Personalized 3D Printing: A Focus on 3D Printing, Customization of Personalized Medicines and 3D printing in Natural Products

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Abstract

The emergence of personalized medicine has transformed contemporary healthcare by customizing therapies for each patient according to their unique genetic, physiological, and lifestyle traits. Meanwhile, 3D printing (3DP) technology has developed into an extremely accurate and versatile instrument that allows for the on-demand production of personalized dosage forms. With a focus on its expanding use in phytotherapy and herbal-based treatments, this paper examines the relationship between 3DP and customized medicine. The introduction of personalized medicines is followed by a summary of 3D printing methods, including inkjet printing, selective laser sintering, and fused deposition modeling (FDM). Customization of dose, form, release kinetics, and combination therapy is made possible by these technologies. It is also highlighted how 3DP can be used to create formulations tailored to individual patients using natural polymers. 3D printing offers exact control over release profiles and biocompatibility, bridging the gap between evidence-based natural product and traditional medications. This cooperative strategy enables better therapeutic results, decreased side effects, and more patient compliance.

Keywords: Personalized medicine, 3D printing, customization, natural products, phytotherapy and tailored dosage form.

1. Introduction

Personalized medicine is a medical care that customized for each patient, including treatment and prevention plans. The field of personalized medicine represents a revolutionary change in healthcare, moving away from standardized methods and toward customized treatments [1]. In personalized medicine, comprehensive analysis of a person's genetic makeup using genomic sequencing is essential. Healthcare practitioners can use this to identify particular genetic mutations and changes that affect medication metabolism, treatment response, and illness susceptibility. Equipped with this understanding, physicians may tailor therapeutic approaches to each patient's unique genetic profile, increasing efficacy and reducing side effects [1, 2 & 3].

In the pharmaceutical and medical industries, three-dimensional (3D) printing technology has become a game-changer, allowing dose forms to be precisely customized to match patient needs [4]. To maximize therapeutic results for each patient, dosage forms with customized drug release profiles, shapes, and sizes can be designed and manufactured via 3D printing [5]. With the advent of 3D printing technologies, healthcare practitioners now have a variety of methods to create individualized medications and medical equipment on demand. 3D printing was first used to create tablets with precise medicine dosages that weren't sold commercially. These days, the technology makes it possible to create intricate systems that serve patients' needs by combining several medications with various release profiles into a single tablet [4, 5 & 6]. Using 3D printing in phytotherapy has the potential to overcome the conventional restrictions on the use of herbal medicines [6]. It makes it possible to precisely dose herbal extracts, which may increase their therapeutic efficiency while reducing treatment outcome variability. In herbal medicine, where the intricacy of plant-derived substances and variations in extract composition can result in inconsistent patient responses, this customization feature is especially beneficial [6, 7 & 8].

Additionally, 3D printing technology makes it easier to create intricate dosage forms that may precisely deliver a variety of herbal chemicals, possibly maximizing the synergistic benefits of phytochemical combinations. This ability could improve the therapeutic potential of herbal remedies by more accurately and carefully simulating conventional combo therapy [9, 10]. Furthermore, individualized 3D-printed dose forms that are created with patient preferences like size, shape, or flavor in mind may improve adherence to herbal therapy regimens. Patient adherence is a crucial component of treatment success [11].

2. Techniques of 3D Printing

Pharmaceutical 3D printing uses a variety of methods to create specialized dosage forms with specific compositions, geometries, and drug release profiles. Here is a thorough explanation of the approaches discussed [4];

2.1 Fused–Deposition Modeling (FDM)

Fused-deposition modeling is a fabrication method utilized for creating 3D scaffolds. In this method, molten polymers or ceramics are extruded via a narrow-opening nozzle in a layer-by layer deposition process **(Figure 1) (Table 1).** The material that was extruded combines with the last layer. The pattern for every layer is determined by mechanical control of the nozzle's x-y location, enabling arbitrary or distinctive designs for every layer that is deposited. 3D scaffolds made of composite materials like polycaprolactone/hydroxyapatite and polymers like high-density polyethylene have been created by the use of fused-deposition modeling [12, 13].

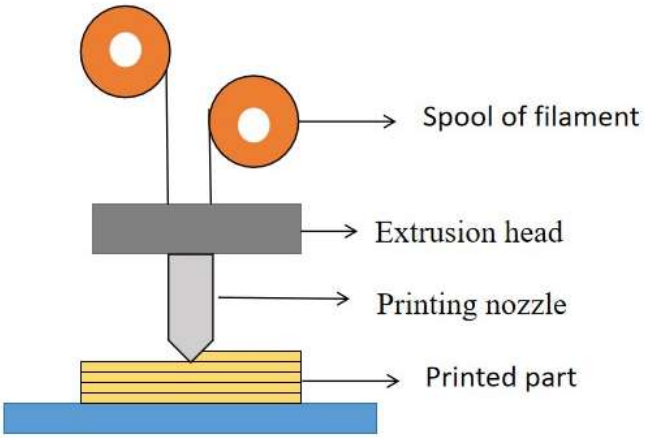

Figure 1: Fused–Deposition Modeling (FDM)

2.2 Hot Melt Extrusion (HME)

Hot melt extrusion is a flexible method for manufacturing pharmaceuticals which involves melting and combining polymers and active pharmaceutical ingredients (APIs) under regulated pressure and heat **(Table 1)**. After that, the molten mixture is extruded through a die to create strands, pellets, or other shapes **(Figure 2).** HME is frequently used in conjunction with other methods, such as fused deposition modeling (FDM), to 3D print bespoke dosage forms, giving exact control over drug release geometries and profiles. The procedure includes precise screw designs, processing temperatures, and polymer choices to guarantee API stability and the intended product properties [13, 14].

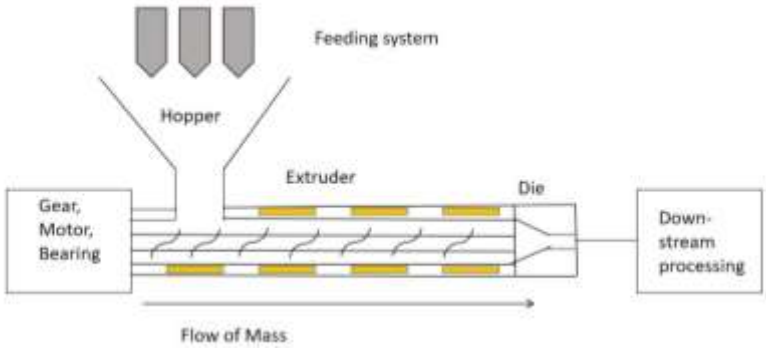

Figure 2: Hot Melt Extrusion (HME)

2.3 Semi-Solid Extrusion (SSE)

Semi-solid extrusion (SSE) is a type of 3D printing technique utilized in pharmaceutical and biomedical applications for fabricating dosage forms or scaffolds. In SSE, a semi-solid substance-typically a paste or gel-containing polymers, biomaterials, or active pharmaceutical ingredients (APIs) is extruded through a nozzle to create things layer by layer **(Figure 3) (Table 1).** Because SSE is semi-solid, it may be deposited without the need for high temperatures, which makes it appropriate for APIs that are sensitive to heat. Printing intricate geometries and personalized dose forms with regulated release profiles is made possible by this method. A variety of materials, such as hydrogels, pastes, and suspensions, can be handled by SSE [15]. When it comes to the feedstock materials utilized, SSE differs significantly from other material extrusion methods such as Direct Powder Extrusion (DPE) and Fused Deposition Modeling (FDM). FDM and DPE use solid filaments or powders, whereas SSE uses semi-solid or semi-molten starting material [16].

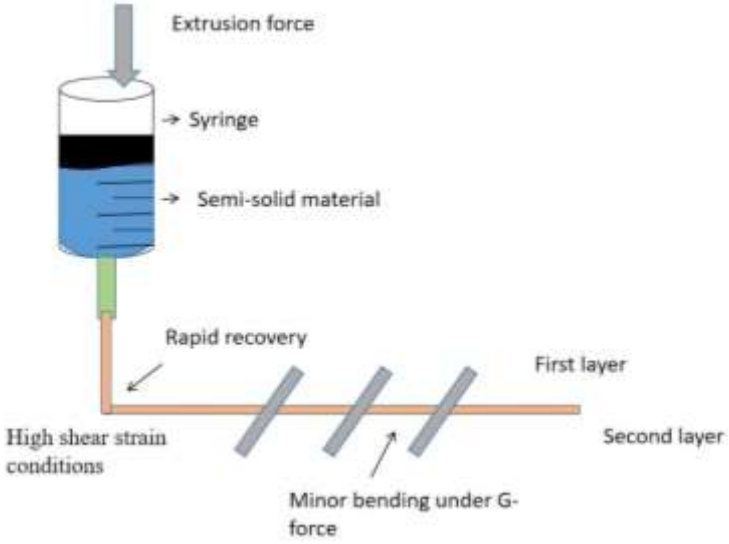

Figure 3: Semi-Solid extrusion (SSE)

2.4 Ink-jet (IJ) 3D Printing

Ink-jet printing is a digital printing technique that emits ink droplets onto surfaces using small nozzles **(Figure 4) (Table 1).** There are two primary modes of ink-jet printing: continuous ink-jet (CIJ) and drop-on-demand (DOD). Both approaches include the passage of liquid through an aperture or nozzle. The fluid is constantly forced through the nozzle in CIJ mode. The instability of Rayleigh-Plateau causes the jet to fragment into droplets. Unlike DOD mode, which creates droplets only when required for printing, field plates are used to charge and deflect droplets onto the substrate, and any droplets that are not used are gathered for recycling [17]. In pharmaceutical applications, ink-jet (IJ) 3D printing creates layers of a dosage form by applying a liquid binding agent to a bed of powdered material. Excipients, solvents, and/or medications make up the liquid binding agent, which is sprayed over the powder bed in precise movements, droplet sizes, and speeds. Particles of powder combine

with the binder during deposition to create a printed layer. This layer is cured or hardened, and then more powder is spread on top of it with a roller. Until the required dosage form geometry is obtained, more layers are printed and bound. A de-powdering procedure is then used to get rid of the unbound powder [18, 19].

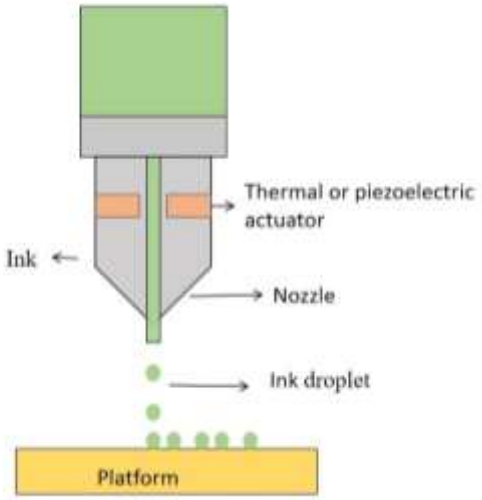

Figure 4: Ink-jet (IJ) 3D Printing

2.5 Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS) is a process that uses a laser to sinter powdered materials, such as excipients and active medicinal substances, into the shape of a computer-aided design (CAD). Powder is put in layers and sintered one after the other until the finished dosage form is finished **(Figure 5) (Table 1).** After removing extra powder, the design is visible [20]. It is a powder-based technique that uses a CO_2 laser to accurately sinter powder regions without the need for liquid binders. This method offers a highly precise, solvent-free, one-step drug delivery method. SLS shortens the time needed for solvent evaporation by sintering powder with a laser. The chamber temperature is kept below the melting point of the raw material, which is normally about 40°C, to avoid stress and curl deformities. SLS works similarly to other powder bed 3D printing technologies in that a laser spreads and scans layers of powder that are between 0.05 and 0.3 mm thick. Whereas sintered powder creates the final structure, unsintered powder acts as a support structure and is eliminated after printing [21, 22].

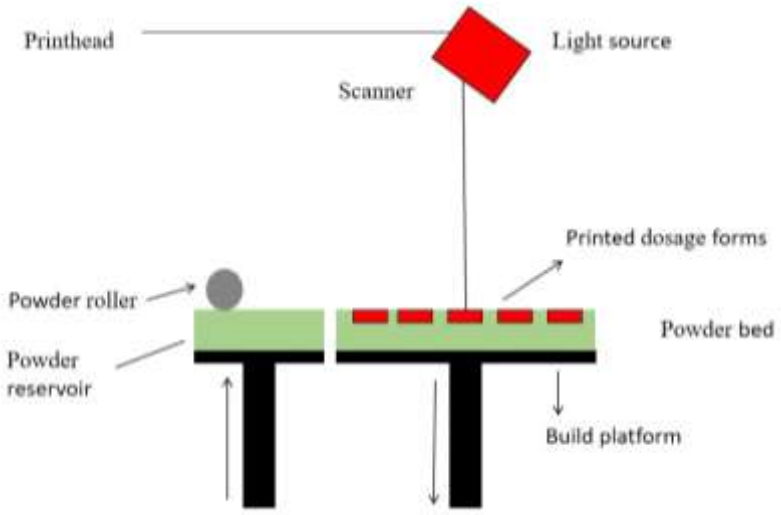

Figure 5: Selective Laser Sintering (SLS)

Table 1: Basic difference between 3D printing techniques with pharmaceutical applications

Sr. no.	Technique*	Material Used	Working Principle	Pharmaceutical Application	References
1	FDM	Solid Polymer Filament	Heats and extrudes drug loaded filament, deposit it layer by layer to form structure.	Fabrication of customized oral tablets, drug-loaded implants, geriatric or pediatric formulations.	[12, 13 & 23]
2	HME	Solid blend of drug and polymer	Apply heat and pressure to mix and shape drug-polymer mixture into filaments or solid forms.	Drug loaded filaments for FDM; solid dispersions for sustained or immediate release.	[14, 24]
3	SSE	Semi-solid paste/gel	Extrudes semi-solid drug formulation using pressure through a nozzle, forming layers without high heat.	Customized buccal films, transdermal patches and oral gels.	[15, 25]
4	IJ	Liquid (solution /suspension)	Deposits tiny droplets of drug-loaded ink onto a substrate or into layers to form structures.	Rapid-dissolving films, oral dispersible tablets, personalized drug layers or sheets.	[4, 18 &19]
5	SLS	Powder (solid)	Uses a laser beam to selectively fuse powder particles layer by layer into a solid film.	Porous tablets, implantable drug delivery devices.	[20, 21 & 26]

Technique*; FDM: Fused–Deposition Modeling, HME: Hot Melt Extrusion, SSE: Semi-Solid Extrusion, IJ: Ink-jet, SLS: Selective Laser Sintering

3. How 3D Printing Technology Enhancing the Personalization

One of the biggest advantages of 3D printing for customization is its capacity to produce one-of-a-kind, custom items without the need for expensive tooling procedures or mass production. 3D printing creates things directly from digital models, layer by layer, in contrast to conventional manufacturing techniques that use assembly lines and molds to create huge quantities of standardized goods [13, 27]. This makes it possible to achieve great levels of personalization without the need for intricate molds or machining, and at comparatively modest costs. This feature makes it possible to design drug delivery systems and dosage forms that are tailored not only in terms of dosage and drug release profiles but also in terms of physical characteristics such as shape, size, flavor, and ease of administration [27].

In medicine, personalization is essential because a "one-size-fits-all" strategy is frequently insufficient due to differences in genetics, metabolism, age, lifestyle, and comorbidities [28]. SPRITAM (levetiracetam), the first FDA-approved 3D-printed medication, is a notable example of the potential of 3D printing in medicine [29]. It was produced using Aprecia Pharmaceuticals ZipDose binder-jet technology and produces a highly porous tablet that dissolves quickly. This helps patients who have trouble swallowing by enabling the administration of large doses (up to 1,000 mg) with little liquid [29, 30].

Another example from the review [31] demonstrates point-of-care applications where polypills containing many medications, such as tamoxifen with venlafaxine or duloxetine for individualized oncology treatment, were made possible by 3D printing. Furthermore, dual-amino acid chewable printlets were created for young children with uncommon metabolic conditions [32].

There are many other instances of personalized medicines made possible by 3D printing technology (**discussed in Table 2**). These examples use customized medicine techniques to improve adherence and therapeutic effects. Because it allows for precise control over dosage form characteristics and allows for the combination of multiple drugs in customized formats. This integration in the pharmaceutical industry thus opens pathways for tailored treatments that address individual patient needs more effectively and advancing personalized healthcare strategies [33].

Table 2: Examples of personalized medicine produced through the use of 3D printing technology

Sr. no.	3D Printing Technologies*	API	Personalized Medicine	References
1	FDM/HME	Monoclonal antibody (mAb)	PLGA-based implantable device loaded with homogenous amorphous solid dispersion of monoclonal antibody (mAb) was made via fused	[34]

			deposition modeling. This implant showed sustained release over 12 weeks of *in-vitro* study and was confirming the stability of the formulation.	
2	FDM	Levodopa, Praziquantel, Pramipexol	The customized oral dosage form of pramipexol, levodopa (BCS 1) and praziquantel (BCS 2) was prepared by fused deposition modeling based on hollow cylinder-design, maintained a zero order release profile over each of 3APIs in varying dosages.	[35]
3	SSE	Phenytoin	The fast disintegrating phenytoin tablet pre-filled in dosing syringes was prepared using "tablet-in-syringe" approach via semisolid extrusion technique. Specially designed for dysphasic patients for easy administration of oral drug with improved dosing accuracy.	[36]
4	SSE	Paracetamol Ibuprofen	Chewable dosage forms of gelatin-based soft "Lego-like" bricks through semisolid extrusion of drug loaded paste directly into a liquid gelatin matrix. Provide dual drug capability with predictable release in simulated intestinal fluid and pediatric-friendly taste and texture.	[37]
5	SSE	Levocetirizine HCl	HPMC oral dispersible films loaded with levocetirizine HCl were printed as cube designs by semi solid extrusion technique. These are designed for simple oral administration and outcomes confirmed precise, tailored dosing, rapid dissolution without water. Especially beneficial for pediatric and dysphagic patients.	[38]
6	SSE	Amikacin sulphate	Custom shaped bone scaffolds with varied internal architectures were	[39]

			loaded with amikacin to match bone defect and personalized local drug delivery implants were produced via semisolid extrusion 3D printing. These were patient specific antimicrobial implants for bone defect infection management.	
7	Ink-jet Printing	Propranolol	The oral dispersible films containing precise dose of propranolol HCl were prepared by inkjet 3d printing technique followed by the coating of saccharin for palatability, especially beneficial for pediatric.	[40]
8	Ink-jet Printing	Thiamine HCl	The oral tablets of thiamine HCl were prepared in highly soluble PVP via water-based inkjet 3D printing to achieve rapid drug release.	[41]
9	SLS	Amlodipine Lisinopril	3D printed polyprintlets were developed by SLS loaded with two drugs at therapeutic doses to achieve personalized multi drug tablets. Polypills were printed as both films and cylindrical prints.	[42]
10	SLS	Paracetamol	Paracetamol loaded gyroid lattice tablets were prepared for customization of drug release without altering the polymer composition. Cylindrical, gyroid-lattice abd bilayer construct were produced using distinct polymers to effectively modulating the release profile across all materials. Designed to achieve patient-specific drug performance with high resolution and cost effective method.	[43]

3D Printing Technologies*; FDM: Fused–Deposition Modeling, HME: Hot Melt Extrusion, SSE: Semi-Solid Extrusion, IJ: Ink-jet, SLS: Selective Laser Sintering

4. Integration of Natural Products into 3D Printing Therapeutic Delivery System

3D printing technology has emerged as a promising approach for the development and delivery of natural products, particularly in the field of personalized medicine and phytotherapy. Natural materials have been widely used as pharmaceutical excipients and

scaffolds, especially natural polymers such proteins (gelatin, collagen) and polysaccharides (alginate, chitosan, cellulose derivatives, starch, pectin) [6, 44]. This is because, in contrast to polymers derived from petroleum, they have superior biocompatibility, biodegradability, safety profile, and sustainable origin. They are particularly well-suited for tissue engineering and drug administration by 3D printing, especially extrusion-based and nozzle-based deposition, including pressure-assisted microsyringe (PAM) systems (uses a syringe based head to extrude semisolid material), because of their moderate hydrogel formation capabilities. These methods avoid high temperatures or organic solvents and are cell-friendly [44, 45 & 46].

There are various natural polymers with biomedical properties like alginate from brown algae gels mildly via calcium ions, mimicking extracellular matrix environments and supporting cell viability. Chitosan from crustacean shells offers biodegradability, mucoadhesion, and antimicrobial properties. Cellulose derivatives and starch enable printable hydrogels with controlled rheology. Pectin from fruit wastes forms adjustable hydrogels for bone tissue scaffolds [45, 47].

In 3D printing, natural polymers must be printable, biocompatible, regulated biodegradable, have mechanical characteristics that resemble target tissues, and permit medication encapsulation or live-cell printing under benign conditions [6]. Natural products gel in moderate environments, meeting these requirements. Due to its simplicity of extrusion, fine control, and compatibility with bioactive materials, PAM, or direct-ink writing, is frequently utilized for printing scaffolds and drug delivery systems made of natural polymers [48]. By simulating the natural extracellular matrix in tissue engineering, natural polymers can distribute medications, growth factors, or cells in situ without causing harm to bioactive [44, 47].

There are various studies showcase the use of natural polymers such as gelatin, oxidized alginate, hydroxy apatite composites, nanocellulose and collagen in 3D printing (**discussed in Table 3**).

Table 3: **3D printed system containing natural products along with printing conditions and scaffolds dimensions.**

Sr. no.	**Natural Product**	**Printer**	**Printing speed & temperature**	**Scaffold dimensions**	**References**
1	Gelatine + oxidized alginate ± 5% HAp	BIOX 3D printer	5-5.5 mm/s speed & 15˚C temperature	10.1×10.1×2.25mm (10 layers)	[49, 50]
2	TEMPO-CNF (nanocellulose hydrogel)	Envision Tec 4th Gen 3D-Bioplotter,	70 mm/s speed & 20˚C temperature	Square-box grid 30×30×5 mm with 1.5 mm spacing	[51]

	1%w/v	direct			
3	Collagen nanocellulose hybrid	Bioscaffolder 3.1 (GeSim)	15 mm/s speed	Circular with 5-7 mm radius and 3-8 mm height	[52]
4	Chitosan and Sodium hyaluronate	3D Bio-printing (Regenovo Bio-printer system)	8 mm/s speed & 37˚C temperature	Cylindrical shape with diameter 10 mm and height 5mm	[53]
5	Beeswax	Inkjet printer (PiXDRO LP50, Meyer Burger Technology, Ltd.)	----------	Cylindrical shape: 0.20, 0.41, 0.61, 122 with diameter 1.83 mm and height 3.22mm	[54]
6	Chitosan and alginate	Markerbot Replicator 2X FDM printer	10 mm/s speed & 200˚C (PVA), 190˚C (EC) temperature	20×20×0.2 mm EC backing layer: 20×20×0.1 mm	[55]
7	Pectin and chitosan	BioBot 1 3D printer (Allevi Philadelphia, PA, USA)	6 mm/s speed with room temperature	23.50×23.50×1.00 mm	[56]

5. Conclusion

In conclusion, by utilizing methods like extrusion and inkjet printing, personalized 3D printing helps to close the gap between phytotherapy and tailored medication. 3D printing makes it possible to precisely customize dose forms to match the needs of each patient by using natural polymers and plant-based active ingredients. This improves therapeutic results and adherence in the contexts of herbal and pharmaceutical medicine. 3D printing's adaptability when using natural materials fosters innovation in individualized medical care.

6. Future Directions

Future directions for personalized 3D printing in medicine and phytotherapy involve expanding applications of natural polymers and refining printing techniques for complex herbal formulations. Research might concentrate on examining novel natural biomaterials that are compatible with 3D printing, scaling manufacturing while preserving personalization, and regulatory issues for customized 3D-printed medications. In both pharmaceutical and herbal contexts, integration with digital health systems for customized dose based on patient data may improve treatment precision and results even further.

7. Acknowledgement
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8. References

[1] Stefanicka-Wojtas, D., & Kurpas, D. (2023). Personalised Medicine—Implementation to the Healthcare system in Europe (Focus Group discussions). *Journal of Personalized Medicine*, *13*(3), 380. https://doi.org/10.3390/jpm13030380.
[2] Pandey, A., & Gupta, S. P. (2024). Personalized Medicine: A Comprehensive review. *Oriental Journal of Chemistry*, *40*(4), 933–944. https://doi.org/10.13005/ojc/400403.
[3] Khan, A., Barapatre, A. R., Babar, N., Doshi, J., Ghaly, M., Patel, K. G., Nawaz, S., Hasana, U., Khatri, S. P., Pathange, S., Pesaru, A. R., Puvvada, C. S., Billoo, M., & Jamil, U. (2025d). Genomic medicine and personalized treatment: a narrative review. *Annals of Medicine and Surgery*. https://doi.org/10.1097/ms9.0000000000002965.
[4] Wang, S., Chen, X., Han, X., Hong, X., Li, X., Zhang, H., Li, M., Wang, Z., & Zheng, A. (2023). A review of 3D printing technology in pharmaceutics: Technology and applications, Now and future. *Pharmaceutics*, *15*(2), 416. https://doi.org/10.3390/pharmaceutics15020416.

[5] Bernatoniene, J., Stabrauskiene, J., Kazlauskaite, J. A., Bernatonyte, U., & Kopustinskiene, D. M. (2025). The Future of Medicine: How 3D Printing Is Transforming Pharmaceuticals. *Pharmaceutics*, *17*(3),
390. https://doi.org/10.3390/pharmaceutics17030390.
[6] Aguilar-De-Leyva, Á., Linares, V., Casas, M., & Caraballo, I. (2020). 3D printed drug delivery systems based on natural products. *Pharmaceutics*, *12*(7), 620. https://doi.org/10.3390/pharmaceutics12070620.
[7] Wang, H., Chen, Y., Wang, L., Liu, Q., Yang, S., & Wang, C. (2023). Advancing herbal medicine: enhancing product quality and safety through robust quality control practices. *Frontiers in Pharmacology*, *14*. https://doi.org/10.3389/fphar.2023.1265178.
[8] Bernatoniene, J., Stabrauskiene, J., Kazlauskaite, J. A., Bernatonyte, U., & Kopustinskiene, D. M. (2025b). The Future of Medicine: How 3D printing is transforming pharmaceuticals. *Pharmaceutics*, *17*(3),
390. https://doi.org/10.3390/pharmaceutics17030390.
[9] Liu, J., Sun, L., Xu, W., Wang, Q., Yu, S., & Sun, J. (2018). Current advances and future perspectives of 3D printing natural-derived biopolymers. *Carbohydrate Polymers*, *207*, 297–316. https://doi.org/10.1016/j.carbpol.2018.11.077.
[10] Peng, H., Han, B., Tong, T., Jin, X., Peng, Y., Guo, M., Li, B., Ding, J., Kong, Q., & Wang, Q. (2024). 3D printing processes in precise drug delivery for personalized medicine. *Biofabrication*, *16*(3), 032001. https://doi.org/10.1088/1758-5090/ad3a14.
[11] Menditto, E., Orlando, V., De Rosa, G., Minghetti, P., Musazzi, U., Cahir, C., Kurczewska-Michalak, M., Kardas, P., Costa, E., Lobo, J. S., & Almeida, I. (2020). Patient Centric Pharmaceutical Drug Product Design—The Impact on Medication Adherence. *Pharmaceutics*, *12*(1), 44. https://doi.org/10.3390/pharmaceutics12010044.

[12] Barajas-Pedroza, M. A., & Rodríguez-Rodríguez, R. (2023). Development of 3D-printed biocompatible materials for bone substitution. In *Elsevier eBooks* (pp. 507–524). https://doi.org/10.1016/b978-0-323-90597-8.00007-4.

[13] Dumpa, N., Butreddy, A., Wang, H., Komanduri, N., Bandari, S., & Repka, M. A. (2021). 3D printing in personalized drug delivery: An overview of hot-melt extrusion-based fused deposition modeling. *International Journal of Pharmaceutics*, *600*, 120501. https://doi.org/10.1016/j.ijpharm.2021.120501.

[14] Li, X., Hong, X., Shuai, S., Han, X., Li, C., Zhang, H., Wang, Z., Ren, M., Jin, L., & Zheng, A. (2024). A review of hot melt extrusion technology: Advantages, applications, key factors and future prospects. *Journal of Drug Delivery Science and Technology*, *98*, 105884. https://doi.org/10.1016/j.jddst.2024.105884.

[15] Seoane-Viaño, I., Januskaite, P., Alvarez-Lorenzo, C., Basit, A. W., & Goyanes, A. (2021). Semi-solid extrusion 3D printing in drug delivery and biomedicine: Personalised solutions for healthcare challenges. *Journal of Controlled Release*, *332*, 367–389. https://doi.org/10.1016/j.jconrel.2021.02.027.

[16] Seoane-Viaño, I., Januskaite, P., Alvarez-Lorenzo, C., Basit, A. W., & Goyanes, A. (2021b). Semi-solid extrusion 3D printing in drug delivery and biomedicine: Personalised solutions for healthcare challenges. *Journal of Controlled Release*, *332*, 367–389. https://doi.org/10.1016/j.jconrel.2021.02.027.

[17] Guo, Y., Patanwala, H. S., Bognet, B., & WK, A., MA. (2017). Inkjet and inkjet-based 3D printing: connecting fluid properties and printing performance. *Rapid Prototyping Journal*, *23*(3), 562–576. https://doi.org/10.1108/rpj-05-2016-0076.

[18] Evans, S. E., Harrington, T., Rivero, M. C. R., Rognin, E., Tuladhar, T., & Daly, R. (2021b). 2D and 3D inkjet printing of biopharmaceuticals – A review of trends and future perspectives in research and manufacturing. *International Journal of Pharmaceutics*, *599*, 120443. https://doi.org/10.1016/j.ijpharm.2021.120443.

[19] Srivastava, S., Misra, S., Kapoor, A., Kant, S., Kumar, R., & Katiyar, A. (2023). 3D Printing Technology: A Contemporary Revolution in Drug Development. *Asian Journal of Pharmaceutics*, *17*(04). https://doi.org/10.22377/ajp.v17i04.5079.

[20] Charoo, N. A., Ali, S. F. B., Mohamed, E. M., Kuttolamadom, M. A., Ozkan, T., Khan, M. A., & Rahman, Z. (2020d). Selective laser sintering 3D printing – an overview of the technology and pharmaceutical applications. *Drug Development and Industrial Pharmacy*, *46*(6), 869–877. https://doi.org/10.1080/03639045.2020.1764027.

[21] Awad, A., Fina, F., Goyanes, A., Gaisford, S., & Basit, A. W. (2020). 3D printing: Principles and pharmaceutical applications of selective laser sintering. *International Journal of Pharmaceutics*, *586*, 119594. https://doi.org/10.1016/j.ijpharm.2020.119594.

[22] Gueche, Y. A., Sanchez-Ballester, N. M., Bataille, B., Aubert, A., Leclercq, L., Rossi, J., & Soulairol, I. (2021). Selective Laser Sintering of Solid Oral Dosage Forms with Copovidone and Paracetamol Using a CO2 Laser. *Pharmaceutics*, *13*(2), 160. https://doi.org/10.3390/pharmaceutics13020160.

[23] Long, J., Gholizadeh, H., Lu, J., Bunt, C., & Seyfoddin, A. (2016). Application of fused deposition Modelling (FDM) method of 3D printing in drug delivery. *Current*

Pharmaceutical Design, *23*(3), 433–439. https://doi.org/10.2174/1381612822666161026162707.

[24] Deshkar, S., Rathi, M., Zambad, S., & Gandhi, K. (2020). Hot Melt Extrusion and its Application in 3D Printing of Pharmaceuticals. *Current Drug Delivery*, *18*(4), 387–407. https://doi.org/10.2174/1567201817999201110193655.

[25] Aina, M., Baillon, F., Sescousse, R., Sanchez-Ballester, N. M., Begu, S., Soulairol, I., & Sauceau, M. (2025). From conception to consumption: Applications of semi-solid extrusion 3D printing in oral drug delivery. *International Journal of Pharmaceutics*, *674*, 125436. https://doi.org/10.1016/j.ijpharm.2025.125436.

[26] Tabriz, A. G., Kuofie, H., Scoble, J., Boulton, S., & Douroumis, D. (2023). Selective Laser Sintering for printing pharmaceutical dosage forms. *Journal of Drug Delivery Science and Technology*, *86*, 104699. https://doi.org/10.1016/j.jddst.2023.104699.

[27] Alzoubi, L., Aljabali, A. a. A., & Tambuwala, M. M. (2023). Empowering Precision Medicine: The impact of 3D printing on personalized Therapeutic. *AAPS PharmSciTech*, *24*(8). https://doi.org/10.1208/s12249-023-02682-w.

[28] Alzoubi, L., Aljabali, A. a. A., & Tambuwala, M. M. (2023). Empowering Precision Medicine: The impact of 3D printing on personalized Therapeutic. *AAPS PharmSciTech*, *24*(8). https://doi.org/10.1208/s12249-023-02682-w

[29] Savoia, C., Volpe, M., Grassi, G., Borghi, C., Rosei, E. A., & Touyz, R. M. (2017). Personalized medicine—a modern approach for the diagnosis and management of hypertension. *Clinical Science*, *131*(22), 2671–2685. https://doi.org/10.1042/cs20160407.

[30] Konta, A., García-Piña, M., & Serrano, D. (2017). Personalised 3D printed medicines: Which techniques and polymers are more successful? *Bioengineering*, *4*(4), 79. https://doi.org/10.3390/bioengineering4040079.

[31] Wang, Z., Han, X., Chen, R., Li, J., Gao, J., Zhang, H., Liu, N., Gao, X., & Zheng, A. (2021). Innovative color jet 3D printing of levetiracetam personalized paediatric preparations. *Asian Journal of Pharmaceutical Sciences*, *16*(3), 374–386. https://doi.org/10.1016/j.ajps.2021.02.003.

[32] Parramon-Teixido, C. J., Rodríguez-Pombo, L., Basit, A. W., Worsley, A., Cañete-Ramírez, C., Alvarez-Lorenzo, C., Cabañas-Poy, M. J., & Goyanes, A. (2025). A framework for conducting clinical trials involving 3D printing of medicines at the point-of-care. *Drug Delivery and Translational Research*. https://doi.org/10.1007/s13346-025-01868-y.

[33] Raijada, D., Wac, K., Greisen, E., Rantanen, J., & Genina, N. (2021). Integration of personalized drug delivery systems into digital health. *Advanced Drug Delivery Reviews*, *176*, 113857. https://doi.org/10.1016/j.addr.2021.113857.

[34] Carlier, E., Marquette, S., Peerboom, C., Amighi, K., & Goole, J. (2021). Development of mAb-loaded 3D-printed (FDM) implantable devices based on PLGA. *International Journal of Pharmaceutics*, *597*, 120337. https://doi.org/10.1016/j.ijpharm.2021.120337.

[35] Windolf, H., Chamberlain, R., & Quodbach, J. (2022). Dose-independent drug release from 3D printed oral medicines for patient-specific dosing to improve therapy safety. *International Journal of Pharmaceutics*, *616*, 121555. https://doi.org/10.1016/j.ijpharm.2022.121555.

[36] Panraksa, P., Zhang, B., Rachtanapun, P., Jantanasakulwong, K., Qi, S., & Jantrawut, P. (2022). 'Tablet-in-Syringe': a novel dosing mechanism for dysphagic patients containing Fast-Disintegrating tablets fabricated using semisolid extrusion 3D printing. *Pharmaceutics*, *14*(2), 443. https://doi.org/10.3390/pharmaceutics14020443.

[37] Rycerz, K., Stepien, K. A., Czapiewska, M., Arafat, B. T., Habashy, R., Isreb, A., Peak, M., & Alhnan, M. A. (2019). Embedded 3D printing of novel bespoke soft dosage form concept for pediatrics. *Pharmaceutics*, *11*(12), 630. https://doi.org/10.3390/pharmaceutics11120630.

[38] Yan, T., Lv, Z., Tian, P., Lin, M., Lin, W., Huang, S., & Chen, Y. (2020). Semi-solid extrusion 3D printing ODFs: an individual drug delivery system for small scale pharmacy. *Drug Development and Industrial Pharmacy*, *46*(4), 531–538. https://doi.org/10.1080/03639045.2020.1734018.

[39] Cui, M., Pan, H., Fang, D., Sun, H., & Pan, W. (2022). 3D printed personalized amikacin sulfate local drug delivery system for bone defect therapy. *Journal of Drug Delivery Science and Technology*, *70*, 103208. https://doi.org/10.1016/j.jddst.2022.103208.

[40] Vakili, H., Nyman, J. O., Genina, N., Preis, M., & Sandler, N. (2016). Application of a colorimetric technique in quality control for printed pediatric orodispersible drug delivery systems containing propranolol hydrochloride. *International Journal of Pharmaceutics*, *511*(1), 606–618. https://doi.org/10.1016/j.ijpharm.2016.07.032.

[41] Cader, H. K., Rance, G. A., Alexander, M. R., Gonçalves, A. D., Roberts, C. J., Tuck, C. J., & Wildman, R. D. (2019). Water-based 3D inkjet printing of an oral pharmaceutical dosage form. *International Journal of Pharmaceutics*, *564*, 359–368. https://doi.org/10.1016/j.ijpharm.2019.04.026.

[42] Trenfield, S. J., Tan, H. X., Goyanes, A., Wilsdon, D., Rowland, M., Gaisford, S., & Basit, A. W. (2020). Non-destructive dose verification of two drugs within 3D printed polyprintlets. *International Journal of Pharmaceutics*, *577*, 119066. https://doi.org/10.1016/j.ijpharm.2020.119066.

[43] Fina, F., Goyanes, A., Madla, C. M., Awad, A., Trenfield, S. J., Kuek, J. M., Patel, P., Gaisford, S., & Basit, A. W. (2018). 3D printing of drug-loaded gyroid lattices using selective laser sintering. *International Journal of Pharmaceutics*, *547*(1–2), 44–52. https://doi.org/10.1016/j.ijpharm.2018.05.044.

[44] Zamboulis, A., Michailidou, G., Koumentakou, I., & Bikiaris, D. N. (2022). Polysaccharide 3D printing for drug delivery applications. *Pharmaceutics*, *14*(1), 145. https://doi.org/10.3390/pharmaceutics14010145.

[45] Hu, T., Fang, J., Shen, Y., Li, M., Wang, B., Xu, Z., & Hu, W. (2024). Advances of naturally derived biomedical polymers in tissue engineering. *Frontiers in Chemistry*, *12*. https://doi.org/10.3389/fchem.2024.1469183.

[46] Somwanshi, A., Wadhwa, P., Raza, A., Hudda, S., Magan, M., & Khera, K. (2023). Natural alternatives to non-biodegradable polymers in 3D printing of pharmaceuticals. *Current Pharmaceutical Design*, *29*(29), 2281–2290. https://doi.org/10.2174/0113816128259971230921111755.

[47]Uysal, B., Madduma-Bandarage, U. S. K., Jayasinghe, H. G., & Madihally, S. (2025). 3D-Printed Hydrogels from Natural Polymers for Biomedical Applications: Conventional

Fabrication Methods, Current Developments, Advantages, and Challenges. *Gels*, *11*(3), 192. https://doi.org/10.3390/gels11030192.

[48] Elbadawi, M., Nikjoo, D., Gustafsson, T., Gaisford, S., & Basit, A. (2021). Pressure-assisted microsyringe 3D printing of oral films based on pullulan and hydroxypropyl methylcellulose. *International Journal of Pharmaceutics*, *595*, 120197. https://doi.org/10.1016/j.ijpharm.2021.120197.

[49] Zhanbassynova, A., Mukasheva, F., Abilev, M., Berillo, D., Trifonov, A., & Akilbekova, D. (2024). Impact of Hydroxyapatite on Gelatin/Oxidized Alginate 3D-Printed cryogel scaffolds. *Gels*, *10*(6), 406. https://doi.org/10.3390/gels10060406.

[50] Jose, J., Sultan, S., Kalarikkal, N., Thomas, S., & Mathew, A. P. (2020). Fabrication and functionalization of 3D-printed soft and hard scaffolds with growth factors for enhanced bioactivity. *RSC Advances*, *10*(62), 37928–37937. https://doi.org/10.1039/d0ra08295c..

[51] Rosendahl, J., Svanström, A., Berglin, M., Petronis, S., Bogestål, Y., Stenlund, P., Standoft, S., Ståhlberg, A., Landberg, G., Chinga-Carrasco, G., & Håkansson, J. (2021). 3D printed nanocellulose scaffolds as a cancer cell culture model system. *Bioengineering*, *8*(7), 97. https://doi.org/10.3390/bioengineering8070097.

[52] Štiglic, A. D., Lackner, F., Nagaraj, C., Beaumont, M., Bračič, M., Duarte, I., Kononenko, V., Drobne, D., Madhan, B., Finšgar, M., Kargl, R., Kleinschek, K. S., & Mohan, T. (2023). 3D-Printed Collagen–Nanocellulose Hybrid Bioscaffolds with Tailored Properties for Tissue Engineering Applications. *ACS Applied Bio Materials*, *6*(12), 5596–5608. https://doi.org/10.1021/acsabm.3c00767.

[53] Chen, S., Shi, Y., Luo, Y., & Ma, J. (2019). Layer-by-layer coated porous 3D printed hydroxyapatite composite scaffolds for controlled drug delivery. *Colloids and Surfaces B Biointerfaces*, *179*, 121–127. https://doi.org/10.1016/j.colsurfb.2019.03.063.

[54] Kyobula, M., Adedeji, A., Alexander, M. R., Saleh, E., Wildman, R., Ashcroft, I., Gellert, P. R., & Roberts, C. J. (2017). 3D inkjet printing of tablets exploiting bespoke complex geometries for controlled and tuneable drug release. *Journal of Controlled Release*, *261*, 207–215. https://doi.org/10.1016/j.jconrel.2017.06.025.

[55] Eleftheriadis, G. K., Ritzoulis, C., Bouropoulos, N., Tzetzis, D., Andreadis, D. A., Boetker, J., Rantanen, J., & Fatouros, D. G. (2019). Unidirectional drug release from 3D printed mucoadhesive buccal films using FDM technology: In vitro and ex vivo evaluation. *European Journal of Pharmaceutics and Biopharmaceutics*, *144*, 180–192. https://doi.org/10.1016/j.ejpb.2019.09.018.

[56] Long, J., Etxeberria, A. E., Nand, A. V., Bunt, C. R., Ray, S., & Seyfoddin, A. (2019). A 3D printed chitosan-pectin hydrogel wound dressing for lidocaine hydrochloride delivery. *Materials Science and Engineering C*, *104*, 109873. https://doi.org/10.1016/j.msec.2019.109873.