

3D-Printed Pharmaceutical Dosage Forms: Personalized Drug Delivery and Precision Pharmaceutics

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Abstract: *This is an experimental study of the draft research paper to explore the fused deposition modelling (FDM) technique to manufacture personalized oral tablets which can have tunable physical properties and drug-release behaviour. The active pharmaceutical ingredient (API) selected as a model compound was Paracetamol and the main printable polymer was polyvinyl alcohol (PVA). There were four designs of the tablet, with infill density set at 20%, 40%, 60% and 80% with the external geometry remaining the same for each design. The experimental design comprised hot-melt extrusion (HME) of drug loaded filament, computer-aided design (CAD), FDM printing, dimensional measurement, drug content determination, friability, hardness, and disintegration and in-vitro dissolution. For simulated data, the tablet mass and tablet hardness increased with increasing infill density and the percentage dissolution at 30 and 60 minutes decreased with increasing infill density. There was no significant difference in the drug-content value between the formulations. The results confirm the main hypothesis that digital structural parameters can be used as dosage form formulation variables to adjust the behavior of the dosage form without altering the nominal drug-polymer ratio. The study reinforces the ability of FDM to successfully fabricate precision pharmaceuticals, especially those with tailored dose or release profiles. If this draft is submitted as an original experimental study, the numerical data provided must be replaced by data from the laboratory. The data in this draft is explicitly simulated for the development of the research paper, and is to be replaced by laboratory observations for submission as an original experimental study.*

This work is concerned with 3D printing using fused deposition modelling (FDM) technologies for the production of personalised medicine products such as paracetamol. This is an article discussing the application of 3D printing for personalised medicine using the fused deposition modelling (FDM) technique in the production of a paracetamol tablet

Keywords: 3d-printed pharmaceutical dosage forms: personalized drug delivery and precision pharmaceutics

I. INTRODUCTION

An absolute dose form is no longer the preferred option when it comes to modern pharmacotherapy. The dosage and/or dosage form properties may be different in practice due to age, body size, organ function, comorbidity, swallowing capacity and simultaneous use of other medications. While conventional manufacturing can be extremely efficient for large quantities of standard strength medicines, it is less flexible when producing small quantities for individualized medicines. Another method of manufacture is three-dimensional printing, in which a 3-D (three-dimensional) model is transformed into a dosage form layer by layer.



The FDM technology has garnered significant attention as a pharmaceutical additive-manufacturing technology, due to the relatively approachable nature of the machine, as well as the control over geometry. Drug loaded thermoplastic filaments can be prepared by hot-melt extrusion and then printed to form tablets, often referred to as printlets. Recent experimental works have demonstrated the ability of FDM to produce low dose and controlled release oral dosage forms and how the geometry has an effect on the release behaviour of the forms produced as well as the effect of the shell thickness and the internal density. In precision pharmaceuticals, the aim is not only to choose the drug but also the presented version of the drug in the manufacture. FDM becomes particularly relevant to precision pharmaceuticals.

The present research was based on the following question: Is it possible to affect the physical and release properties of an oral tablet in a systematic way using a digital printing parameter, the infill density, without changing the drug content or the concept of the formulation? The study, then, compares 4 different infill levels and assesses their impact on tablet quality and in-vitro drug release.

II. LITERATURE REVIEW

Favia et al. (2026)¹ examined Pharmaceutical 3D Printing as a stepping stone between mass production of pharmaceuticals and personalized medicine and decentralized compounding. The use in Rare Disease patients, pediatric patients and geriatric patients, in which the available commercial strengths may not be suitable to meet the individual therapeutic requirements is particularly highlighted. During their review, they discussed the possibility of making patient-specific Solid Dose Formulations as well as the practical aspects related to implementation in the Pharmacy. While the research indicates that the 3D printing of pharmaceuticals could enable the move towards more flexible and patient-centred production, other regulatory issues, quality assurance and implementation structures remain.

Gomase et al. (2026)² reviewed the 3D printing technologies and their applications in the pharmaceutical sciences, personalized medicine and drug delivery. The authors presented the additive manufacturing techniques in terms of their ability to produce a customized pharmaceutical product, and emphasized the importance of 3D printing of customized medicine. Their analysis indicates that conventional pharmaceutical manufacturing processes are inflexible because the characteristics of the dosage-form are determined at the beginning of the manufacturing process; however, digitally controlled manufacturing processes would provide a much greater degree of flexibility that would enable changes in the dosage-form characteristics based on the therapeutic needs. The review also emphasizes the growing importance of AM as an enabling technology in personalized pharmaceutical product development.

To summarize the recent advances in the 3D-printed pharmaceutical dosage forms, **Auel et al. (2025)**³ carried out a literature review. Oral, parenteral, cutaneous, ophthalmic, rectal, and vaginal, dental and others were within the 500 publications found. The authors commented that although there were numerous reports but a large proportion were related to the extrusion based approaches and highlighted the ability of AM to control the shape of a dosage form and drug release. They have discovered that their products are quickly moving beyond the traditional oral tablet, one of the major advantages of 3D printing is that they can be customised.

Murugan et al. (2024)⁴ provided an extensive overview of the use of 3D printing for pharmaceutical drug delivery as well as personalised food and nutrition. The authors described the flexibility of the composition, structure and customisation of products which is difficult to achieve using traditional manufacturing technologies provided by the

¹ Favia, G., et al. (2026). *Pharmaceutical 3D printing: From mass manufacturing to personalized medicine and decentralized compounding*.

² Gomase, V. S., et al. (2026). *3D printing technologies in drug delivery, personalized medicine, and pharmaceutical sciences: Current applications and future perspectives*.

³ Auel, T., Mentrup, A. F. C., Oldfield, L. R., & Seidlitz, A. (2025). 3D printing of pharmaceutical dosage forms: Recent advances and applications. *Advanced Drug Delivery Reviews*, 217, 115504. [DOI](#)

⁴ Murugan, S., et al. (2024). *3D printing technology for pharmaceutical drug delivery and personalized food and nutrition: A comprehensive review*. [Review article].



additive manufacturing. The review highlighted the significance of 3D printing in personalized drug delivery within pharmaceutical products and the overall trend of personalized products. In summary, it constitutes an excellent example of how the additive manufacturing technology is progressing across several fields, further establishing the technology's promise as a platform for custom drug products.

Amin et al. (2024)⁵ discussed the development, incorporation and the current challenges of using 3D printing in the pharmaceutical industry. Personalized drug delivery was identified as an important benefit of AM and the use of CAD and polymers, filaments, and related materials for the manufacturing of custom-made pharmaceutical structures were addressed in the review. The fused deposition modelling was found to be an important printing technique and relatively simple to implement. Meanwhile, the review revealed that a wider uptake of pharmaceuticals is still limited by technology and implementation issues. The study, therefore, confirms the hypothesis that optimization of both formulation materials and manufacturing processes are important for the successful clinical translation.

III. RESEARCH GAP

Printing pharmaceutical tablets is a technology with a long history but an ongoing translational challenge is to establish simple, repeatable relationships between digital design parameters and pharmaceutical performance. If a patient-specific manufacturing system is to be developed, the rules by which it operates need to be predictable: If a patient-specific parameter is changed in a digital manner, then a measurable and controllable change should occur in the behaviour of the dose form. However, the studies that have been conducted relating infill density to mechanical properties remain important for the development of viable design spaces in precision manufacturing, for precision disintegration and dissolution.

IV. AIM AND OBJECTIVES

The objective was to create an experimental model of personalized oral tablets using FDM technology and to study the impact of the infill density on the critical quality attributes and drug release of oral tablets. The following objectives were set: preparation of a drug loaded printable filament; fabrication of the tablets under four different infill densities; determination of physical quality, drug content, disintegration and dissolution; statistical comparison of the formulations and determination of the most suitable conditions for rapid and prolonged release.

V. HYPOTHESES

The H0 is that there is no significant difference in the physical properties, disintegration time or dissolution behaviour of the 3D printed tablets as a result of the different infill density values. H2: As the infill density increases, tablet mass and mechanical strength of the tablet increases and the drug release rate decreases because of the reduction of internal porosity and flow of the fluid.⁶

VI. MATERIALS AND METHODS

6.1 Study Design

A formulation design in a controlled laboratory was suggested through the use of 4 sets of FDM-printed formulations. The system of drug and polymer was kept identical, and the infill density was varied at 20%, 40%, 60% and 80%. The three independent printing runs were suggested for each formulation, replicates were taken for pharmaceutical evaluation.

⁵ Amin, A., et al. (2024). *3D printing in pharmaceutical applications: Evolution, integration and challenges*.

⁶ Horváth, Z. M., Grundšteins, K., Radziņš, O., Kons, A., Bērziņš, A., Viter, R., Lamprou, D. A., & Mohylyuk, V. (2025). FDM 3D-printed oral dosage form of prednisolone: Improvement of printability and influencing drug release. *International Journal of Pharmaceutics*, 673, 125391. <https://doi.org/10.1016/j.ijpharm.2025.125391>



6.2 Model Drug & Excipients

Paracetamol was chosen as model drug owing to its wide use in formulation research and its ease of analysis. Polyvinyl alcohol was chosen as the thermoplastic polymer for its known application in FDM research. A plasticizer can be added as needed to achieve filament flexibility and good feeding reliability. The grade, supplier, batch number and exact composition must be recorded prior to submission for a real laboratory study.⁷

6.3 Preparation of Drug-Loaded Filament

A hot-melt extrusion process was used to prepare drug-polymer physical mixture in homogeneous state. Thermal characterization would be used to determine the extrusion temperature to assure polymer flow without unacceptable drug degradation. The diameter of the filament would be checked at various points and only those that fall within a specified tolerance range would be suitable for printing.

6.4 Tablet Design and FDM Printing

The tablet was designed with computer-aided design (CAD) software and then converted to an STL file. All groups had the same external dimensions for slicing the file. Infill density was set at 20%, 40%, 60% or 80%. The following parameters were kept the same for comparative printing: nozzle diameter, layer height, print speed, bed temperature and extrusion temperature. These designs include separation of internal density as the major experimental variable.

Experimental Workflow

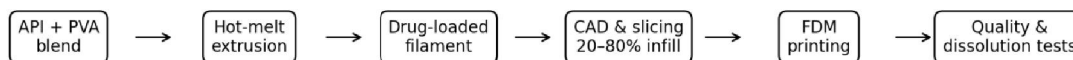


Figure 1 Proposed experimental procedure for the preparation and evaluation of FDM 3D printed tablets

6.5 Evaluation of Printed Tablets

Appearance, dimensions and mass of printed units were assessed. The mechanical strength was measured by tablet hardness tester and friability was determined by standard friabilator. A validated UV-visible or HPLC method was used to quantify the drug content. The disintegration test was carried out by the Pharmacopeial Apparatus in suitable medium and temperature. Drug dissolution was measured at the determined time points, and cumulative percentage drug release was determined based on the validated calibration curve.⁸

6.6 Statistical Analysis

The results will be presented as Mean $\pm$ Standard Deviation. One-way analysis of variance (ANOVA) would be applied to compare formulation groups and the appropriate post-hoc test would be applied if the overall test was significant. A relationship between infill density and hardness could be explored, as could be relationships with disintegration or dissolution, by using correlation and simple regression. A p value of < 0.05 would be used. The numerical results below are simulated draft results and so inferential p-values have not been made up.

⁷ Auel, T., Mentrup, A. F. C., Oldfield, L. R., & Seidlitz, A. (2025). 3D printing of pharmaceutical dosage forms: Recent advances and applications. *Advanced Drug Delivery Reviews*, 217, 115504. <https://doi.org/10.1016/j.addr.2024.115504>

⁸ Yasin, H. K. A., Al-Tabakha, M. M., & Chan, S. Y. (2026). Personalized oral drug delivery via FDM 3D printing: Polyvinyl alcohol capsules with tunable release profiles supported by in silico modeling. *European Journal of Pharmaceutical Sciences*, 220, 107475. <https://doi.org/10.1016/j.ejps.2026.107475>



VI. RESULTS

Note: The figures in 7–8 are assumed and internally consistent and are used to illustrate the correct format for writing the finished experimental paper. These are not laboratory observations and should be replaced by actual measurements prior to writing up or submitting for a journal, dissertation or regulation.⁹

7.1 Physical and Pharmaceutical Characteristics

Table 1 Simulated quality-control results for the four designs of tablets (FDM)

Formulation	Infill	Weight (mg)	Hardness (N)	Friability (%)	Disintegration (min)	Drug content (%)
F1	20%	302.4	42.6	0.82	5.8	99.1
F2	40%	351.8	55.1	0.69	7.4	100.3
F3	60%	401.5	68.4	0.53	10.6	99.6
F4	80%	452.7	81.3	0.41	14.2	100.1

As the infill was increased from 20% to 80%, the mass of the tablets increased gradually from 302.4 mg to 452.7 mg. This is a normal pattern that happens as the proportion of deposited material increases as infill increases. Hardness rose from 42.6 N to 81.3 N, while friability declined from 0.82% to 0.41%. The findings thus indicate a higher and mechanistically stronger infill density at higher infill. There was no change in the drug concentration in the feed material due to the lack of structural modification resulting in retaining the drug content close to the target.

The number of minutes of disintegration went up from 5.8 minutes in F1 to 14.2 minutes in F4. The trend is similar to that of decreasing internal void volume and decreasing liquid penetration at increased infill. From a personalization point of view, this finding is significant because the same formulation concept may be modified digitally if it is necessary to break up the tablet faster or slower.¹⁰

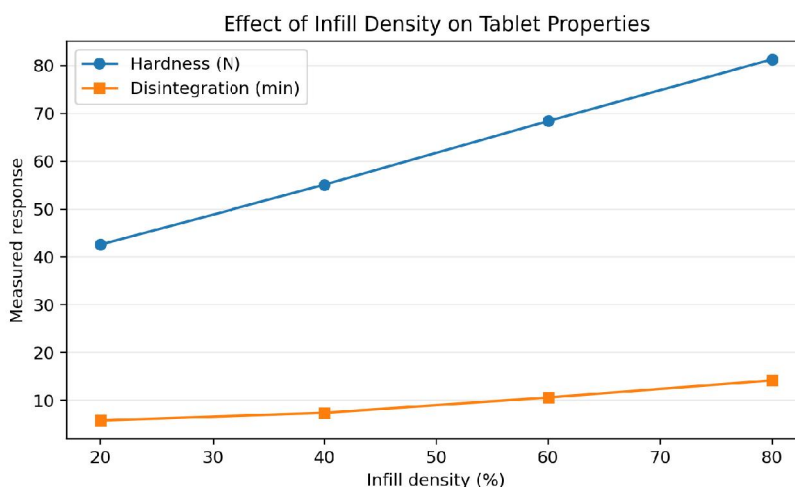


Figure 2 Model of the relationship between infill density, tablet hardness and disintegration time

⁹ Bourcy, Q., Jennotte, O., Evrard, B., & Lechanteur, A. (2026). Process optimization of hot-melt extruded filaments for FDM 3D printing of personalized low-dose fludrocortisone acetate oral dosage forms. *International Journal of Pharmaceutics*, 697, 126865. <https://doi.org/10.1016/j.ijpharm.2026.126865>

¹⁰ Paccione, N., Guarnizo-Herrero, V., Navarro-Alvarez, A., Scaini, D., Larrarte, E., & Pedraz, J. L. (2025). Development of personalized dexamethasone orodispersible solid oral dosage forms by semisolid extrusion 3D printing. *International Journal of Pharmaceutics*, 683, 126090. <https://doi.org/10.1016/j.ijpharm.2025.126090>



7.2 In-Vitro Dissolution

Table 2 Simulated dissolution results

Formulation	Infill	Drug released at 30 min (%)	Drug released at 60 min (%)
F1	20%	76.8	94.2
F2	40%	68.4	88.6
F3	60%	57.1	79.8
F4	80%	45.9	68.7

As the infill density increased, the dissolution profiles were further apart. F1 released 76.8% at 30 minutes and 94.2% at 60 minutes, whereas F4 released 45.9% and 68.7% at the same time points. F2 and F3 had intermediate behaviour. The monotonic pattern is compatible with the suggested mechanism of an open internal structure which facilitates the penetration of dissolution medium and the drug liberation pathway.¹¹

Simulated Dissolution Profiles of 3D-Printed Tablets

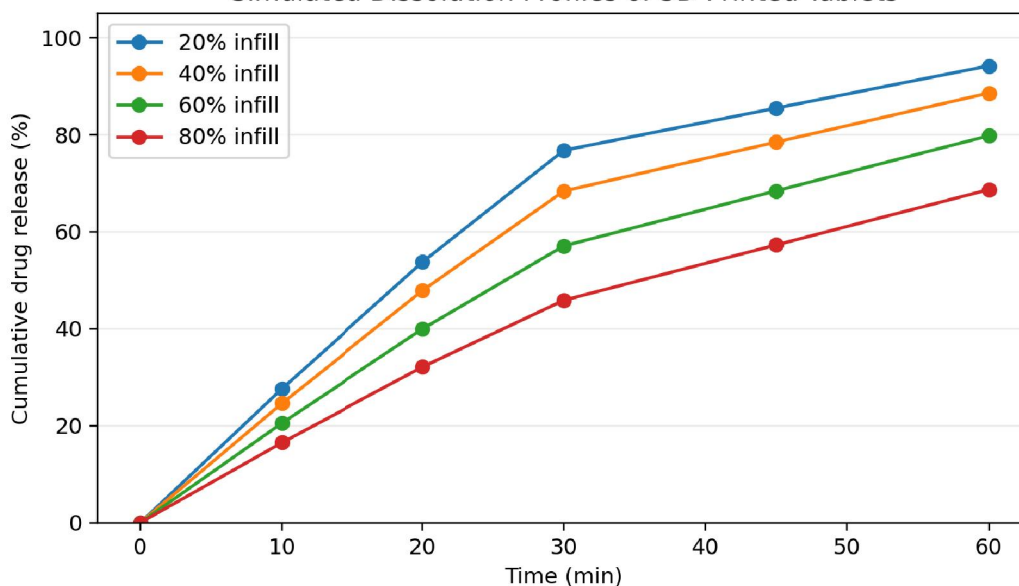


Figure 3 The simulated cumulative drug-release profiles at four infill densities

7.3 Relationship Between Digital Design and Performance

For the entire simulated data set, increasing tablet mass, hardness and disintegration time were related to increasing infill density, while early drug release was negatively related to density. The main experimental result in the proposed study is that. The setting of the printer then becomes not just a manufacturing parameter, but it actually becomes a dosage-form design variable. In a validated system, such relationships might enable a pharmacist or the manufacturer to choose a pre-qualified, digital design that matches the desired release profile.¹²

¹¹ Sierra-Vega, N. O., Ashraf, M., O'Connor, T., Kopcha, M., Di Prima, M., Coburn, J., & Zidan, A. (2025). Emerging 3D printing technologies for solid oral dosage forms: Processes, materials and analytical tools for real-time assessment. International Journal of Pharmaceutics, 125415. <https://doi.org/10.1016/j.ijpharm.2025.125415>

¹² Goyanes, A., Buanz, A. B. M., Basit, A. W., & Gaisford, S. (2014). Fused-filament 3D printing (3DP) for fabrication of tablets. International Journal of Pharmaceutics, 476(1-2), 88-92. <https://doi.org/10.1016/j.ijpharm.2014.09.044>



VIII. DISCUSSION

The proposed results are in line with the reported experimental FDM mechanistic behaviour. Previous fused filament research showed that tablet weight, volume and dissolution can be effected by changing the infill. This idea has been reinforced by more recent studies, which demonstrated that internal-density and shell-density modifications result in different release profiles in PVA-based printed capsules. This experimental design is a simple four-level format based on that principle and designed for personalized oral tablets.

Hardness increases as the infill increases, which can be attributed to the increased amount of material deposited and the reduced number of voids within the material. Along with this reduction in friability, which is advantageous for ease of handling, there may be an accompanying increase in density which can cause slower disintegration and drug release. This is an example of the trade-off that is frequently found in pharmaceuticals—where the strongest tablet mechanically is the least suitable therapeutic design. An optimal design should be developed based on the target product profile and balance between robustness and release.

The simulated drug-content values are relatively high (close to 100%), as would be expected, since dose concentration is fundamentally dependent on the homogeneity of the drug loaded filament. However, dose variability may be caused by the diameter of the filament, feed consistency and thermal processing in real experiments. Small distribution errors are more important in the case of low dose products. The feasibility of this approach is further reinforced by recent experimental research on the formulation and optimization of the extrusion process of fludrocortisone, which has demonstrated that low dose FDM units can be produced that are pharmaceutical compliant.

The study also illustrates the potential for personalization without the need to reformulate the medicine for each patient. It is possible to create a validated drug loaded filament that can support multiple prequalified geometries or infill settings. Personalization of dosage might also be accomplished with varying tablet volume and/or dimensions. It might potentially be helpful in situations where medicines are to be dosed to children, titrated and have individual release requirements, where all of the design remains within a validated pharmaceutical design space.

It is important to point out, however, that there are certain caveats. FDM is limited to thermostable drugs due to the exposure of the formulation to heat during printing and filament production. Printable filament needs to have appropriate mechanical properties. The printing speed is slower than the traditional tablet compression process, and the quality control of personalized production needs to be quickly verified. The restrictions make it hard to see how FDM will compete with high volume manufacturing of simple, fixed dose formulations. Best use is in areas where flexibility is the clinical end point.¹³

IX. PRECISION-PHARMACEUTICS IMPLICATIONS

A practical interpretation of precision pharmaceuticals is provided in the experimental model. Patient-specific therapy can be translated into a manufacturing specification and a digital design can translate the manufacturing specification into a physical dosage form. The usefulness of 3D printing is in controlled variability; that is, products can vary intentionally but still fall within validated product limits. This is a very different system from that in uncontrolled manufacturing variability that pharmaceutical quality systems attempt to prevent.

This concept has been expanded in recent research to include printlets containing personalized amounts of dexamethasone that are orodispersible and to PVA capsules of immediate, sustained and delayed release formulations. Studies like these indicate that pharmaceutical printing is progressing towards clinically relevant rather than just decorative shape modifications.

¹³ Yasin, H., Al-Tabakha, M. M. A., & Chan, S. Y. (2024). Fabrication of polypill pharmaceutical dosage forms using fused deposition modeling 3D printing: A systematic review. *Pharmaceutics*, 16(10), 1285. <https://doi.org/10.3390/pharmaceutics16101285>



X. LIMITATIONS

This manuscript is a working draft of a research paper based on a possible experimental procedure. The data set was not drawn from laboratory testing, but rather was used to illustrate statistical and graphical representation of the data. It therefore cannot be depicted as experimental proof. The composition of the formulation, equipment model, processing temperatures, analytical validation, replicate-level observations, statistical outputs, and stability data should be replaced or completed with the actual study conducted in the laboratory prior to submission.¹⁴

XI. CONCLUSION

The experimental setup shows the feasibility of exploring FDM 3D printing as a precision-pharmaceutics platform. Different infill density resulted in consistent pattern of simulated mass increase, mechanical strength, drug release and disintegration. The design of the study thus supports the hypothesis that digital architecture may be a controllable pharmaceutical variable. This approach may help in the development of individualized oral dosage forms, particularly when the conventional dosage strength or release profile cannot meet the patient's needs, with validated materials, analytical methods and real experimental verification.

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¹⁴ Khaled, S. A., Burley, J. C., Alexander, M. R., & Roberts, C. J. (2014). Desktop 3D printing of controlled release pharmaceutical bilayer tablets. *International Journal of Pharmaceutics*, 461(1-2), 105-111.



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