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Revolutionizing Drug Delivery: The Impact of 3D Printing on Personalized Medicine and Healthcare Practice

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Abstract: Three-dimensional (3D) printing has caused a paradigm shift in pharmaceuticals and clinical pharmacy practice, moving away from the conventional mass production of pharmaceuticals and toward individualized therapeutic products that are unique to each patient. The idea could benefit patients, pharmacists, and the pharmaceutical industry by enabling the on-demand design and production of flexible formulations with personalized dosages, forms, sizes, drug release, and multi-drug combinations. This is a pivotal moment in the history of 3D printing technology in the pharmaceutical sector, and the collaboration and support of medical professionals—including doctors, nurses, pharmacists, and pharmacy technicians—will be necessary for its broad integration into clinical practice. This paper emphasizes the significance that healthcare professionals are to the future use of 3D printing in the pharmaceutical sector. The most recent cutting-edge 3D printing methods are also outlined, along with the primary benefits and justifications for 3D printing in the pharmaceutical sector.

Keywords: Three-dimensional printing, personalized medicine, Healthcare professionals, pharmaceutical sector etc.

Introduction: The idea of personalized medicine, which entails customizing medical care for each patient, has surfaced in recent years. Traditionally, pharmaceuticals are manufactured in large quantities in a few different strengths, primarily using processes that date back more than 200 years. Crucially, the dosage schedules selected match the quantity required for the "average" patient to have a successful and safe outcome [1]. However, in the UK, up to 70% of patients do not benefit from traditional mass manufacturing procedures, 90% of pharmaceuticals only work in 30–50% of people, and adverse drug reactions account for 7% of hospital admissions [2, 3].

Clinical pharmacy practice is undergoing a paradigm shift as a result of the development of 3D printing and other digital health technologies. This shift is leading to a vision of a novel and digitalized treatment route that can adjust to the changing demands of each individual patient [4]. Levetiracetam was the only 3D printed medication approved for human use by the US Food and Drug Administration (FDA) in 2016 [5]. In February 2021, the FDA authorized a clinical study evaluating a 3D-printed pharmaceutical product designed for the treatment of rheumatoid arthritis [6, 7]. Shortly thereafter, in March 2021, the UK Medicines and Healthcare Products Regulatory Agency (MHRA) proposed an updated regulatory framework to facilitate point-of-care (POC) manufacturing and distribution, including the production of personalized medicines through 3D-printing technologies. According to the proposal, medicines manufactured at POC facilities would continue to undergo safety assessments based on conventional drug development approaches, including preclinical and clinical investigations. However, these regulatory requirements would be adapted to address the unique challenges associated with decentralized manufacturing across multiple sites. The proposed framework aims to support the timely production of patient-specific therapies by eliminating certain regulatory constraints, such as the need for individual POC sites to be specified within the marketing authorization or subjected to separate MHRA inspections. Further details regarding the proposed framework can be found in the MHRA guidance document [8].

Thanks to the recent development and adoption of non-invasive drug and disease-monitoring strategies (e.g., smart wearable devices combined with artificial intelligence [AI]) and electronic prescriptions, 3D printing offers a unique platform that can produce medicines in response to changing situations and patient needs in a rapid, digital, and decentralized manner [9]. Several studies have shown how AI and 3D printing technologies may be combined to offer several benefits, including determining printability and ensuring the quality and safety of the final printed medication [10, 11]. This concept could herald in a new era of digital pharmacies by enabling the transmission of electronic prescriptions to a decentralized 3D printer site for real-time tailored drug delivery (see Figure 1). Numerous stakeholders, including major pharmaceutical companies, biotech start-ups, clinical pharmacists, physicians, academic researchers, and research funding organizations, are investigating this concept worldwide [12]. In order to advance innovations like 3D printing into practice, the Academy of

Pharmaceutical Sciences (APS) formed the APS Emerging innovations Focus Group in March 2021. In order to debate the concept of 3D printing medications, the Academy also organized the 2019 Additive Manufacturing Symposium, which brought together academics, business, biotech firms, and regulators.

This article presents an overview of the principal 3D-printing technologies employed in the pharmaceutical sector, highlighting the key factors driving their adoption and the most advanced applications currently being explored. It also examines the significant contribution of healthcare professionals in fostering innovation and facilitating the implementation of 3D-printing technologies within pharmaceutical practice. Furthermore, the article discusses the major challenges and barriers that continue to affect the successful integration of these technologies into routine pharmaceutical manufacturing and healthcare systems.

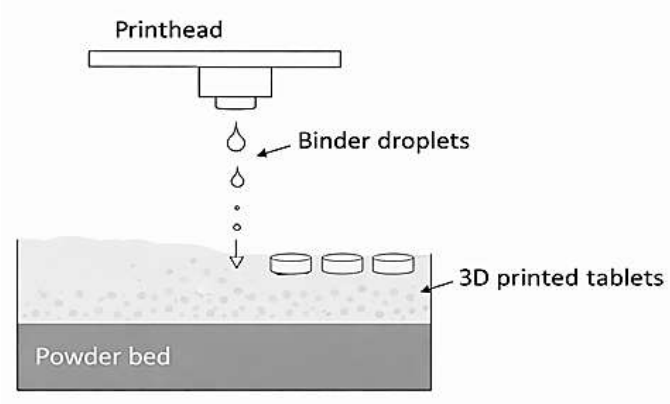

Fig. no. 1: Simple schematic representation of binder jet 3D printing process used for pharmaceutical dosage forms.

Types of Pharmaceutical 3D-Printing Systems

Three-dimensional (3D) printing was first developed and commercialized by Charles Hull in 1986, marking the beginning of a technology that has since evolved into multiple distinct printing approaches [13, 14]. Today, the term "3D printing" encompasses a broad range of additive manufacturing techniques that are increasingly being explored for pharmaceutical applications. Despite differences in operating principles, these technologies generally follow a similar workflow for the fabrication of pharmaceutical dosage forms, often referred to as the "3Ds of 3D Printing" [15].

Design: The process begins with the digital design of the dosage form using computer-aided design (CAD) software. This stage enables pharmacists or formulation scientists to customize characteristics such as the size, shape, and geometry of the printlet according to specific preclinical or clinical requirements. Once finalized, the digital design is transferred to the selected 3D-printing system for fabrication.

Develop: In the development stage, a suitable printing material or "ink," containing the active pharmaceutical ingredient along with selected excipients, is prepared and loaded into the printer. Printing parameters are then optimized based on factors such as the printing technology employed, physicochemical properties of the drug, and desired product attributes. Variables including printing temperature, layer resolution, and printing speed are carefully adjusted to ensure successful production of the dosage form.

Dispense: The final stage involves the automated fabrication of the designed dosage form by the 3D printer. The formulation is constructed sequentially in a layer-by-layer manner according to the digital blueprint. Once manufacturing is complete, the printed medicine is available for dispensing to the patient by the pharmacist.

Currently, six major 3D-printing technologies have been investigated for pharmaceutical manufacturing, as summarized in Table 1. These include fused deposition modelling (FDM), selective laser sintering (SLS), stereolithography (SLA), binder jet (BJ) printing, direct powder extrusion (DPE), and semi-solid extrusion (SSE) [16, 17].

Each of these technologies operates through distinct manufacturing principles and requires specific technical conditions. Their versatility enables the production of individualized dosage forms with diverse drug-release profiles and therapeutic characteristics. Depending on the selected printing method and formulation design, dosage forms can be engineered to provide immediate drug release, rapid disintegration, delayed release, or sustained-release performance. Table 1 presents a detailed overview of these technologies, their operating mechanisms, and the range of pharmaceutical products that can be fabricated using each approach [18, 19].

Motivations for 3D printing medicines

The potential of 3D printing to customize therapies in an automated and decentralized manner can benefit patients, pharmacists, clinicians, and the pharmaceutical industry.

Benefits to patients

One major benefit of 3D printing drugs is the ability to truly tailor a treatment to a patient's therapeutic or specific demands. Patients may be prompted to select a formulation type from a catalog in the future, giving them the option to select characteristics like flavor, texture, color, shape, and size. In addition to increasing patient autonomy and engagement with treatment paths, this would enhance drug adherence [20]. Enabling the production of pharmaceuticals with precise dosages or even mixing flexible quantities of multiple substances to create a 3D printed polyprintlet can improve treatment efficacy and reduce the likelihood of negative effects from improper dosing [21, 22].

Pediatrics

The pediatric population stands to benefit significantly from advances in 3D-printing technology, particularly because conventional mass-manufactured medicines often fail to meet the specific needs of children. Limitations such as unsuitable

dosage strengths, poor taste, and difficulties in swallowing can reduce treatment adherence and therapeutic effectiveness [23, 24]. By enabling the production of medicines with customized doses, shapes, sizes, and flavors, 3D printing offers a promising approach to developing child-friendly pharmaceutical formulations.

Several investigations have explored the use of 3D printing for the fabrication of pediatric dosage forms, including chewable preparations and confectionery-inspired medicines designed to improve acceptability among young patients [25, 26]. For instance, Scoutaris et al. (2018) employed fused deposition modelling (FDM) to manufacture "candy-like" drug formulations containing active ingredients such as indomethacin. These printlets were designed to resemble commercially available Haribo Starmix® sweets, thereby enhancing their appeal to children [27]. Nevertheless, while improved palatability can increase medication adherence, excessive resemblance to confectionery products may raise concerns regarding accidental overconsumption and patient safety.

In another study, Januskaite et al. (2020) investigated the visual preferences of children aged 4–11 years toward printlets produced using four different 3D-printing technologies: digital light processing (DLP), selective laser sintering (SLS), semi-solid extrusion (SSE), and fused deposition modelling (FDM) [70]. The formulations were assessed based on perceived appearance, texture, familiarity, and expected flavor. DLP-generated printlets were identified as the most visually attractive by approximately 62% of participants, followed by those produced using SLS, FDM, and SSE. Interestingly, when informed that SSE printlets were chewable, nearly 79% of children revised their initial preference, highlighting a strong inclination toward chewable dosage forms [28].

A landmark clinical investigation conducted in 2019 demonstrated the practical application of pharmaceutical 3D printing within a hospital pharmacy environment [29,30]. Implemented at the Clinic Hospital of the University of Santiago de Compostela in Spain, the study focused on children aged 3–16 years diagnosed with maple syrup urine disease, a rare inherited metabolic disorder characterized by impaired amino acid metabolism and the accumulation of toxic metabolites in blood and urine.

Using semi-solid extrusion technology, researchers fabricated personalized chewable isoleucine printlets in multiple colors, flavors, and dosage strengths. The study evaluated both patient acceptance and blood isoleucine concentrations following treatment. After six months, the 3D-printed formulations demonstrated improved tolerability and more favorable pharmacokinetic outcomes compared with conventional isoleucine therapy. Although individual flavor preferences differed among participants, all formulations received positive acceptance overall [31].

Further advancements in this area are ongoing. Researchers at Alder Hey Hospital in Liverpool are currently exploring the development of personalized 3D-printed hydrocortisone formulations tailored specifically for pediatric patients, highlighting the growing potential of additive manufacturing in individualized pediatric pharmacotherapy [32].

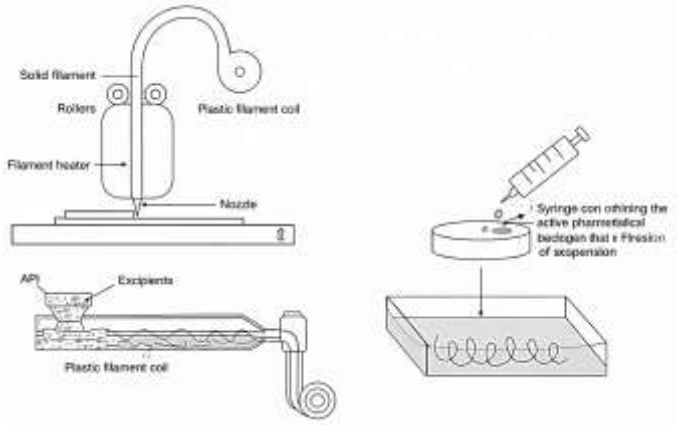

Figure no. 2: Chewable printlets in different flavours, colours and with different doses of isoleucine for the world-first clinical study using 3D printed chewable tablets to treat children with maple syrup urine disease (33, 34).

Older people

Older people or those on complicated dosage schedules where polypharmacy is prevalent and results in a high tablet load may benefit from 3D printing. Polypharmacy has been shown in studies to increase patient confusion and non-adherence, which increases the chance of dose errors [35].

Traditional manufacturing procedures now only produce fixed-dose combinations, despite the potential benefits of mixing multiple drugs, doses, and/or drug-release patterns into a single formulation for enhancing medication adherence and reducing administration errors. Because of its versatility and capacity to precisely disperse drugs in space, 3D printing offers the potential to produce "polyprintlets" [36]. Many studies have demonstrated the production of polyprintlets using a range of technologies [37, 38]. In 2019, for example, Robles-Martinez et al. employed SLA to produce 3D printed polyprintlets with six different drugs (prednisolone, aspirin, caffeine, paracetamol, naproxen, and chloramphenicol) separated into six compartments. This made it possible to reduce the number of pills from six to one [39].

Low-dose antihypertensive polypills including atenolol, ramipril, pravastatin, aspirin, and hydrochlorothiazide were created using FDM 3D printing in a 2015 study [40]. It should be mentioned that although 3D printing makes it possible to print polypills, this will probably only be appropriate for medications with modest therapeutic dosages (microgram to milligram dose strength) in order to guarantee that the formulation's size is appropriate for administration.

A partnership between Gustave Roussy, a top oncology hospital in Paris, and FabRx, a spin-out biotech business from University College London [UCL], was announced in June

2021 with the goal of bringing multi-drug 3D printed formulations into the clinic [41]. As part of this collaboration, patients with early-stage breast cancer will be treated with customized, multi-drug 3D printed dosage forms that combine anticancer therapy and anti-side effect medication into a single pill. The printed drugs will be assessed in a multi-center clinical study to see how well they enhance acceptance, adherence, and ultimately patient outcomes when compared to the traditional treatment regimen.

3D printing technologies may make pharmaceuticals more independent. Oral disintegrating printlets with Braille and moon patterns on the surface of dosage forms have been made using SLS to assist visually impaired patients in identifying their medications (see Figure 3) [42]. The printlets were also made in other forms to offer additional details, such as the dosing schedule.

Benefits of 3D Printing in Clinical Pharmacy Practice

The compact size, portability, and operational simplicity of modern 3D printers make them highly suitable for implementation within both community and hospital pharmacy settings. Among the available technologies, fused deposition modeling (FDM), semi-solid extrusion (SSE), and direct powder extrusion (DPE) are particularly attractive for point-of-care pharmaceutical manufacturing. The growing interest in integrating 3D printing into clinical pharmacy stems from its ability to provide an automated and highly flexible compounding platform capable of producing patient-specific medications on demand.

A major advantage of this technology is its capacity to fabricate dosage forms with customized dimensions, geometries, and drug contents. Pharmacists can tailor formulations according to individual therapeutic requirements by adjusting dose strengths, modifying excipient compositions, or incorporating different active pharmaceutical ingredients as clinical circumstances evolve [43]. Such flexibility supports the principles of personalized medicine and allows treatment regimens to be optimized for individual patients.

Although large-scale industrial manufacturing is expected to remain the dominant method for producing many pharmaceutical products, 3D printing offers significant benefits in situations where personalized therapy is required [44, 45]. Conventional oral medications are frequently available only in limited strengths or dosage forms, forcing pharmacists to rely on extemporaneous compounding or specialized manufacturers to meet unique patient needs [46]. These approaches often require substantial time, labor, and financial resources, creating barriers to timely access to appropriate therapies.

Another challenge associated with conventional practice is tablet splitting to achieve individualized doses. Dividing tablets manually may result in inaccurate dosing, inconsistent dose distribution, and potential alterations in drug-release characteristics, particularly in modified-release or enteric-coated products [47, 48]. Consequently, patient safety and treatment effectiveness may be compromised.

Several studies have demonstrated the potential of 3D printing to address these limitations by producing dose-flexible formulations of drugs with narrow therapeutic indices, including tacrolimus, levothyroxine, and warfarin [15,28,49,50]. In a study conducted by Zheng et al., the accuracy and uniformity of 3D-printed spironolactone tablets were compared with commercially available tablets that had been manually divided by pharmacists. The findings indicated that the 3D-printed formulations provided superior dosing precision and improved safety compared with split tablets [51].

Beyond clinical advantages, 3D printing may also contribute to more sustainable pharmaceutical manufacturing practices. Additive manufacturing techniques typically utilize only the materials required for production, minimizing wastage of active ingredients and excipients. This feature is particularly valuable when working with high-cost medications, where material conservation can significantly reduce overall expenses [15]. Furthermore, medicines can be produced only when needed, decreasing inventory requirements, reducing product losses during storage, and minimizing the environmental impact associated with transportation and cold-chain logistics.

The availability of on-site pharmaceutical 3D printers could improve patient access to personalized therapies, reduce production costs, and shorten treatment delays by enabling rapid formulation preparation within healthcare facilities. Such systems may prove especially useful in resource-limited or time-sensitive environments, including emergency departments, disaster-response settings, ambulances, remote healthcare locations, and even long-duration space missions, where immediate access to tailored medications is essential.

Despite these promising developments, several challenges must be addressed before widespread clinical implementation can occur. Future efforts should focus on establishing robust quality assurance systems for point-of-care manufacturing, developing comprehensive regulatory frameworks for 3D-printed medicines, and encouraging greater participation of healthcare professionals, particularly pharmacists and clinicians, in the adoption and management of this emerging technology.

Benefits to the pharmaceutical industry

The pharmaceutical business can profit greatly from 3D printing technologies, particularly in the early stages of drug development [52]. From drug development to a commercially available formulation, the process takes ten to fifteen years and costs an average of £1.3 billion [53]. As demonstrated by the recent COVID-19 pandemic, which necessitated quick therapeutic development and repurposing studies, there is a pressing need to shorten time and cost to market in order to accelerate drug development timelines.

During pre-clinical and clinical formulation development, 3D printing could be used as a quick prototyping method to assess one-off or small batches of various therapeutic product iterations [54]. This rapid prototyping may speed up the assessment of how different formulation compositions affect critical quality metrics (such drug efficacy in in vitro and in

vivo models). Thus far, 3D printed formulations have been tested on a variety of pre-clinical animal models [55, 56, 57]. Therefore, 3D printing may provide an earlier understanding of formulation and process factors compared to time-consuming traditional manufacturing methods, which could result in a quicker entry into first-in-human (FIH) clinical trials and a reduction in development time and expenditure. Additionally, during pre-clinical and early phase clinical trials to evaluate safety and efficacy, small quantities of dose-flexible medical items could be manufactured on demand utilizing 3D printing [58]. In order to produce large numbers of personalized or customized drugs, the pharmaceutical industry may use 3D printing as an alternative production method. From an economic perspective, it is likely that conventional manufacturing methods (such tableting or encapsulation) for drugs with large quantities and little added value will remain economical in centralized facilities [10]. Nonetheless, 3D printed formulas that need to be customized to enhance therapeutic results have merit. Formulations might be mass-customized to patient needs via 3D printing at local centers, as is already the case in the healthcare industry. Approximately 1,000 customized hearing aids are produced daily by several large manufacturers using 3D printing, each of which is shaped and scaled to fit the patient's ear canal [59].

Pharmaceutical companies may employ 3D printing to produce drugs on demand in decentralized settings like pharmacies, clinics, or even a patient's home. Additionally, this could assist pharmaceutical companies in lowering their overall logistics and transportation costs, which would lessen the carbon footprint of the transportation industry and do away with the need for energy-intensive storage conditions, such as cold-chain storage for medications that are sensitive to temperature changes [60]. Even though 3D printing's potential is still being explored, a shift in business strategy and methodology will be required for its integration into the pharmaceutical industry before it is widely used.

The future of pharmacy: a roadmap to 3D printing integration

There are many published research papers demonstrating the potential and role of 3D printing technologies for medicines manufacture and patient care[61]. Figure 4 shows a timeline of 3D printing in pharmaceuticals and highlights the major milestones of this technology in the sector.

In order to promote 3D printing technology for practical benefits for patients and pharmacists, we are at a turning point that requires support from a variety of important stakeholders, including researchers, regulators, physicians, pharmacists, and patients. Before widespread integration in the pharmaceutical industry is feasible, a number of obstacles must be overcome, such as regulatory requirements, expanding the body of evidence proving safety and efficacy, and the continued development of pharmaceutically appropriate 3D printers and dosage forms that are widely accepted by patients, clinicians, and pharmacists [62].

Significant progress has been made in overcoming these obstacles. Previously, 3D printers that were sold commercially were not standardized or suitable for manufacturing pharmaceuticals (i.e., they were not verified to adhere to good manufacturing practices [GMP]). Pharmaceutical 3D printers have been developed in recent years by biotech businesses and regulatory bodies to produce safe and efficient printlets for pharmaceutical usage. A pharmaceutical 3D printer created by FabRx is one example [63]. This multi-nozzle GMP printer was created in close consultation with hospital end users and regulatory bodies, such as the MHRA, to design a system that is appropriate for the manufacturing of pharmaceuticals.

Aprecia Pharmaceutical's ZipDose technology, a scaled-up binder jet printing method that allows for the mass production of extremely porous and quickly dissolving oral medicinal formulations including levetiracetam for the treatment of epilepsy, is another pharmaceutical printer [38].

Additionally, Triastek has introduced a scaled-up melt extrusion method that makes it possible to produce distinctive pharmaceutical products for clinical trials [64]. GMP-compliant pharmaceutical printers are being developed by other businesses such as DiHeSys, Vitae Industries, and Craft Health; however, no studies utilizing these printing technologies have been published as of yet [65, 66, 67].

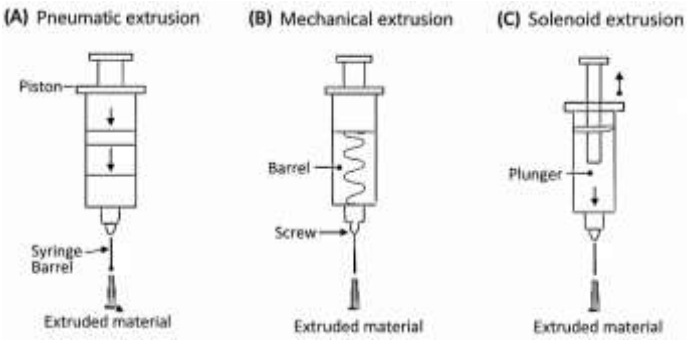

Figure no. 3: Graphical timeline of the advances in 3D printed medicines between 1995 and the present day

Despite the abundance of data that supports 3D printing in the pharmaceutical sector, more needs to be done to guarantee that everyone is at ease utilizing the technology. Many technological and regulatory challenges remain, such as how to ensure the quality and safety of the pharmaceuticals that are produced. The traditional manufacturing of pharmaceuticals requires adherence to GMP and strict testing criteria, such as evaluating the risk of cross-contamination, weight uniformity, and strict cleaning requirements [15]. However, because of their inherent cost, duration, and hazardous nature, current testing techniques are inappropriate for assessing 3D printed drugs.

New and real-time approaches to guaranteeing the quality and safety of pharmaceutical formulations created with 3D printers are being investigated in an attempt to overcome this problem. For example, researchers have investigated the application of real-time analytical technologies such as near-infrared spectroscopy and Raman spectroscopy [68, 69]. Others have suggested using "track and trace" techniques, which include data matrices and QR codes on formulations that can be

scanned with a smartphone or barcode readers, to ensure the safety and quality of pharmaceutical items [70, 71, 72]. Others have highlighted the potential of a block chain to enhance security and track printed formulas [73]. Additionally, as previously stated, several companies are developing GMP-compliant 3D printers that can be properly cleaned and validated to ensure the quality and safety of printed pharmaceutical products. These innovative methods will provide a means of facilitating the integration of 3D printed technology in healthcare settings and assure the quality of 3D printed tablets in real time.

There are still certain technological challenges to be solved before the method is extensively used; for instance, there are now not enough materials and excipients suitable for the production of 3D printed drugs [74]. Furthermore, the use of 3D printing in decentralized areas is likely to give rise to ethical and legal concerns, such as those concerning the security and protection of patient data, the potential for counterfeit goods, patient safety and liability issues, and the necessity of pharmacovigilance procedures and guidelines to ensure that side effects are appropriately identified and addressed.

To far, few studies have been carried out in "real-world" clinical settings involving patients to evaluate the acceptability of 3D-printed formulations and pharmacists as the end users of the technology. It is crucial to move toward a multidisciplinary approach to 3D printing research, and all important stakeholders—including patients, physicians, pharmacists, and big pharma—must talk about how this technology will advance in the industry moving forward. Increased funding from research donors and support from regulatory bodies are also essential.

The Role of Pharmacy in 3D-Printed Medicines

The successful implementation of pharmaceutical 3D printing depends heavily on the active involvement of pharmacists and pharmacy technicians working across academia, industry, healthcare institutions, governmental organizations, and regulatory agencies. Owing to their expertise in drug formulation, manufacturing, and patient care, pharmacy professionals are uniquely positioned to guide the development, adoption, and regulation of 3D-printing technologies within pharmaceutical practice. Their contributions are essential in determining the most appropriate applications, settings, and implementation strategies for these emerging manufacturing systems.

Pharmacists have played a pioneering role in advancing pharmaceutical 3D printing and were among the first healthcare professionals to recognize its potential for personalized medicine production. Significant milestones in this field were achieved through research conducted by academic pharmacists at UCL School of Pharmacy, who demonstrated the feasibility of using fused deposition modelling (FDM), stereolithography (SLA), and selective laser sintering (SLS) for pharmaceutical manufacturing in 2014, 2016, and 2017, respectively. Since then, numerous pharmacy schools and research institutions worldwide have expanded investigations into the application of additive manufacturing technologies for drug delivery and personalized therapeutics [75, 76, 77].

The integration of 3D printing into routine clinical practice may enable pharmacists to re-establish their traditional role as formulation specialists. Rather than relying exclusively on commercially manufactured dosage forms, pharmacists could prepare individualized medicines tailored to the specific therapeutic needs of each patient. Through the use of automated 3D-printing systems, customized formulations could be produced rapidly at the point of care, improving both treatment flexibility and patient outcomes.

One proposed model for future implementation envisions a user-friendly printing system comparable to a capsule-based beverage machine. In this approach, drug-containing cartridges would be manufactured and quality-assured at centralized production facilities before being supplied to community or hospital pharmacies. Authorized pharmacy personnel could then use these cartridges to produce patient-specific medicines on demand. To ensure safety and accountability, biotechnology companies are developing systems that incorporate comprehensive tracking mechanisms and restrict operation to trained and certified users [78].

This innovative manufacturing paradigm offers a potential solution to several longstanding challenges associated with conventional pharmaceutical production, particularly those related to individualized therapy and dosage flexibility. However, its successful adoption will require a substantial shift in current pharmaceutical manufacturing practices and professional perspectives. Clinical pharmacists are expected to play a leading role in this transformation by collaborating closely with researchers, physicians, pharmaceutical manufacturers, regulatory authorities, and clinical trial organizations to facilitate the translation of 3D-printing technologies into healthcare settings.

Education and workforce development will also be critical for the future success of pharmaceutical 3D printing. Pharmacy students, preregistration pharmacists, and practicing professionals should receive appropriate training in the principles, applications, and safe operation of 3D-printing technologies [79]. Such training should include guidance on selecting suitable clinical scenarios for 3D printing, overseeing manufacturing procedures, maintaining product quality standards, and educating patients about personalized printed medicines. By developing these competencies, future pharmacists will be better equipped to support the safe and effective integration of 3D printing into modern pharmaceutical care [80].

Conclusion

3D printing has the potential to revolutionize clinical pharmacy practice. It has the potential to replace conventional mass-production techniques for pharmaceuticals with the on-demand production of tiny amounts of incredibly flexible and adjustable dose forms. The unique advantages of this technology, such as safer and more efficient treatments, benefit patients, pharmacists, and the pharmaceutical industry.

Healthcare professionals, including doctors, nurses, and pharmacists, will be vital in helping to integrate this technology as well as in advising academics, the pharmaceutical industry, and biotech companies on how to use 3D printing to transform the industry.

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Not applicable

Conflicts of interest
No conflict of interest.

References:

1. Bethany C.G., Jayda L.E., Sarah Y.L., Chengpeng C., Dana M.S. Evaluation of 3D Printing and Its Potential Impact on Biotechnology and the Chemical Sciences. Anal. Chem. 2014;86:3240–3253. doi: 10.1021/ac403397r.
2. Belhabib S., Guessasma S. Compression Performance of Hollow Structures: From Topology Optimisation to Design 3D Printing. Int. J. Mech. Sci. 2017;133:728–739. doi: 10.1016/j.ijmecsci.2017.09.033.
3. Ishita M., Gurvinder K., Amir S., Aneesah M., Cato T.L. Progress in 3D Bioprinting Technology for Tissue/Organ Regenerative Engineering. Biomaterials. 2020;226:119536. doi: 10.1016/j.biomaterials.2019.119536.
4. Jiménez M., Romero L., Domínguez I.A., del Mar Espinosa M., Domínguez M. Additive Manufacturing Technologies: An Overview about 3D Printing Methods and Future Prospects. Complexity. 2019;2019:1–30. doi: 10.1155/2019/9656938.
5. Trenfield S.J., Madla C.M., Basit A.W., Gaisford S. The Shape of Things to Come: Emerging Applications of 3D Printing in Healthcare. In: Basit A.W., Gaisford S., editors. 3D Printing of Pharmaceuticals. Volume 31. Springer International Publishing; Cham, Switzerland: 2018. pp. 1–19. (AAPS Advances in the Pharmaceutical Sciences Series).
6. Vaz V.M., Kumar L. 3D Printing as a Promising Tool in Personalized Medicine. AAPS PharmSciTech. 2021;22:49. doi: 10.1208/s12249-020-01905-8.
7. Jacob S., Nair A.B., Patel V., Shah J. 3D Printing Technologies: Recent Development and Emerging Applications in Various Drug Delivery Systems. AAPS PharmSciTech. 2020;21:220. doi: 10.1208/s12249-020-01771-4.
8. Trenfield S.J., Awad A., Madla C., Hatton G., Firth J., Goyanes A., Gaisford S., Basit A.W. Shaping the Future: Recent Advances of 3D Printing in Drug Delivery and Healthcare. Expert Opin. Drug Deliv. 2019;16:1081–1094. doi: 10.1080/17425247.2019.1660318.
9. Jamróz W., Szafraniec J., Kurek M., Jachowicz R. 3D Printing in Pharmaceutical and Medical Applications—Recent Achievements and Challenges. Pharm. Res. 2018;35:176. doi: 10.1007/s11095-018-2454-x.
10. Cader H.K., Rance G.A., Alexander M.R., Gonçalves A.D., Roberts C.J., Tuck C.J., Wildman R.D. Water-Based 3D Inkjet Printing of an Oral Pharmaceutical Dosage Form. Int. J. Pharm. 2019;564:359–368. doi: 10.1016/j.ijpharm.2019.04.026.
11. Mancilla-De-la-Cruz J., Rodriguez-Salvador M., An J., Chua C.K. Three-Dimensional Printing Technologies for Drug Delivery Applications: Processes, Materials, and Effects. Int. J. Bioprinting. 2022;8:622. doi: 10.18063/ijb.v8i4.622.
12. Giangreco N.P., Elias J.E., Tatonetti N.P. No Population Left behind: Improving Paediatric Drug Safety Using Informatics and Systems Biology. Br. J. Clin. Pharmacol. 2022;88:1464–1470. doi: 10.1111/bcp.14705.
13. Shibata Y., Itoh H., Matsuo H., Nakajima K. Differences in Pharmaceutical Intervention Triggers for the Optimization of Medication by Patient Age: A University Hospital Study. Biol. Pharm. Bull. 2021;44:1060–1066. doi: 10.1248/bpb.b21-00143.
14. Pelkonen O. Metabolism and Pharmacokinetics in Children and the Elderly. Expert Opin. Drug Metab. Toxicol. 2007;3:147–148. doi: 10.1517/17425255.3.2.147.
15. Pratico A.D., Longo L., Mansueto S., Gozzo L., Barberi I., Tiralongo V., Salvo V., Falsaperla R., Vitaliti G., La Rosa M., et al. Off-Label Use of Drugs and Adverse Drug Reactions in Pediatric Units: A Prospective, Multicenter Study. Curr. Drug Saf. 2018;13:200–207. doi: 10.2174/1574886313666180619120406.
16. Singhvi G., Patil S., Girdhar V., Chellappan K., Gupta G., Dua K. 3D-Printing: An Emerging and a Revolutionary Technology in Pharmaceuticals. Panminerva Med. 2018;60:622. doi: 10.23736/S0031-0808.18.03467-5.
17. Scoutaris N., Ross S.A., Douroumis D. 3D Printed "Starmix" Drug Loaded Dosage Forms for Paediatric Applications. Pharm. Res. 2018;35:34. doi: 10.1007/s11095-017-2284-2.
18. Tabriz A.G., Fullbrook D.H.G., Vilain L., Derrar Y., Nandi U., Grau C., Morales A., Hooper G., Hiezl Z., Douroumis D. Personalised Tasted Masked Chewable 3D Printed Fruit-Chews for Paediatric Patients. Pharmaceutics. 2021;13:1301. doi: 10.3390/pharmaceutics13081301.
19. Tabriz A.G., Nandi U., Scoutaris N., Sanfo K., Alexander B., Gong Y., Hui H.-W., Kumar S., Douroumis D. Personalised Paediatric Chewable Ibuprofen Tablets Fabricated Using 3D Micro-Extrusion Printing Technology. Int. J. Pharm. 2022;626:122135. doi: 10.1016/j.ijpharm.2022.122135.
20. Preis M., Öblom H. 3D-Printed Drugs for Children-Are We Ready Yet? AAPS PharmSciTech. 2017;18:303–308. doi: 10.1208/s12249-016-0704-y.
21. Lafeber I., Ruijgrok E.J., Guchelaar H.-J., Schimmel K.J.M. 3D Printing of Pediatric Medication: The End of Bad Tasting Oral Liquids?-A Scoping Review.

Pharmaceutics. 2022;14:416. doi: 10.3390/pharmaceutics14020416.
22. van Kampen E.E.M., Willemsteijn L., Ruijgrok E.J. 3D Printing of Drugs: Expanding the Options for Child-Tailored Pharmacotherapy. Arch. Dis. Child. 2021 doi: 10.1136/archdischild-2021-321629.
23. Goyanes A., Madla C.M., Umerji A., Duran Piñeiro G., Giraldez Montero J.M., Lamas Diaz M.J., Gonzalez Barcia M., Taherali F., Sánchez-Pintos P., Couce M.-L., et al. Automated Therapy Preparation of Isoleucine Formulations Using 3D Printing for the Treatment of MSUD: First Single-Centre, Prospective, Crossover Study in Patients. Int. J. Pharm. 2019;15:118497. doi: 10.1016/j.ijpharm.2019.118497.
24. Roulon S., Soulairol I., Lavastre V., Payre N., Cazes M., Delbreilh L., Alié J. Production of Reproducible Filament Batches for the Fabrication of 3D Printed Oral Forms. Pharmaceutics. 2021;13:472. doi: 10.3390/pharmaceutics13040472.
25. Li J., Wu M., Chen W., Liu H., Tan D., Shen S., Lei Y., Xue L. 3D Printing of Bioinspired Compartmentalized Capsular Structure for Controlled Drug Release. J. Zhejiang Univ. Sci. B. 2021;22:1022–1033. doi: 10.1631/jzus.B2100644.
26. Zheng Y., Deng F., Wang B., Wu Y., Luo Q., Zuo X., Liu X., Cao L., Li M., Lu H., et al. Melt Extrusion Deposition (MEDTM) 3D Printing Technology—A Paradigm Shift in Design and Development of Modified Release Drug Products. Int. J. Pharm. 2021;602:120639. doi: 10.1016/j.ijpharm.2021.120639.
27. Seoane-Viaño I., Januskaite P., Alvarez-Lorenzo C., Basit A.W., Goyanes A. Semi-Solid Extrusion 3D Printing in Drug Delivery and Biomedicine: Personalised Solutions for Healthcare Challenges. J. Control. Release Off. J. Control. Release Soc. 2021;332:367–389. doi: 10.1016/j.jconrel.2021.02.027.
28. Smith D.M., Kapoor Y., Klinzing G.R., Procopio A.T. Pharmaceutical 3D Printing: Design and Qualification of a Single Step Print and Fill Capsule. Int. J. Pharm. 2018;544:21–30. doi: 10.1016/j.ijpharm.2018.03.05.
29. Trenfield S.J., Madla C.M., Basit A.W., Gaisford S. Binder Jet Printing in Pharmaceutical Manufacturing. In: Basit A.W., Gaisford S., editors. 3D Printing of Pharmaceuticals. Volume 31. Springer International Publishing; Cham, Switzerland: 2018. pp. 41–54. (AAPS Advances in the Pharmaceutical Sciences Series).
30. Chen G., Xu Y., Chi Lip Kwok P., Kang L. Pharmaceutical Applications of 3D Printing. Addit. Manuf. 2020;34:101209. doi: 10.1016/j.addma.2020.101209.
31. Ameeduzzafar, Alruwaili N.K., Rizwanullah M., Abbas Bukhari S.N., Amir M., Ahmed M.M., Fazil M. 3D Printing Technology in Design of Pharmaceutical Products. Curr. Pharm. Des. 2018;24:5009–5018. doi: 10.2174/1381612825666190116104620.
32. Kozakiewicz-Latała M., Nartowski K.P., Dominik A., Malec K., Gołkowska A.M., Złocińska A., Rusińska M., Szymczyk-Ziółkowska P., Ziółkowski G., Górniak A., et al. Binder Jetting 3D Printing of Challenging Medicines: From Low Dose Tablets to Hydrophobic Molecules. Eur. J. Pharm. Biopharm. 2022;170:144–159. doi: 10.1016/j.ejpb.2021.11.001.
33. Prasad L.K., Smyth H. 3D Printing Technologies for Drug Delivery: A Review. Drug Dev. Ind. Pharm. 2016;42:1019–1031. doi: 10.3109/03639045.2015.1120743.
34. Bergeron V., Bonn D., Martin J.Y., Vovelle L. Controlling Droplet Deposition with Polymer Additives. Nature. 2000;405:772–775. doi: 10.1038/35015525.
35. Fromm J.E. Numerical Calculation of the Fluid Dynamics of Drop-on-Demand Jets. IBM J. Res. Dev. 1984;28:322–333. doi: 10.1147/rd.283.0322.
36. Jang D., Kim D., Moon J. Influence of Fluid Physical Properties on Ink-Jet Printability. Langmuir. 2009;25:2629–2635. doi: 10.1021/la900059m.
37. Range K., Feuillebois F. Influence of Surface Roughness on Liquid Drop Impact. J. Colloid Interface Sci. 1998;203:16–30. doi: 10.1006/jcis.1998.5518.
38. Levin B.Z., Hobbs P.V. Splashing of Water Drops on Solid and Wetted Surfaces: Hydrodynamics and Charge Separation. Philos. Trans. R. Soc. Lond. 1971;269:555–585. doi: 10.1098/rsta.1971.0052.
39. Yarin A.L. Drop Impact Dynamics: Splashing, Spreading, Receding, Bouncing…. Annu. Rev. Fluid Mech. 2006;38:159–192. doi: 10.1146/annurev.fluid.38.050304.092144.
40. Stow C.D., Hadield M.G. An Experimental Investigation of Fluid Flow Resulting from the Impact of a Water Drop with an Unyielding Dry Surface. Proc. R. Soc. Lond. A Math. Phys. Sci. 1981;373:419–441. doi: 10.1098/rspa.1981.0002.
41. Stow C.D., Stainer R.D. The Physical Products of a Splashing Water Drop. J. Meteorol. Soc. Jpn. 1977;55:518–532. doi: 10.2151/jmsj1965.55.5_518.
42. Scoutaris N., Alexander M.R., Gellert P.R., Roberts C.J. Inkjet Printing as a Novel Medicine Formulation Technique. J. Control. Release. 2011;156:179–185. doi: 10.1016/j.jconrel.2011.07.033.
43. Hirshfield L., Giridhar A., Taylor L.S., Harris M.T., Reklaitis G.V. Dropwise Additive Manufacturing of Pharmaceutical Products for Solvent-Based Dosage Forms. J. Pharm. Sci. 2014;103:496–506. doi: 10.1002/jps.23803.
44. Meléndez P.A., Kane K.M., Ashvar C.S., Albrecht M., Smith P.A. Thermal Inkjet Application in the Preparation of Oral Dosage Forms: Dispensing of Prednisolone Solutions and Polymorphic Characterization by Solid-State Spectroscopic Techniques. J. Pharm. Sci. 2008;97:2619–2636. doi: 10.1002/jps.21189.
45. Wang Y., Müllertz A., Rantanen J. Structured Approach for Designing Drug-Loaded Solid Products by Binder Jetting 3D Printing. Eur. J. Pharm. Sci. 2022;178:106280. doi: 10.1016/j.ejps.2022.106280.

46. Wu B.M., Borland S.W., Giordano R.A., Cima L.G., Sachs E.M., Cima M.J. Solid Free-Form Fabrication of Drug Delivery Devices. J. Control. Release. 1996;40:77–87. doi: 10.1016/0168-3659(95)00173-5.
47. Wang Y., Müllertz A., Rantanen J. Additive Manufacturing of Solid Products for Oral Drug Delivery Using Binder Jetting Three-Dimensional Printing. AAPS PharmSciTech. 2022;23:196. doi: 10.1208/s12249-022-02321-w.
48. Wang Z., Han X., Chen R., Li J., Gao J., Zhang H., Liu N., Gao X., Zheng A. Innovative Color Jet 3D Printing of Levetiracetam Personalized Paediatric Preparations. Asian J. Pharm. Sci. 2021;16:374–386. doi: 10.1016/j.ajps.2021.02.003.
49. Sen K., Mehta T., Sansare S., Sharifi L., Ma A.W.K., Chaudhuri B. Pharmaceutical Applications of Powder-Based Binder Jet 3D Printing Process—A Review. Adv. Drug Deliv. Rev. 2021;177:113943. doi: 10.1016/j.addr.2021.113943.
50. Brunello G., Sivolella S., Meneghello R., Ferroni L., Gardin C., Piattelli A., Zavan B., Bressan E. Powder-Based 3D Printing for Bone Tissue Engineering. Biotechnol. Adv. 2016;34:740–753. doi: 10.1016/j.biotechadv.2016.03.009.
51. Lin K.-F., He S., Song Y., Wang C.-M., Gao Y., Li J.-Q., Tang P., Wang Z., Bi L., Pei G.-X. Low-Temperature Additive Manufacturing of Biomimic Three-Dimensional Hydroxyapatite/Collagen Scaffolds for Bone Regeneration. ACS Appl. Mater. Interfaces. 2016;8:6905–6916. doi: 10.1021/acsami.6b00815.
52. Wang Z., Li J., Hong X., Han X., Liu B., Li X., Zhang H., Gao J., Liu N., Gao X., et al. Taste Masking Study Based on an Electronic Tongue: The Formulation Design of 3D Printed Levetiracetam Instant-Dissolving Tablets. Pharm. Res. 2021;38:831–842. doi: 10.1007/s11095-021-03041-9.
53. Chang S.-Y., Jin J., Yan J., Dong X., Chaudhuri B., Nagapudi K., Ma A.W.K. Development of a Pilot-Scale HuskyJet Binder Jet 3D Printer for Additive Manufacturing of Pharmaceutical Tablets. Int. J. Pharm. 2021;605:120791. doi: 10.1016/j.ijpharm.2021.120791.
54. Kreft K., Lavrič Z., Stanić T., Perhavec P., Dreu R. Influence of the Binder Jetting Process Parameters and Binder Liquid Composition on the Relevant Attributes of 3D-Printed Tablets. Pharmaceutics. 2022;14:1568. doi: 10.3390/pharmaceutics14081568.
55. Wang C.-C., Tejwani Motwani M.R., Roach W.J., Kay J.L., Yoo J., Surprenant H.L., Monkhouse D.C., Pryor T.J. Development of near Zero-Order Release Dosage Forms Using Three-Dimensional Printing (3-DP) Technology. Drug Dev. Ind. Pharm. 2006;32:367–376. doi: 10.1080/03639040500519300.
56. Yu D.G., Yang X.L., Huang W.D., Liu J., Wang Y.G., Xu H. Tablets With Material Gradients Fabricated by Three-Dimensional Printing. J. Pharm. Sci. 2007;96:2446–2456. doi: 10.1002/jps.20864.
57. Yu D., Liu J., Yang Y., Yang X. Studies on Preparation of Controlled-Release Delivery Systems with Drug Gradients Using Three Dimensional Printing Technique. Zhongguo Yaoxue Zazhi (1989) 2006;41:1080–1083.
58. Hong X., Han X., Li X., Li J., Wang Z., Zheng A. Binder Jet 3D Printing of Compound LEV-PN Dispersible Tablets: An Innovative Approach for Fabricating Drug Systems with Multicompartmental Structures. Pharmaceutics. 2021;13:1780. doi: 10.3390/pharmaceutics13111780.
59. Acosta-Vélez G., Linsley C., Zhu T., Wu W., Wu B. Photocurable Bioinks for the 3D Pharming of Combination Therapies. Polymers. 2018;10:1372. doi: 10.3390/polym10121372.
60. Bose S., Banerjee D., Robertson S., Vahabzadeh S. Enhanced In Vivo Bone and Blood Vessel Formation by Iron Oxide and Silica Doped 3D Printed Tricalcium Phosphate Scaffolds. Ann. Biomed. Eng. 2018;46:1241–1253. doi: 10.1007/s10439-018-2040-8.
61. Nandi S.K., Fielding G., Banerjee D., Bandyopadhyay A., Bose S. 3D Printed β-TCP Bone Tissue Engineering Scaffolds: Effects of Chemistry on in Vivo Biological Properties in a Rabbit Tibia Model. J. Mater. Res. 2018;33:1939–1947. doi: 10.1557/jmr.2018.233.
62. Ke D., Bose S. Effects of Pore Distribution and Chemistry on Physical, Mechanical, and Biological Properties of Tricalcium Phosphate Scaffolds by Binder-Jet 3D Printing. Addit. Manuf. 2018;22:111–117. doi: 10.1016/j.addma.2018.04.020.
63. Chai W., Wei Q., Yang M., Ji K., Guo Y., Wei S., Wang Y. The Printability of Three Water Based Polymeric Binders and Their Effects on the Properties of 3D Printed Hydroxyapatite Bone Scaffold. Ceram. Int. 2020;46:6663–6671. doi: 10.1016/j.ceramint.2019.11.154.
64. Ahn J.-H., Kim J., Han G., Kim D., Cheon K.-H., Lee H., Kim H.-E., Kim Y.-J., Jang T.-S., Jung H.-D. 3D-Printed Biodegradable Composite Scaffolds with Significantly Enhanced Mechanical Properties via the Combination of Binder Jetting and Capillary Rise Infiltration Process. Addit. Manuf. 2021;41:101988. doi: 10.1016/j.addma.2021.101988.
65. Cailleaux S., Sanchez-Ballester N.M., Gueche Y.A., Bataille B., Soulairol I. Fused Deposition Modeling (FDM), the New Asset for the Production of Tailored Medicines. J. Control. Release. 2021;330:821–841. doi: 10.1016/j.jconrel.2020.10.056.
66. Awad A., Gaisford S., Basit A.W. Fused Deposition Modelling: Advances in Engineering and Medicine. In: Basit A.W., Gaisford S., editors. 3D Printing of Pharmaceuticals. Volume 31. Springer International Publishing; Cham, Switzerland: 2018. pp. 107–132. (AAPS Advances in the Pharmaceutical Sciences Series).
67. Goole J., Amighi K. 3D Printing in Pharmaceutics: A New Tool for Designing Customized Drug Delivery Systems. Int. J. Pharm. 2016;499:376–394. doi: 10.1016/j.ijpharm.2015.12.071.

68. Quodbach J., Bogdahn M., Breitkreutz J., Chamberlain R., Eggenreich K., Elia A.G., Gottschalk N., Gunkel-Grabole G., Hoffmann L., Kapote D., et al. Quality of FDM 3D Printed Medicines for Pediatrics: Considerations for Formulation Development, Filament Extrusion, Printing Process and Printer Design. Ther. Innov. Regul. Sci. 2022;56:910–928. doi: 10.1007/s43441-021-00354-0.
69. Melocchi A., Uboldi M., Cerea M., Foppoli A., Maroni A., Moutaharrik S., Palugan L., Zema L., Gazzaniga A. A Graphical Review on the Escalation of Fused Deposition Modeling (FDM) 3D Printing in the Pharmaceutical Field. J. Pharm. Sci. 2020;109:2943–2957. doi: 10.1016/j.xphs.2020.07.011.
70. Korte C., Quodbach J. Formulation Development and Process Analysis of Drug-Loaded Filaments Manufactured via Hot-Melt Extrusion for 3D-Printing of Medicines. Pharm. Dev. Technol. 2018;23:1117–1127. doi: 10.1080/10837450.2018.1433208.
71. Nober C., Manini G., Carlier E., Raquez J.-M., Benali S., Dubois P., Amighi K., Goole J. Feasibility Study into the Potential Use of Fused-Deposition Modeling to Manufacture 3D-Printed Enteric Capsules in Compounding Pharmacies. Int. J. Pharm. 2019;569:118581. doi: 10.1016/j.ijpharm.2019.118581.
72. Parulski C., Jennotte O., Lechanteur A., Evrard B. Challenges of Fused Deposition Modeling 3D Printing in Pharmaceutical Applications: Where Are We Now? Adv. Drug Deliv. Rev. 2021;175:113810. doi: 10.1016/j.addr.2021.
73. Wang P., Zou B., Xiao H., Ding S., Huang C. Effects of Printing Parameters of Fused Deposition Modeling on Mechanical Properties, Surface Quality, and Microstructure of PEEK. J. Mater. Process. Technol. 2019;271:62–74. doi: 10.1016/j.jmatprotec.2019.03.016.
74. Mania S., Ryl J., Jinn J.-R., Wang Y.-J., Michałowska A., Tylingo R. The Production Possibility of the Antimicrobial Filaments by Co-Extrusion of the PLA Pellet with Chitosan Powder for FDM 3D Printing Technology. Polymers. 2019;11:1893. doi: 10.3390/polym11111893.
75. Basa B., Jakab G., Kállai-Szabó N., Borbás B., Fülöp V., Balogh E., Antal I. Evaluation of Biodegradable PVA-Based 3D Printed Carriers during Dissolution. Materials. 2021;14:1350. doi: 10.3390/ma14061350.
76. Alhijjaj M., Belton P., Qi S. An Investigation into the Use of Polymer Blends to Improve the Printability of and Regulate Drug Release from Pharmaceutical Solid Dispersions Prepared via Fused Deposition Modeling (FDM) 3D Printing. Eur. J. Pharm. Biopharm. Off. J. Arb. Fur Pharm. Verfahr. E.V. 2016;108:111–125. doi: 10.1016/j.ejpb.2016.08.016.
77. Qi S., Belton P., Nollenberger K., Clayden N., Reading M., Craig D.Q.M. Characterisation and Prediction of Phase Separation in Hot-Melt Extruded Solid Dispersions: A Thermal, Microscopic and NMR Relaxometry Study. Pharm. Res. 2010;27:1869–1883. doi: 10.1007/s11095-010-0185-8.
78. Aho J., Bøtker J.P., Genina N., Edinger M., Arnfast L., Rantanen J. Roadmap to 3D-Printed Oral Pharmaceutical Dosage Forms: Feedstock Filament Properties and Characterization for Fused Deposition Modeling. J. Pharm. Sci. 2019;108:26–35. doi: 10.1016/j.xphs.2018.11.012.
79. Mackay M.E., Swain Z.R., Banbury C.R., Phan D.D., Edwards D.A. The Performance of the Hot End in a Plasticating 3D Printer. J. Rheol. 2017;61:229–236. doi: 10.1122/1.4973852.
80. Technique: Material Considerations-Printability-Process Modulation, with Consecutive Effects on in Vitro Release, Stability and Degradation. Eur. J. Pharm. Sci. Off. J. Eur. Fed. Pharm. Sci. 2019;129:110–123. doi: 10.1016/j.ejps.2018.12.019.