

average particle size of 150 nm exhibit noticeably better water solubility and quicker dissolution [35-37].

Zeta Potential

Zeta potential predicts the physical stability of nanoparticles in dispersion and reveals their surface charge. Millivolts (mV) are used to measure it [38]. Aggregation is prevented by the repulsion of particles with high positive or negative zeta potential. Good stability is often indicated by readings above +30 mV or below –30 mV. Particle clumping and sedimentation during storage may result from low zeta potential. For instance, because chitosan has a positive charge, insulin-carrying chitosan nanoparticles may exhibit a zeta potential of +35 mV, improving stability and mucoadhesion [39, 40].

Drug Entrapment Efficiency

The percentage of medicine that is successfully incorporated into nanoparticles in relation to the total amount employed during formulation is known as entrapment efficiency. Because it guarantees sufficient

drug loading and reduces waste, high entrapment efficiency is preferred [41]. Drug examination using UV spectroscopy or HPLC is often performed after free drug is separated from nanoparticles by centrifugation or filtration. Formula: **Entrapment Efficiency (%) = (Entrapped Drug Amount/Total Drug Added) × 100** For instance, an ibuprofen formulation in solid lipid nanoparticles may exhibit 85% entrapment efficiency, demonstrating effective drug integration inside the lipid matrix [42-44].

PDI (Polydispersity Index)

The uniformity of the particle size distribution within a sample of nanoparticles is measured by PDI. It has a range of 0 to 1. Higher PDI values suggest a wide size distribution, whilst lower values show a more homogeneous and uniform system. For stable nanoparticle compositions, a PDI of less than 0.3 is typically regarded as acceptable. For instance,

a nanoemulsion with a particle size of 120 nm and a PDI of 0.18 shows good formulation consistency and a limited size dispersion [45].

Morphology (SEM/TEM)

The shape, surface properties, and structural appearance of nanoparticles are referred to as their morphology. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) are used to study it [46]. While TEM exposes internal structure and precise particle size, SEM provides information regarding surface texture and exterior shape. Drug release behavior, permeability, and interaction with biological membranes are all influenced by morphology [47]. For instance, SEM images of polymeric nanoparticles may show smooth, round particles with homogeneous surfaces, while TEM images of liposomes may display spherical vesicular features [48].

Table 3: Printing Process Evaluation [49-51]

Parameters	FDM	SSE	Inkjet printing	SLA
Printing Temperature	High	Low	Low	Low
Suitable for Thermolabile Drugs	Low	High	High	Moderate
Resolution	Moderate	Low	High	Very High
Nanoparticle Stability	Moderate	High	High	Moderate
Cost	Low	Low	Moderate	High

Table 4: Drug Release Comparison of Different Printed Tablet Geometries

Time (hr)	Conventional Tablet	Cylinder 3D Tablet	Porous Honeycomb Tablet	Nanoparticles Loaded Tablet
1	20%	30%	45%	55%
2	35%	48%	65%	75%
4	55%	68%	85%	95%
8	80%	92%	100%	100%

Printability

The ability of a formulation material to be effectively printed into the desired pattern without clogging, distortion, or processing faults is referred to as printability. Smooth extrusion, precise deposition, and repeatable dose forms are all ensured by good printability [52]. Temperature, nozzle diameter, printer parameters, and material characteristics all play a role. Broken structures, asymmetrical shapes, or missing layers might be the result of poor printability. For instance, strong printability is demonstrated by a PVA-based filament that contains paracetamol and extrudes smoothly through the nozzle to form a clearly defined tablet [53].

Layer Resolution

Each printed layer's thickness and accuracy are described by layer resolution. Higher resolution results in smoother surfaces, more intricate structures, thinner layers, and improved dimensional accuracy [54, 55]. It is particularly crucial for intricate dose forms like multi-compartment tablets, scaffolds, and microneedles. Poor structural fidelity and uneven surfaces can result from low layer resolution. For instance, stereolithography (SLA) can create extremely accurate microneedle arrays with sharp tips that are appropriate for transdermal distribution with a layer thickness of 50 micrometers [56].

Mechanical Strength

The ability of the printed dosage form to endure handling, packing, transit, and administration without shattering or deforming is known as mechanical strength. Layer adhesion, infill density, polymer type, and printing conditions all affect it. Implants and tablets need to be strong enough to allow for appropriate medication release [57, 58].

Filament Flexibility

In Fused Deposition Modeling (FDM), where the drug-loaded filament must bend slightly while being fed through the printer without breaking or jamming, filament flexibility is very crucial. Overly soft filaments may distort and not print correctly, while extremely brittle filaments may break while feeding. Moisture content, plasticizers, and polymer composition all affect flexibility. For instance, adding polyethylene glycol (PEG) to a PLA filament increases its flexibility and enhances its feeding performance during tablet printing [59].

Viscosity/Rheology

The flow characteristics of printing materials, such as molten polymers, inks, pastes, or gels, are described by viscosity and rheology. Extrusion-based printing, can be ascertained through rheological investigations. For instance, a semi-solid hydrogel with nanoparticles may have shear-thinning

characteristics that make it simple to extrude through the nozzle while preserving its structure after printing [59].

Finished Dosage Form Evaluation

Following the successful preparation of 3D printed pharmaceutical products, a final dosage form evaluation is conducted to ensure the products' quality, homogeneity, stability, and therapeutic efficacy. These tests confirm that the final dose form meets pharmacopeial requirements and correctly administers the medicine. Important variables include weight variation, hardness, friability, thickness, drug content, disintegration time, and dissolution investigations [59].

Weight Variation

The homogeneity of weight between individual dose units is assessed using a weight variation test. It indirectly reflects dose consistency and guarantees that every pill or printed dosage form has a constant amount of formulation material. The average weight is computed after a predetermined number of units are weighed separately. Inconsistent material flow or printing problems could be the cause of excessive variance. For instance, ten 500 mg 3D-printed pills should stay within the pharmacopeial weight deviation allowable range [59].

Hardness

The ability of a pill or dosage form to withstand breaking during handling, packing, and transportation is referred to as hardness. A hardness tester that applies pressure until the tablet breaks is typically used to measure it. Sufficient hardness is required to preserve structural integrity while permitting appropriate drug release and breakdown. For instance, a 3D printed sustained-release tablet with a hardness of 6 kg/cm² might be able to endure handling while still delivering extended drug release [59].

Friability

Friability quantifies a tablet's propensity to chip, crumble, or lose weight as a result of mechanical stress. A friabilator is used to test it, rotating and repeatedly dropping tablets for a predetermined amount of time. It calculates the percentage of weight loss. In general, a friability value of less than 1% is regarded as acceptable. For instance, the friability is 0.5%, showing good resistance to abrasion, if twenty tablets weighing 10 g collectively lose only 0.05 g after testing [59].

Thickness

A thickness test guarantees consistent dosage form dimensions, which is crucial for packaging, appearance, and dose uniformity. A micrometer or vernier caliper is used to measure it. Inconsistent printer calibration or

incorrect layer deposition can cause variations in thickness. For instance, a batch of oral disintegrating printlets with a 3 mm thickness should exhibit little variation among units [59].

Drug Content

The precise quantity of active medicinal ingredient in the dosage form is ascertained through drug content analysis. It guarantees that the medicine is distributed uniformly throughout the formulation and that the dose is accurate. The drug is measured using UV spectroscopy, HPLC, or other analytical techniques after the dosage form has been dissolved in an appropriate solvent. For instance, according to regulations, a tablet labeled as containing 100 mg of paracetamol should ideally have a drug content of between 95 and 105 mg [59].

Disintegration Time

The amount of time needed for a pill or dose form to disintegrate into smaller particles under particular circumstances is known as the disintegration time. It is particularly crucial for orodispersible formulations and immediate-release tablets. Patient convenience and start of action are enhanced by rapid disintegration.

For instance, in a saliva-like liquid, an orodispersible 3D printed tablet might dissolve in 30 seconds [60].

Dissolution Study

The rate and degree of drug release from the dosage form into a dissolve media are assessed by a dissolution study. It is among the most crucial tests for forecasting the effectiveness of drugs in vivo. Under carefully regulated temperature and stirring conditions, the investigation is conducted utilizing USP dissolving equipment. Periodically, samples are taken out and examined for drug release. For instance, a sustained-release metformin printlet may exhibit controlled release behavior by releasing 30% of the medication in the first hour and continuing to do so for 12 hours [60].

Advanced Characterization

For a thorough examination of 3D printed dosage forms loaded with nanoparticles, sophisticated characterisation methods are necessary. These techniques offer details on the drug's physical condition, excipient compatibility, crystallinity, surface morphology, and formulation stability over the long run. These investigations aid in verifying formulation quality, forecasting performance, and guaranteeing product dependability throughout use and storage [60].

DSC (Differential Scanning Calorimetry)

A thermal analysis method called differential scanning calorimetry is used to investigate drug-excipient interactions, crystallization,

glass transition temperature, and melting behavior. It aids in determining whether the medicine has undergone processing and is still crystalline or has changed into an amorphous state. Melting peak changes could be a sign of successful drug encapsulation or problems with compatibility. For instance, pure curcumin may exhibit a prominent melting peak at its characteristic temperature, but the drug may be distributed in an amorphous state inside the polymer matrix if this peak is absent or reduced in nanoparticles [60].

XRD (X-Ray Diffraction)

Drugs and excipients can be classified as crystalline or amorphous using X-ray diffraction. While broad halos imply an amorphous shape, sharp diffraction peaks indicate crystalline material. XRD is very helpful for verifying crystallinity changes following the creation of nanoparticles or 3D printing. Drug solubility and dissolution rate are frequently enhanced by decreased crystallinity. Ibuprofen crystals, for instance, have distinct XRD peaks; nevertheless, these peaks may become less intense when inclusion into solid lipid nanoparticles, suggesting partial amorphization [59].

FTIR (Fourier Transform Infrared Spectroscopy)

Functional groups and potential chemical interactions between the medication, polymer,

and other excipients can be found via FTIR. Peak shifts, disappearance, or appearance could be signs of deterioration, complex formation, or hydrogen bonding. Compatibility studies are a popular usage for it while developing formulations. For instance, variations in the amine or hydroxyl group peaks in a chitosan nanoparticle formulation may verify the interaction between chitosan and the medicine it contains [59].

SEM (Scanning Electron Microscopy)

High-resolution pictures of the surface morphology, particle shape, texture, and structural features of printed dosage forms or nanoparticles can be obtained using scanning electron microscopy. Surface smoothness, porosity, layer organization, and flaws like cracks or abnormalities can all be assessed with SEM. For instance, SEM pictures of a 3D printed tablet can reveal distinct printed layers and pores, whereas polymeric nanoparticles might show up as smooth, spherical particles [59].

Stability Studies

Stability studies are carried out to assess how external elements like light, humidity, and temperature affect the formulation's quality over time. According to ICH recommendations, parameters such as drug concentration, particle size, appearance,

dissolution, and mechanical strength are monitored during storage under specific settings. Studies on stability aid in determining storage conditions and shelf life. For instance, a tablet containing nanoparticles that has been kept at 40°C and 75% relative humidity for three months may be examined on a regular basis to make sure that neither the drug release nor its appearance have changed significantly. bottom of the form [59].

Applications

There are numerous therapeutic uses for combining nanoparticle drug delivery with 3D printing in various healthcare domains. Customized dosages can be created in personalized medicine based on patient-specific characteristics such as age, body weight, genotype, and renal function. Chewable, flavored, low-dose printlets enhance compliance and convenience of administration for both pediatric and elderly patients. Targeted nanoparticle systems and localized implants aid in the direct delivery of anticancer medications to the tumor location while lowering systemic toxicity in oncology. Multi-drug tablets with timed or programmed release can help control neurological illnesses like Parkinson's disease and epilepsy. Antimicrobial nanoparticle-containing 3D printed scaffolds aid in tissue regeneration and infection control during wound healing.

Microneedle systems loaded with proteins, peptides, or mRNA can be used to administer vaccines and biologics in a less invasive manner. Personalized polypills with several medications in one dosage form can improve patient adherence and streamline treatment for chronic conditions like diabetes, hypertension, and epilepsy.

Advantages [60]

In contemporary pharmaceuticals, combining 3D printing with nanoparticle medicine delivery has many benefits. It enables personalized therapy by providing patient-specific doses and formulations, while reducing side effects through targeted and controlled drug release. Better patient compliance can be achieved with customized dosage forms such as chewable tablets, films, or polypills. Nanoparticles increase the therapeutic efficacy of poorly soluble medications by increasing their bioavailability. Additionally, the technology facilitates on-demand manufacturing, which enables the production of medications at the appropriate time and location. Complex release patterns such as immediate, sustained, or pulsatile release can be designed with precision. Multiple drugs can be combined into a single dosage form, simplifying treatment regimens [60].

Limitations and Challenges

When combining 3D printing with the delivery of nanoparticle medicines, there are several challenges and limitations. High equipment and maintenance costs can hinder adoption, especially in small firms and research settings. The ongoing lack of pharmaceutically approved printable excipients limits formulation options. Scaling up for large-scale commercial production is still difficult when compared to conventional manufacturing methods. The regulatory uncertainty around quality standards, validation, and approval processes is another major barrier. Maintaining the stability of nanoparticles during printing can be challenging, particularly when they are exposed to heat, pressure, or light. Heat sensitivity in fused deposition modeling (FDM) can destroy thermolabile drugs and excipients. Achieving reliable batch-to-batch repeatability is essential, despite the technical difficulties. Prospects for the Future [60].

CONCLUSION

One extremely promising development in contemporary pharmaceuticals is the combination of nanoparticle medication delivery and 3D printed dosage forms. It creates individualized, efficient, and multipurpose medications by fusing precision engineering with nanoscale therapeutic

benefits. When compared to traditional formulations, these systems—which range from tablets and films to implants and microneedles—offer better control over dose, release, and targeting. Clinical translation is anticipated to be accelerated by continued advancements in materials science, printer technology, and digital healthcare, despite persistent issues with regulation, scalability, and stability. The future of pharmaceutical production and patient-centered treatment could be completely transformed by this hybrid technology.

REFERENCES

- [1] Jain K, Shukla R, Yadav A, Ujjwal RR, Flora SJS. 3D printing in development of nanomedicines. *Nanomaterials*. 2021;11(2):420.
- [2] Cardoso PHN, Araújo ES. An approach to 3D printing techniques, polymer materials, and their applications in the production of drug delivery systems. *Compounds*. 2024;4(1):71-105.
- [3] Li X, Zhang Y, Chen H, et al. 3D printing of drug delivery systems enhanced with micro/nano-technology. *Adv Drug Deliv Rev*. 2025;216:115479.
- [4] Ahmed S, Khan R, Patel M, et al. Additive manufacturing in nano drug

- delivery systems. *Pharm Sci Adv.* 2024;100036.
- [5] Gao G, Ahn M, Cho WW, Kim BS, Cho DW. 3D printing of pharmaceutical application: drug screening and drug delivery. *Pharmaceutics.* 2021;13(9):1373.
- [6] Sharma PK, Choudhury D, Yadav V, Murty USN, Banerjee S. 3D printing of nanocomposite pills through desktop vat photopolymerization for drug delivery reasons. *Prog Addit Manuf.* 2022;8(1):3.
- [7] Norman J, Madurawe RD, Moore CMV, Khan MA, Khairuzzaman A. A new chapter in pharmaceutical manufacturing: 3D-printed drug products. *Adv Drug Deliv Rev.* 2017;108:39-50.
- [8] Goyanes A, Buanz ABM, Hatton GB, Gaisford S, Basit AW. 3D printing of medicines: engineering novel oral devices with unique design and drug release characteristics. *Mol Pharm.* 2015;12(11):4077-84.
- [9] Goyanes A, Det-Amornrat U, Wang J, Basit AW, Gaisford S. 3D scanning and 3D printing as innovative technologies for fabricating personalized topical dosage forms. *J Control Release.* 2016;234:41-48.
- [10] Jamróz W, Szafraniec J, Kurek M, Jachowicz R. 3D printing in pharmaceutical and medical applications – recent achievements and challenges. *Pharm Res.* 2018;35:176.
- [11] Trenfield SJ, Madla CM, Basit AW, Gaisford S. The shape of things to come: emerging applications of 3D printing in healthcare. *Adv Drug Deliv Rev.* 2018;132:60-75.
- [12] Awad A, Trenfield SJ, Pollard TD, Basit AW, Gaisford S. Connected healthcare: improving patient outcomes using 3D printing. *Ther Deliv.* 2018;9(11):809-823.
- [13] Khaled SA, Burley JC, Alexander MR, Yang J, Roberts CJ. 3D printing of tablets containing multiple drugs with defined release profiles. *Int J Pharm.* 2015;494(2):643-650.
- [14] Genina N, Boetker JP, Colombo S, Harmankaya N, Rantanen J, Bohr A. Anti-tuberculosis drug combination for controlled oral delivery using 3D printed formulations. *Int J Pharm.* 2017;527:40-46.
- [15] Wang J, Goyanes A, Gaisford S, Basit AW. Stereolithographic 3D printing of oral modified-release

- dosage forms. *Int J Pharm.* 2016;503:207-212.
- [16] Sadia M, Arafat B, Ahmed W, Forbes RT, Alhnan MA. Channelled tablets: an innovative approach to accelerating drug release from 3D printed tablets. *J Control Release.* 2018;269:355-363.
- [17] Alhnan MA, Okwuosa TC, Sadia M, Wan K-W, Ahmed W, Arafat B. Emergence of 3D printed dosage forms: opportunities and challenges. *Pharm Res.* 2016;33:1817-1832.
- [18] Melocchi A, Uboldi M, Maroni A, Foppoli A, Palugan L, Zema L, et al. 3D printing by fused deposition modeling of pharmaceutical devices. *Int J Pharm.* 2020;579:119155.
- [19] Beck RC, Chaves PS, Goyanes A, Vukosavljevic B, Buanz A, Windbergs M, et al. 3D printed tablets loaded with nanoparticles. *Eur J Pharm Biopharm.* 2021;158:91-102.
- [20] Pereira BC, Isreb A, Forbes RT, Does F, Habashy R, Petit JB, et al. Additive manufacturing of oral tablets containing polymeric nanoparticles. *Int J Pharm.* 2020;589:119820.
- [21] Chai X, Chai H, Wang X, Yang J, Li J, Zhao Y, et al. Fused deposition modeling of ibuprofen tablets with controlled release. *Eur J Pharm Biopharm.* 2017;117:296-302.
- [22] Okwuosa TC, Pereira BC, Arafat B, Cieszyńska M, Isreb A, Alhnan MA. Fabricating dosage forms using selective laser sintering. *Int J Pharm.* 2017;533:1-9.
- [23] Goole J, Amighi K. 3D printing in pharmaceuticals: a new tool for designing personalized dosage forms. *Int J Pharm.* 2016;499:376-394.
- [24] Skowrya J, Pietrzak K, Alhnan MA. Fabrication of extended-release tablets using desktop 3D printing. *Eur J Pharm Sci.* 2015;68:11-17.
- [25] Kollamaram G, Croker DM, Walker GM, Goyanes A, Basit AW, Gaisford S. Low-temperature fused deposition modeling for thermolabile drugs. *Int J Pharm.* 2018;545:144-152.
- [26] Vuddanda PR, Chakraborty S, Singh S. 3D printing in personalized drug delivery. *Pharmaceutics.* 2018;10:1-25.
- [27] Prasad LK, Smyth HDC. 3D printing technologies for drug delivery: a

- review. *Drug Dev Ind Pharm.* 2016;42:1019-1031.
- [28] Azad MA, Olawuni D, Kimbell G, Badruddoza AZM, Hossain MS, Sultana T. Polymers for extrusion-based pharmaceutical printing. *Adv Drug Deliv Rev.* 2020;163-164:26-46.
- [29] Sandler N, Preis M. Printed drug-delivery systems for improved patient treatment. *Trends Pharmacol Sci.* 2016;37:1070-1080.
- [30] Beer N, Hegger I, Kaae S, de Bruin M, Genina N, Alves TL, et al. Scenarios for 3D printing of personalized medicines. *AAPS PharmSciTech.* 2020;21:1-15.
- [31] Basit AW, Gaisford S. 3D printing of pharmaceuticals and the future of personalized medicine. *Ther Innov Regul Sci.* 2018;52:181-188.
- [32] Ventola CL. Medical applications for 3D printing: current and projected uses. *P T.* 2014;39:704-711.
- [33] Javaid M, Haleem A. Current status and applications of 3D printing in healthcare. *Clin Epidemiol Glob Health.* 2019;7:228-233.
- [34] Muwaffak Z, Goyanes A, Clark V, Basit AW, Hilton ST, Gaisford S. Patient-specific 3D scanned and printed films. *Int J Pharm.* 2017;527:161-170.
- [35] Jamróz W, Kurek M, Łyszczarz E, Szafraniec J, Knapik-Kowalczyk J, Jachowicz R. 3D printed orodispersible films. *Pharm Res.* 2017;34:744-755.
- [36] Economidou SN, Lamprou DA, Douroumis D. 3D printing applications for transdermal systems. *Pharmaceutics.* 2018;10:1-19.
- [37] Trenfield SJ, Awad A, Madla CM, Hatton GB, Firth J, Goyanes A, et al. Shaping the future: 3D printing for personalized medicines. *Br J Clin Pharmacol.* 2019;85:241-252.
- [38] Awad A, Yao A, Trenfield SJ, Gaisford S, Basit AW. 3D printed implants and medical devices. *Drug Discov Today.* 2020;25:1668-1681.
- [39] El Aita I, Rahman J, Breitzkreutz J, Quodbach J. 3D printing of pediatric medicines. *Eur J Pharm Biopharm.* 2020;157:9-18.
- [40] Januskaite P, Xu X, Ranmal S, Gaisford S, Basit AW, Tuleu C, et al. I am more flexible than you think: patient-centric dosage forms by 3D printing. *Int J Pharm.* 2020;579:119154.

- [41] Algahtani MS, Mohammed AA, Ahmad J. 3D printing in personalized medicine and drug delivery. *Pharmaceutics*. 2021;13:1-22.
- [42] Xu X, Trenfield SJ, Goyanes A, Basit AW, Gaisford S. SLS 3D printing for oral dosage forms. *Pharmaceutics*. 2020;12:1-18.
- [43] Ibrahim M, Barnes M, McMillin R. Nanoparticle-loaded scaffolds for wound healing. *J Drug Deliv Sci Technol*. 2021;63:102476.
- [44] Basha M, Abd El-Alim SH, Shamma RN. Smart nanoparticle systems for targeted therapy. *Drug Deliv*. 2020;27:1479-1496.
- [45] Danaei M, Dehghankhold M, Ataei S, Hasanzadeh Davarani F, Javanmard R, Dokhani A, et al. Impact of particle size and polydispersity index in nanoparticles. *Pharmaceutics*. 2018;10:57.
- [46] Honary S, Zahir F. Effect of zeta potential on nanoparticle properties. *Trop J Pharm Res*. 2013;12:255-264.
- [47] ICH Harmonised Guideline. Stability testing of new drug substances and products Q1A(R2). Geneva: ICH; 2003.
- [48] United States Pharmacopeia. Tablet friability <1216>. USP 43-NF 38. Rockville: USP; 2020.
- [49] United States Pharmacopeia. Dissolution <711>. USP 43-NF 38. Rockville: USP; 2020.
- [50] United States Pharmacopeia. Disintegration <701>. USP 43-NF 38. Rockville: USP; 2020.
- [51] Maulvi FA, Shah MJ, Solanki BS, Soni TG. Application of FTIR in preformulation studies. *J Pharm Bioallied Sci*. 2011;3:287-291.
- [52] Chawla G, Bansal AK. FTIR and DSC studies in compatibility testing. *Drug Dev Ind Pharm*. 2008;34:101-108.
- [53] Bhattacharjee S. DLS and zeta potential—what they are and what they are not. *J Control Release*. 2016;235:337-351.
- [54] Malvern Instruments. Dynamic light scattering common applications. Malvern Tech Note. 2019.
- [55] Patel A, Cholkar K, Agrahari V, Mitra AK. Ocular nanoparticle drug delivery systems. *Expert Opin Drug Deliv*. 2013;10:1517-1532.
- [56] Pardeike J, Hommoss A, Müller RH. Lipid nanoparticles for oral delivery. *Int J Pharm*. 2009;366:170-184.

-
- [57] Müller RH, Radtke M, Wissing SA. Solid lipid nanoparticles and nanostructured lipid carriers. *Adv Drug Deliv Rev.* 2002;54:S131-S155.
- [58] Torchilin VP. Liposomes in drug delivery. *Nat Rev Drug Discov.* 2005;4:145-160.
- [59] Shakeel F, Ramadan W. Nanoemulsions as carriers for topical and oral delivery. *Drug Deliv.* 2010;17:1-15.
- [60] Wang AZ, Langer R, Farokhzad OC. Nanoparticle delivery systems for cancer therapy. *Annu Rev Med.* 2012;63:185-198.