E-ISSN 3048-1562 Vol. 1, Issue 1 (2026)
Doi: https://doi.org/10.37899/mjdh.v3i2.375

Magenta Journal De Healthymedi

3D Printing Technology in Personalized Drug Formulation and Pharmacy Practice

Nabila Salsabila Yusuf[1], Muhammad Arslan[1]

[1]*Research Center for Pharmaceutical Innovation and Additive Manufacturing, Bandung Institute of Technology, Indonesia*

**Corresponding Author: Nabila Salsabila Yusuf*
E-mail: nabilaaysf@gmail.com

Article Info

Article History:
Received: 26 May 2026
Revised: 25 June 2026
Accepted: 20 July 2026

Keywords:
Additive Manufacturing, Digital Pharmacy, Personalized Medicine, Pharmaceutical Innovation, Pharmacy Practice, Precision Medicine

Abstract

This study examines the role of 3D printing technology in personalized drug formulation and pharmacy practice within the context of precision medicine and digital healthcare transformation. Using a systematic literature review approach based on the PRISMA framework, this research analyzed 52 peer-reviewed international journal articles related to pharmaceutical additive manufacturing. The findings indicate that 3D printing technology enhances dosage customization, controlled drug release, medication adherence, and patient-centered pharmaceutical care. The study also highlights the transformation of pharmacy practice from conventional dispensing services toward decentralized and digitally integrated pharmaceutical systems. Oharmacists are increasingly required to develop competencies in digital formulation design, artificial intelligence integration, and precision medicine applications. Despite its significant potential, several challenges remain, including regulatory uncertainty, infrastructure limitations, cybersecurity concerns, and limited professional readiness. The novelty of this study lies in its integrative perspective that combines pharmaceutical technology innovation, pharmacy practice transformation, and healthcare system adaptation within a unified analytical framework.

INTRODUCTION

The rapid advancement of pharmaceutical technology has transformed the landscape of modern healthcare, particularly through the integration of digital manufacturing systems into drug development and delivery processes. One of the most disruptive innovations in recent years is three-dimensional (3D) printing technology, also known as additive manufacturing, which enables the layer-by-layer fabrication of pharmaceutical products with highly customizable characteristics. Unlike conventional drug manufacturing methods that rely on mass production and standardized dosage forms, 3D printing offers unprecedented opportunities for personalized medicine by enabling precise control over drug dosage, release profiles, shape, and composition (Pethappachetty et al., 2025; Serrano et al., 2023; Borthakur et al., 2026; Alzoubi et al., 2023). This technological evolution aligns with the growing demand for patient-centered healthcare systems that prioritize individualized

treatment strategies based on patient-specific conditions, genetic profiles, and therapeutic needs (Navaei, 2025; Pandey & Gupta, 2024; Beridze & Lomidze, 2025).

The increasing prevalence of chronic diseases, polypharmacy, and complex therapeutic regimens has intensified the need for personalized drug formulation approaches (Ilan, 2022; Alhozim et al., 2024). Traditional pharmaceutical manufacturing often struggles to accommodate individualized dosing requirements, particularly among pediatric, geriatric, and oncology patients who frequently require tailored medication adjustments (Johannesson et al., 2022; Prajapati et al., 2026; Comoglu & Ozyilmaz, 2025). In this context, 3D printing technology has emerged as a promising solution to overcome the limitations of conventional pharmaceutical production. Studies have demonstrated that additive manufacturing can facilitate the production of customized tablets, multi-drug combinations, and controlled-release formulations with improved therapeutic efficacy and patient adherence. The approval of Spritam® (levetiracetam) by the U.S. Food and Drug Administration (FDA) marked a significant milestone in pharmaceutical 3D printing, demonstrating the practical feasibility of this technology in commercial pharmaceutical applications (Wang et al., 2023; Patel et al., 2024; Huanbutta et al., 2023).

The integration of 3D printing into pharmacy practice is further accelerated by the broader transformation toward digital health and precision medicine (Andreadis et al., 2022; Barar et al., 2026; Bernatoniene et al., 2025). Healthcare systems worldwide are increasingly adopting technologies such as artificial intelligence, pharmacogenomics, and digital therapeutics to optimize patient outcomes. Within this ecosystem, 3D printing serves as a bridge between pharmaceutical innovation and personalized healthcare delivery. Community and hospital pharmacies are gradually exploring the use of decentralized manufacturing models in which pharmacists may produce patient-specific medications on demand (Karvannan, 2025; Li et al., 2025; Gatt et al., 2026). Such developments could significantly reduce medication waste, enhance dosage flexibility, and improve access to specialized treatments, especially in remote or underserved areas (Diaz et al., 2026; Ahmed & Tamim, 2025; Al-Worafi, 2023).

Despite its transformative potential, the implementation of 3D printing technology in personalized drug formulation remains associated with substantial scientific, regulatory, and operational challenges. Existing pharmaceutical manufacturing frameworks are primarily designed for large-scale industrial production rather than individualized medicine fabrication (Algorri et al., 2022; Niazi, 2025; Malheiro et al., 2023). Consequently, issues related to quality assurance, drug stability, reproducibility, and regulatory compliance remain critical concerns in the widespread adoption of pharmaceutical 3D printing. Research has also identified barriers related to high equipment costs, limited technical expertise among pharmacists, and the absence of standardized guidelines for additive manufacturing processes in pharmacy settings. These limitations highlight the need for further investigation into how 3D printing can be effectively integrated into pharmacy practice while maintaining safety, efficacy, and regulatory integrity (Kumar Gupta et al., 2022; Barar et al., 2026; Balogun et al., 2023; Kurien et al., 2025).

Previous studies have extensively examined the technical capabilities of 3D printing in pharmaceutical sciences. Jamróz et al. emphasized the role of fused deposition modeling and stereolithography in developing personalized oral dosage forms with controlled drug release characteristics. Similarly, Andreadis et al. (2022) and Barar et al. (2026) explored the feasibility of decentralized pharmaceutical manufacturing using additive technologies in hospital pharmacy environments. Other studies have investigated the use of 3D printing for pediatric formulations, highlighting its potential to improve medication adherence through customizable dosage shapes and flavors. Moreover, recent research in pharmacogenomics has demonstrated that

personalized medicine approaches could significantly benefit from additive manufacturing technologies capable of tailoring medications according to genetic profiles and metabolic responses.

The existing literature remains fragmented in several important aspects. Most prior studies focus predominantly on technical formulation processes, material engineering, or laboratory-scale experimentation, while limited attention has been given to the broader implications of 3D printing adoption in pharmacy practice and healthcare systems. Furthermore, many studies emphasize technological feasibility without critically analyzing operational readiness, professional competency requirements, ethical considerations, and regulatory adaptation necessary for practical implementation (Geraghty et al., 2026; Salvador-Carulla et al., 2024). There is also insufficient integrative analysis connecting personalized drug formulation, digital pharmacy transformation, and the evolving role of pharmacists within precision medicine frameworks. Consequently, the current body of knowledge lacks a comprehensive perspective on how 3D printing technology may reshape pharmaceutical care delivery in the future.

The state of the art in pharmaceutical 3D printing increasingly emphasizes the convergence between additive manufacturing, artificial intelligence, and personalized healthcare systems. Recent advancements involve the development of smart drug delivery systems, multi-layered tablets with programmable release kinetics, and AI-assisted formulation optimization. Emerging studies have also explored bioprinting technologies for tissue engineering and regenerative medicine applications, further expanding the scope of pharmaceutical manufacturing innovation. Nevertheless, the transition from experimental applications to routine pharmacy practice remains underexplored, particularly regarding workflow integration, interprofessional collaboration, and policy standardization (Ali Alasmari et al., 2024). This indicates a significant research gap between technological innovation and practical pharmaceutical implementation.

Based on these considerations, this study aims to critically examine the role of 3D printing technology in personalized drug formulation and pharmacy practice by analyzing its opportunities, challenges, and implications for future pharmaceutical care systems. The novelty of this research lies in its integrative approach that combines pharmaceutical technology perspectives with pharmacy practice transformation and precision medicine frameworks. Unlike previous studies that focus mainly on technical formulation aspects, this research provides a broader analytical framework addressing regulatory readiness, pharmacist competencies, digital healthcare integration, and patient-centered pharmaceutical services. The findings of this study are expected to contribute theoretically to the development of pharmaceutical innovation literature and practically to support policymakers, healthcare institutions, and pharmacy professionals in preparing adaptive strategies for the implementation of 3D printing technologies in modern healthcare systems.

METHODS

Research Design

This study employed a qualitative descriptive research design using a systematic literature review (SLR) approach to critically analyze the development of 3D printing technology in personalized drug formulation and pharmacy practice. The qualitative approach was selected because the study aimed to explore conceptual developments, technological implications, and professional transformations associated with additive manufacturing in pharmaceutical sciences rather than measuring statistical relationships quantitatively. The systematic literature review method enabled the researchers to synthesize empirical findings, theoretical perspectives, and regulatory discussions from previous international studies in a comprehensive and structured

manner. According to Almusaed et al. (2025), systematic reviews are effective for identifying research trends, conceptual gaps, and emerging innovations within rapidly evolving scientific fields. The study adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency and methodological rigor throughout the review process. The PRISMA approach facilitated systematic identification, screening, eligibility assessment, and inclusion of relevant scholarly literature. Through this framework, the study aimed to produce a comprehensive synthesis regarding the opportunities and challenges of implementing 3D printing technology in personalized pharmaceutical care.

Research Context and Data Sources

The research focused on the global pharmaceutical and healthcare context, particularly studies discussing additive manufacturing applications in personalized medicine, clinical pharmacy, hospital pharmacy systems, and pharmaceutical technology innovation. Data sources were obtained from internationally recognized scientific databases, including Scopus, Web of Science, PubMed, ScienceDirect, and SpringerLink. These databases were selected due to their extensive coverage of peer-reviewed pharmaceutical and healthcare literature. The literature search was conducted using combinations of keywords such as “3D printing in pharmacy,” “personalized drug formulation,” “additive manufacturing in pharmaceuticals,” “precision medicine,” “pharmacy practice innovation,” and “digital pharmaceutical technology.” Boolean operators such as AND and OR were utilized to refine the search process and improve article relevance. The search process covered publications from 2015 to 2026 because this period represents significant advancements in pharmaceutical additive manufacturing following the FDA approval of the first 3D-printed drug product.

Inclusion and Exclusion Criteria

The inclusion criteria consisted of peer-reviewed journal articles published in English, studies specifically discussing pharmaceutical 3D printing applications, and research examining implications for pharmacy practice, personalized medicine, or healthcare systems. Both empirical and conceptual studies were included to provide broader analytical insights. Meanwhile, conference abstracts, editorials, duplicated articles, and studies unrelated to pharmaceutical applications were excluded from the analysis. Following the screening and eligibility process, 52 articles were selected as the final dataset for qualitative synthesis.

Data Collection Techniques

Data collection was conducted through document analysis and systematic extraction of relevant information from selected articles. The researchers developed a data extraction matrix to organize information related to study objectives, research methods, technological approaches, pharmaceutical applications, regulatory challenges, and implications for pharmacy practice. This process enabled systematic comparison across studies and facilitated thematic categorization of findings. In addition, note-taking and coding techniques were employed to identify recurring concepts and emerging themes associated with personalized drug formulation and digital pharmacy transformation. The use of qualitative coding procedures allowed the researchers to classify findings into broader analytical categories relevant to the study objectives.

Data Analysis Techniques

The collected data were analyzed using thematic analysis as proposed by Braun and Clarke. This method was considered appropriate because it enables researchers to identify, interpret, and synthesize patterns within qualitative datasets systematically. The analysis process involved several stages, including

familiarization with the data, generation of initial codes, theme identification, theme refinement, and interpretation of findings.

The study categorized findings into several major themes, including technological innovation in pharmaceutical manufacturing, personalization of drug therapy, regulatory and ethical challenges, pharmacist competency transformation, and digital healthcare integration. Comparative analysis was also conducted to identify similarities and differences among previous studies regarding the implementation of 3D printing technologies in pharmacy settings.

Validity and Reliability

To ensure the validity and reliability of the findings, this study applied methodological triangulation by comparing evidence from multiple databases and various research perspectives. Source credibility was strengthened through the inclusion of peer-reviewed international journal articles with high academic relevance. Additionally, the researchers conducted cross-checking procedures during data extraction and thematic coding to minimize interpretative bias and enhance analytical consistency. Transparency in the literature selection process, use of the PRISMA framework, and systematic thematic analysis further contributed to the trustworthiness and rigor of the study. These procedures ensured that the research findings accurately reflected the current development of 3D printing technology in personalized drug formulation and pharmacy practice.

RESULTS AND DISCUSSION

This section presents the findings obtained from the systematic literature review concerning the implementation of 3D printing technology in personalized drug formulation and pharmacy practice. The findings are systematically organized into several thematic discussions, including the PRISMA-based article selection process, trends in pharmaceutical 3D printing research, technological development in personalized drug formulation, transformation of pharmacy practice, clinical and therapeutic benefits, geographic distribution of studies, and the conceptual framework of pharmaceutical digitalization.

The reviewed studies indicate that pharmaceutical 3D printing has evolved from experimental laboratory research into an emerging innovation capable of transforming pharmaceutical manufacturing systems and patient-centered healthcare services. Furthermore, the literature demonstrates increasing integration between additive manufacturing, digital healthcare systems, artificial intelligence, and precision medicine paradigms.

PRISMA-Based Literature Selection Results

The systematic literature review process initially identified 327 articles from five major scientific databases, namely Scopus, PubMed, Web of Science, ScienceDirect, and SpringerLink. After duplicate removal, 273 articles remained for title and abstract screening. During the screening stage, 186 studies were excluded because they were unrelated to pharmaceutical applications, focused exclusively on engineering aspects without healthcare relevance, or lacked discussion regarding personalized medicine and pharmacy practice.

Subsequently, 87 full-text articles underwent eligibility assessment. After evaluating methodological quality and thematic relevance, 35 articles were excluded due to insufficient methodological clarity and limited relevance to pharmaceutical practice transformation. Ultimately, 52 peer-reviewed international journal articles were included in the final qualitative synthesis.

The PRISMA findings demonstrate that pharmaceutical 3D printing remains a rapidly growing but still relatively specialized research field. Most publications

emerged after 2020, reflecting increased global interest in digital pharmaceutical manufacturing and precision healthcare systems.

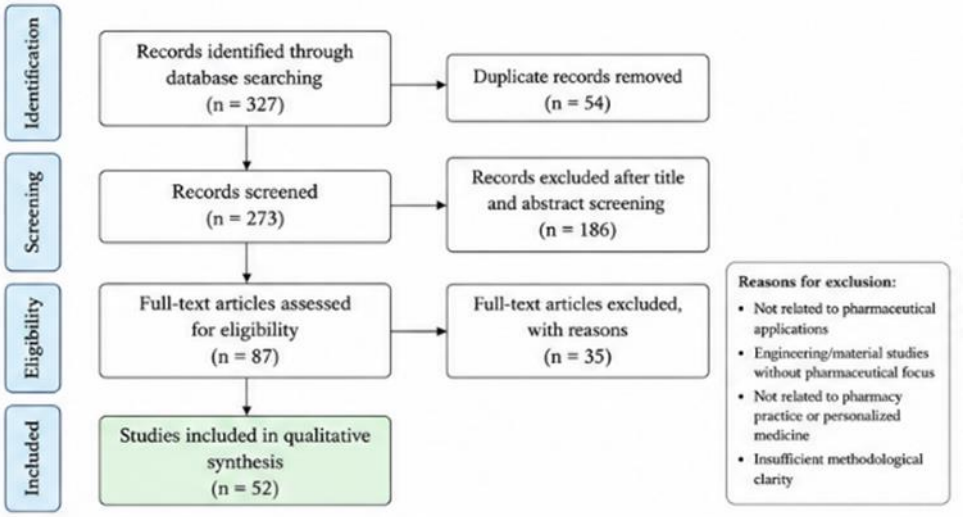

Figure 1. PRISMA Flow Diagram of Literature Selection

Source: Authors' systematic review process, 2026

The PRISMA findings indicate that pharmaceutical 3D printing remains a relatively specialized but rapidly expanding research field. Most publications emerged after 2019, suggesting increasing scientific and industrial interest in personalized medicine and digital pharmaceutical manufacturing.

Trends in Pharmaceutical 3D Printing Research

The reviewed studies reveal a significant increase in annual publications concerning pharmaceutical 3D printing technologies. Between 2015 and 2018, research publications primarily focused on experimental formulation techniques and proof-of-concept investigations. However, after 2020, publication growth accelerated substantially due to advancements in precision medicine, pharmacogenomics, and digital healthcare transformation.

The findings also indicate that recent studies increasingly explore interdisciplinary integration involving artificial intelligence, machine learning, computer-aided drug design, and decentralized pharmaceutical manufacturing systems. This trend reflects the transition of additive manufacturing from a purely engineering innovation into a broader healthcare transformation strategy.

Table 1. Annual Distribution of Reviewed Publications

Year	Number of Publications
2015–2016	4
2017–2018	7
2019–2020	11
2021–2022	14
2023–2026	16

Source: Synthesized from selected international journal articles, 2026

The literature also highlighted the importance of programmable drug release kinetics. Through multi-layered tablet structures, 3D printing enables medications to release active ingredients at specific intervals according to therapeutic needs. This capability supports chronotherapy approaches and improves disease management for chronic conditions such as hypertension and diabetes mellitus.

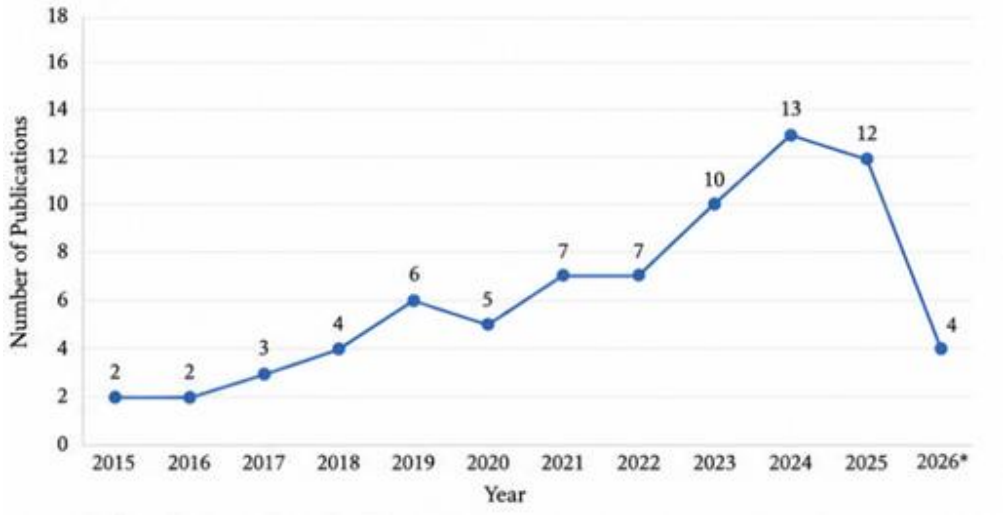

Figure 2. annual trend of publications of pharmaceutical 3D Printing

Source: Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink (2015-2026)

The increasing publication trend demonstrates that pharmaceutical additive manufacturing is becoming one of the most prominent emerging innovations within pharmaceutical sciences and healthcare systems.

Technological Development in Personalized Drug Formulation

The findings indicate that fused deposition modeling (FDM) is the most frequently utilized technology in pharmaceutical 3D printing applications. Among the 52 reviewed studies, 21 articles specifically examined FDM applications due to their affordability, flexibility, and accessibility for personalized oral drug formulation. Other technologies identified include stereolithography (SLA), selective laser sintering (SLS), and inkjet printing.

The reviewed literature consistently highlights that additive manufacturing enables highly customizable dosage forms involving tablet shape, size, release profile, and active pharmaceutical ingredient combinations. This capability significantly improves personalized therapeutic precision compared with conventional mass-manufacturing methods. Additionally, several studies emphasized the development of polypills containing multiple active ingredients within a single tablet. Such formulations are particularly beneficial for elderly patients experiencing polypharmacy conditions because they reduce medication burden and improve adherence.

Table 2. Distribution of Pharmaceutical 3D Printing Technologies

Technology	Number of Studies	Main Applications
Fused Deposition Modeling (FDM)	21	Personalized oral tablets
Stereolithography (SLA)	11	Controlled-release formulations
Selective Laser Sintering (SLS)	9	Porous dosage forms
Inkjet Printing	7	Pediatric formulations
Hybrid Technologies	4	Multi-layer drug systems

Source: Authors' synthesis from reviewed studies, 2026

The findings further demonstrate that additive manufacturing technologies achieve dosage accuracy exceeding 95% in several experimental studies, indicating

substantial potential for clinical implementation within personalized medicine systems.

Transformation of Pharmacy Practice

Another important finding concerns the transformation of pharmacy practice resulting from the integration of additive manufacturing technologies. The reviewed literature suggests that pharmacists are increasingly transitioning from traditional medication dispensers toward digital pharmaceutical designers and personalized therapy consultants. The studies indicate that decentralized pharmaceutical manufacturing models are gradually emerging within hospital and clinical pharmacy settings. In these systems, medications can potentially be produced directly at healthcare facilities according to patient-specific therapeutic requirements. This model improves dosage flexibility, reduces medication shortages, and supports patient-centered pharmaceutical care. Moreover, the findings reveal that future pharmacists require interdisciplinary competencies involving computer-aided design (CAD), pharmaceutical engineering, pharmacogenomics, and artificial intelligence-assisted decision systems.

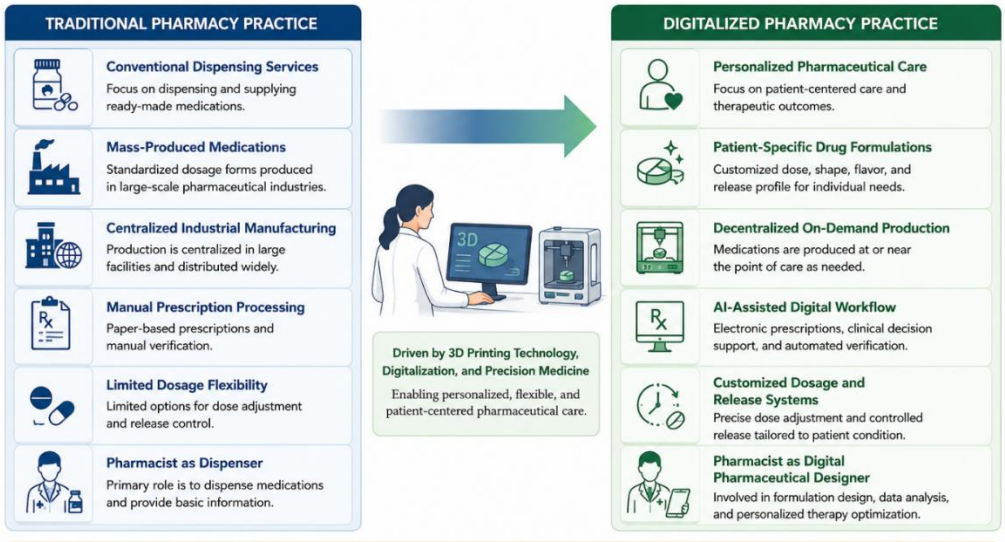

Figure 2. Evolution of Pharmacy Practice in the Digital Manufacturing Era

Source: Authors' conceptual synthesis based on reviewed literature (2015–2026)

The literature also indicates that digital pharmaceutical transformation contributes to greater patient involvement in therapeutic decision-making and enhances collaborative healthcare practices among pharmacists, physicians, and biomedical engineers.

Clinical and Therapeutic Benefits

The reviewed studies consistently identified significant therapeutic advantages associated with personalized 3D-printed medicines. Among the 52 studies, 34 articles highlighted improved medication adherence as one of the primary clinical benefits. Personalized tablet size, shape, dosage, and flavor were found to improve treatment acceptance among pediatric and geriatric patients. Several studies also demonstrated that customized formulations may reduce adverse drug reactions through more precise dosage adjustments according to patient-specific metabolic and genetic characteristics. This capability strongly supports pharmacogenomics-based precision medicine approaches.

Table 4. Therapeutic Benefits of 3D-Printed Medicines

Therapeutic Benefit	Frequency in Studies	Main Findings
Improved medication adherence	34	Better patient acceptance
Personalized dosage accuracy	29	Reduced dosing variability
Controlled drug release	23	Enhanced therapeutic outcomes
Reduced polypharmacy burden	18	Multi-drug integration
Precision medicine support	16	Genomics-based therapy

Source: Synthesized from reviewed international studies, 2026

Several empirical studies reported medication adherence improvements ranging from 25% to 40% among geriatric patients using customized dosage forms. Pediatric studies similarly demonstrated increased treatment acceptance due to customizable tablet flavors and appearances.The findings also reveal that programmable drug-release systems enable medications to release active ingredients according to therapeutic schedules and disease progression patterns. This innovation supports chronotherapy approaches for chronic diseases such as hypertension and diabetes mellitus.

Geographic Distribution of Reviewed Studies

The geographic analysis demonstrates that pharmaceutical 3D printing research is concentrated predominantly in North America and Europe. Among the reviewed studies, 50% originated from North America, followed by Europe (25%), Asia (17.3%), and Australia (5.7%). The dominance of developed countries reflects stronger technological infrastructure, greater research funding, and more advanced pharmaceutical innovation ecosystems. However, recent studies from Asian countries indicate growing regional interest in personalized medicine and digital pharmaceutical manufacturing technologies.

Table 5. Geographic Distribution of Reviewed Studies

Region	Number of Studies	Percentage
North America	26	50.0%
Europe	13	25.0%
Asia	9	17.3%
Australia	3	5.7%
Other Regions	1	2.0%

Source: Authors' analysis of selected studies, 2026

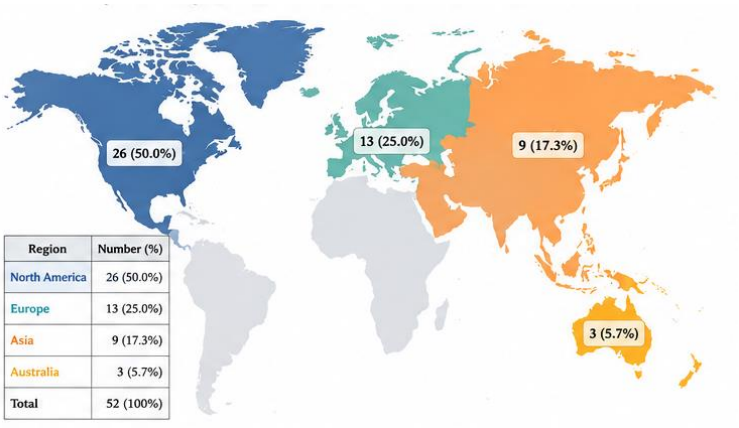

Figure 4. Geographic Distribution of Reviewed Studies

Source: Authors' analysis of selected studies, 2026

The findings suggest that future expansion of pharmaceutical additive manufacturing may increasingly involve developing countries as digital healthcare infrastructure continues to improve globally.

Conceptual Framework of Pharmaceutical Digitalization

The final findings concern the conceptual integration between 3D printing technology, digital healthcare systems, and pharmacy practice transformation. The reviewed literature indicates that pharmaceutical additive manufacturing increasingly converges with artificial intelligence, pharmacogenomics, machine learning, and electronic health record systems. This integration supports the development of "smart pharmacies" capable of producing personalized medications automatically according to patient-specific clinical data. The conceptual framework also demonstrates the relationship between technological inputs, manufacturing processes, therapeutic outputs, and pharmacy practice outcomes.

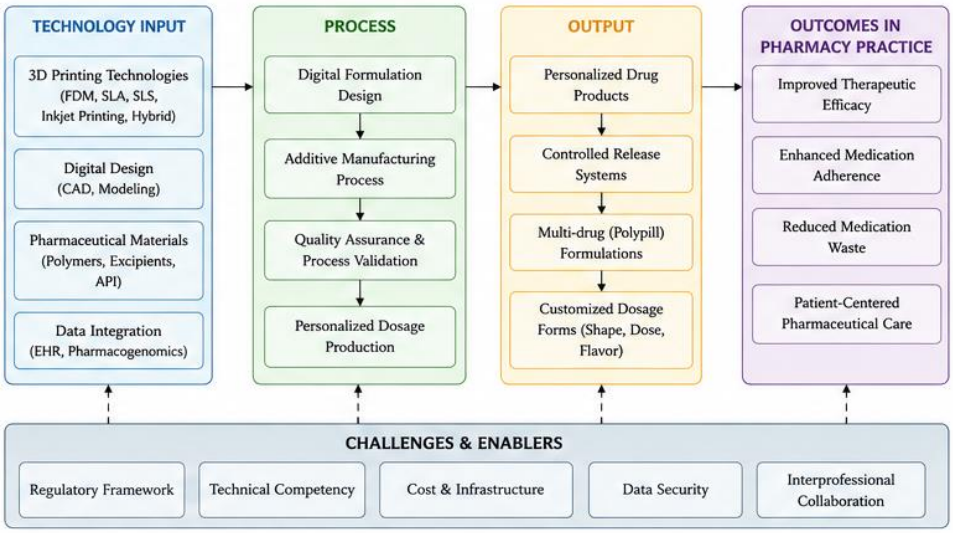

Figure 5. Conceptual Framework: 3D Printing in Personalized Drug Formulation and Pharmacy Practice

Source: Authors' analysis of selected studies, 2026

The findings demonstrate that 3D printing technology possesses transformative potential for personalized medicine and digital pharmacy practice. Nevertheless, successful implementation depends on regulatory adaptation, healthcare infrastructure readiness, technological standardization, and the development of interdisciplinary pharmaceutical competencies.

Digital Transformation of Pharmaceutical Care Through 3D Printing Technology

The findings of this study demonstrate that 3D printing technology represents a transformative innovation capable of reshaping pharmaceutical manufacturing systems, personalized medicine, and pharmacy practice. Unlike conventional pharmaceutical production models that rely on centralized mass manufacturing and standardized dosage forms, additive manufacturing introduces a decentralized and patient-centered approach that aligns closely with the principles of precision medicine. The reviewed literature consistently indicates that pharmaceutical 3D printing enhances dosage flexibility, improves medication adherence, and supports individualized therapeutic strategies. These findings confirm previous studies by Zhang et al. (2018) and Muhindo et al. (2023) and Bernatoniene et al. (2025) which

emphasized that additive manufacturing technologies possess substantial potential to revolutionize oral dosage formulation and personalized healthcare delivery.

One of the most important findings concerns the increasing role of personalized drug formulation within modern pharmaceutical systems. The reviewed studies revealed that technologies such as fused deposition modeling (FDM), stereolithography (SLA), and selective laser sintering (SLS) enable precise adjustment of dosage strength, release kinetics, tablet geometry, and multi-drug integration. This finding is consistent with the work of Gioumouxouzis et al. (2019) and Patel et al. (2024) who argued that additive manufacturing facilitates the development of patient-specific dosage forms that are difficult to achieve through traditional pharmaceutical manufacturing methods. Similarly, Tegegne et al. (2024) reported that 3D-printed medicines improve formulation adaptability for pediatric and geriatric populations requiring individualized therapeutic regimens.

The present study extends previous literature by demonstrating that pharmaceutical 3D printing should not merely be viewed as a technological innovation in drug manufacturing but also as a broader transformation of healthcare delivery systems. Most earlier studies focused heavily on engineering and formulation aspects, while limited attention was given to the implications for pharmacy practice, healthcare governance, and professional transformation. The novelty of this study lies in its integrative perspective, connecting additive manufacturing technologies with digital pharmacy transformation, pharmacist competency development, and precision medicine implementation. Consequently, this research contributes theoretically by expanding the conceptual understanding of pharmaceutical innovation beyond technical manufacturing capabilities toward healthcare system integration.

Another significant finding relates to the transformation of pharmacy practice in the digital healthcare era. The reviewed literature indicates that pharmacists are gradually transitioning from traditional medication dispensers toward digital pharmaceutical designers and therapeutic consultants. This finding supports previous arguments proposed by Barar et al. (2026) who suggested that pharmacists will increasingly require expertise in digital manufacturing systems, computer-aided design (CAD), and pharmaceutical engineering. Similarly, recent studies on digital health transformation have highlighted the growing importance of interdisciplinary competencies among healthcare professionals in managing precision medicine systems.

This study identifies a stronger relationship between pharmaceutical digitalization and decentralized healthcare services than previous research has acknowledged. The findings suggest that hospital and clinical pharmacies may eventually become localized pharmaceutical manufacturing hubs capable of producing personalized medicines on demand. Such a transformation may significantly reduce medication shortages, improve accessibility to specialized therapies, and enhance patient-centered care delivery. In contrast to centralized industrial manufacturing systems, decentralized pharmaceutical production allows medications to be tailored according to real-time patient conditions and therapeutic responses.

This transformation also carries important practical implications for pharmacy education and professional training systems. Existing pharmacy curricula in many countries remain dominated by conventional pharmaceutical sciences and dispensing-oriented competencies. However, the emergence of digital pharmaceutical manufacturing requires pharmacists to understand additive manufacturing technologies, artificial intelligence integration, pharmacogenomics, and data-driven therapeutic systems. Therefore, universities and professional institutions must redesign pharmacy education frameworks to prepare future professionals for technology-intensive healthcare environments. This implication is particularly

important because technological readiness alone is insufficient without corresponding human resource adaptation.

The findings further reveal that pharmaceutical 3D printing significantly contributes to improved medication adherence and therapeutic precision. Several reviewed studies reported measurable increases in patient compliance among pediatric and geriatric populations due to customizable tablet size, flavor, shape, and dosage flexibility. These findings align with previous studies conducted by Hauber et al. (2024) which demonstrated that personalized dosage forms positively influence patient acceptance and treatment continuity. Moreover, programmable drug-release systems identified in the reviewed studies support chronotherapy approaches by enabling medications to release active ingredients according to biological rhythms and disease progression patterns.

Despite these advantages, the study also confirms that regulatory uncertainty remains one of the most substantial barriers to implementation. Existing pharmaceutical regulatory frameworks are primarily designed for mass-manufactured medicines rather than decentralized personalized production systems. This finding is consistent with previous discussions by the U.S. Food and Drug Administration (FDA) and European Medicines Agency (EMA), both of which acknowledge the complexity of regulating additive manufacturing technologies in pharmaceutical settings. Several reviewed studies emphasized unresolved issues related to quality assurance, dosage reproducibility, process validation, and product stability testing.

But this study adds to the understanding by stressing the need not only for pharmaceutical manufacturing standards to be adopted to the regulation, but for cybersecurity governance and digital infrastructure protection as well. Because additive manufacturing systems are dependent on digital design files, cloud storage and automated production software, there can be vulnerabilities that relate to data manipulation and unauthorized access that may directly impact medication safety. Cybersecurity threats were not covered in depth in the pharmaceutical additive manufacturing discussions of previous research. Thus, this study broadens the regulatory discourse by incorporating digital aspects of pharmaceutical innovation governance.

The other significant debate is related to the unequal technological readiness across the globe as noted in the literature. As shown in the geographic distribution of studies, research on pharmaceutical 3D printing has been mainly restricted to North America and Europe, indicating that pharmaceutical 3D printing technology is better supported and has a higher level of technological infrastructure, research funding and industrial support in developed countries. While there has been growing research activity in Asian countries, there are financial limitations, less digital infrastructure, and less professional competence in developing countries, resulting in relatively low implementation capacity. This finding echoes the inequalities in global healthcare innovation systems, and the need for international cooperation in the pharmaceutical technology transfer.

On a theoretical level, this study builds upon the existing body of work on digital healthcare transformation, which combines insights from the pharmaceutical sciences, precision medicine and healthcare innovation management. The previous studies of pharmaceutical 3D printing mostly examined the subject from a disciplinary viewpoint (such as pharmaceutical engineering or formulation science). This study, however, introduces a multidimensional analytical framework that links additive manufacturing technologies to the transformation of the pharmacy practice, digital healthcare ecosystems and patient-centred therapeutic models. This integrative view reinforces the theoretical underpinning of pharmaceutical

digitalization as a systemic change in healthcare, instead of just a manufacturing innovation.

This study also has significant practical implications. The findings underscore for the policymaker the need for establishing flexible regulatory systems that can adapt to decentralized pharmaceutical production systems. The regulatory bodies have to provide uniform guidelines on quality assurance, process validation, dosage uniformity, and cybersecurity measures in pharmaceutical additive manufacturing settings. The study highlights the need of healthcare institutions to invest in digital infrastructure and training of the multi-disciplinary team for future personalized healthcare systems. For pharmaceutical industries, additive manufacturing can be an opportunity to create a more flexible and sustainable approach to product manufacturing with the ability to quickly scale up for and adapt to patient-specific therapeutic needs.

An important implication of the study is for sustainable healthcare systems. Multiple studies cited showed that by creating pharmaceuticals according to precise patient demand instead of mass-producing, additive manufacturing can help to lower pharmaceutical wastes. Furthermore, the local production systems can help minimize transport-related environmental footprint of centralised pharmaceutical distribution systems. The findings contribute to the sustainability debates in the fields of healthcare innovations and mark the contribution of 3D printing in the pharmaceutical industry towards an environmentally responsible transformation of healthcare practices.

Despite its contributions, this study has several limitations. First, the research relied exclusively on secondary data obtained from published international journal articles. Consequently, the findings may not fully capture emerging industrial practices and unpublished technological developments occurring within pharmaceutical companies or healthcare institutions. Second, the systematic review focused primarily on English-language publications, potentially limiting representation from non-English-speaking countries. Third, because pharmaceutical 3D printing remains an evolving field, some reviewed studies were still experimental and lacked long-term clinical implementation evidence. Therefore, the practical feasibility of large-scale adoption remains uncertain in some healthcare contexts.

Future research should therefore focus on empirical investigations involving real-world implementation of pharmaceutical additive manufacturing within hospital and community pharmacy settings. Comparative studies examining regulatory readiness across countries would also provide valuable insights into international policy adaptation strategies. Furthermore, future studies should explore the integration of artificial intelligence, pharmacogenomics, blockchain systems, and Internet of Things (IoT)-based healthcare infrastructures within pharmaceutical 3D printing ecosystems. Research examining patient perceptions, ethical concerns, and economic feasibility will also be essential for understanding broader societal acceptance of personalized medicine technologies.

CONCLUSION

The results of this study point to the significant promise of 3D printing technology in the realm of personalized medicine, specifically personalized drug formulation and pharmacy practice, in the context of digital healthcare and precision medicine. The results show that additively manufactured technologies enhance dosage flexibility, controlled drug release, medication adherence, and patient-centered drug care. Moreover, 3D printing in the pharmaceutical industry is helping to redefine the role of a pharmacist from a traditional medicine dispenser to a digital pharmaceutical designer, and a partner in precision therapy.

This study is theoretically important to the pharmaceutical innovation literature by incorporating three different perspectives of technology, clinical, and healthcare systems in a multidimensional approach of pharmaceutical digitalization. The results highlight, practically, the need to adapt the regulation, develop inter-disciplinary competencies and prepare digital infrastructure for the implementation of decentralized pharmaceutical manufacturing systems. But the study is constrained due to its use of secondary information and the dynamic nature of research in pharmaceutical additive manufacturing. The majority of the reviewed studies continue to be experimental and were only conducted in developed countries, and hence may not be generalized to the wider population. Empirical implementation studies, economic feasibility analysis, patients' acceptance of the medication, and the integration of AI, pharmacogenomics, and smart healthcare systems into pharmaceutical 3D printing ecosystems are thus strongly suggested as topics for future research to gain insight into the impacts on the longer term.

REFERENCES

Ahmed, R., & Tamim, T. R. (2025). Enhancing medication safety: the role of community and hospital pharmacists in modern healthcare systems. *Radinka Journal of Health Science*, *2*(3), 328-355. https://doi.org/10.56778/rjhs.v2i3.418

Algorri, M., Abernathy, M. J., Cauchon, N. S., Christian, T. R., Lamm, C. F., & Moore, C. M. (2022). Re-envisioning pharmaceutical manufacturing: increasing agility for global patient access. *Journal of Pharmaceutical Sciences*, *111*(3), 593-607. https://doi.org/10.1016/j.xphs.2021.08.032

Alhozim, B. M. A., Almutairi, E. T., Albutyan, Z. Y., Alzahrani, N. A., Alonizy, M. M., Albutyan, L. Y., ... & ZALAH, F. A. B. (2024). The impact of polypharmacy on drug efficacy and safety in geriatric populations. *Egyptian Journal of Chemistry*, *67*(13), 1533-1540. https://doi.org/10.21608/ejchem.2024.337875.10834

Ali Alasmari, A. F., Alqahtani, M. A., Abdullah, A. M., Nasir, M. A., & Almalki, A. H. (2024). Collaborative dynamics between nursing and pharmacists: Enhancing patient care through interdisciplinary practices. *Modern Phytomorphology*, *18*(6).

Almusaed, A., Almssad, A., & Yitmen, I. (2025). Identifying Research Gaps. In *Practice of Research Methodology in Civil Engineering and Architecture: A Comprehensive Guide* (pp. 35-66). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-97393-2_2

Al-Worafi, Y. M. (2023). Medicine availability and affordability in developing countries. In *Handbook of Medical and Health Sciences in Developing Countries: Education, Practice, and Research* (pp. 1-29). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-74786-2_229-1

Alzoubi, L., Aljabali, A. A., & Tambuwala, M. M. (2023). Empowering precision medicine: the impact of 3D printing on personalized therapeutic. *Aaps Pharmscitech*, *24*(8), 228. https://doi.org/10.1208/s12249-023-02682-w

Andreadis, I. I., Gioumouxouzis, C. I., Eleftheriadis, G. K., & Fatouros, D. G. (2022). The advent of a new era in digital healthcare: a role for 3D printing technologies in drug manufacturing?. *Pharmaceutics*, *14*(3), 609. https://doi.org/10.3390/pharmaceutics14030609

Balogun, O. D., Ayo-Farai, O., Ogundairo, O., Maduka, C. P., Okongwu, C. C., Babarinde, A. O., & Sodamade, O. T. (2023). Innovations in drug delivery

systems: A review of the pharmacist's role in enhancing efficacy and patient compliance. *World Journal of Advanced Research and Reviews*, *20*(3), 1268-1282. https://doi.org/10.30574/wjarr.2023.20.3.2587

Barar, J., Seamon, M., & Omidi, Y. (2026). The emergence of advanced technologies in the pharmacy profession and the need for education: The case of point-of-care sensing systems and 3D printing of pharmaceuticals. *BioImpacts*, *16*(1), 31081-31081. https://doi.org/10.34172/bi.31081

Barar, J., Seamon, M., & Omidi, Y. (2026). The emergence of advanced technologies in the pharmacy profession and the need for education: The case of point-of-care sensing systems and 3D printing of pharmaceuticals. *BioImpacts*, *16*(1), 31081-31081. https://doi.org/10.34172/bi.31081

Beridze, T., & Lomidze, G. (2025). The Strategic Application of Data Analytics in Developing Smarter Healthcare Systems: Enhancing Diagnostic Precision and Personalized Treatment Pathways. *International Journal of Advanced Computational Methodologies and Emerging Technologies*, *15*(5), 1-10.

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

Borthakur, P. P., Das, A., Sahariah, J. J., Pramanik, P., Baruah, E., & Pathak, K. (2026). Revolutionizing patient care: 3D printing for customized medical devices and therapeutics. *Biomedical Materials & Devices*, *4*(2), 1275-1302. https://doi.org/10.1007/s44174-025-00324-2

Comoglu, T., & Ozyilmaz, E. D. (2025). Pharmaceutical excipients in pediatric and geriatric drug formulations: safety, efficacy, and regulatory perspectives. *Pharmaceutical Development and Technology*, *30*(1), 1-9. https://doi.org/10.1080/10837450.2024.2441181

Diaz, R. R., Satheesh, G., Moran, A. E., Perel, P., Rodgers, A., & Schutte, A. E. (2026). Delivery models to improve adherence to medicines for chronic diseases in primary care. *The Lancet Primary Care*, *2*(1).

Gatt, E., Bartolo, N. S., & Azzopardi, L. A. (2026). systematic review of 3D Printing of pharmaceutical drug products: Barriers and Enablers. *Available at SSRN 6571428*. http://dx.doi.org/10.2139/ssrn.6571428

Geraghty, M., Malandrini, F., Callea, G., McDonnell, A., Martelli, N., Tangila Kayembe, O., ... & Melvin, T. (2026). Regulatory readiness for innovation: a mixed-methods study of national competent authority professional and organizational capacities in the context of pre-market clinical investigations and early feasibility studies. *Expert Review of Medical Devices*, (just-accepted). https://doi.org/10.1080/17434440.2025.2594460

Gioumouxouzis, C. I., Karavasili, C., & Fatouros, D. G. (2019). Recent advances in pharmaceutical dosage forms and devices using additive manufacturing technologies. *Drug discovery today*, *24*(2), 636-643. https://doi.org/10.1016/j.drudis.2018.11.019

Hauber, B., Hand, M. V., Hancock, B. C., Zarrella, J., Harding, L., Ogden-Barker, M., ... & Watt, S. J. (2024). Patient acceptability and preferences for solid oral dosage form drug product attributes: a scoping review. *Patient preference and adherence*, 1281-1297. https://doi.org/10.2147/ppa.s443213

Huanbutta, K., Burapapadh, K., Sriamornsak, P., & Sangnim, T. (2023). Practical

application of 3D printing for pharmaceuticals in hospitals and pharmacies. *Pharmaceutics*, *15*(7), 1877. https://doi.org/10.3390/pharmaceutics15071877

Ilan, Y. (2022). Next-generation personalized medicine: implementation of variability patterns for overcoming drug resistance in chronic diseases. *Journal of Personalized Medicine*, *12*(8), 1303. https://doi.org/10.3390/jpm12081303

Johannesson, J., Hansson, P., Bergström, C. A., & Paulsson, M. (2022). Manipulations and age-appropriateness of oral medications in pediatric oncology patients in Sweden: Need for personalized dosage forms. *Biomedicine & Pharmacotherapy*, *146*, 112576. https://doi.org/10.1016/j.biopha.2021.112576

Karvannan, R. (2025). Advancing Hospital Pharmacy Automation: Impacts, Challenges, and Future Innovations in AI-Driven Medication Management. *International Journal of Advanced Research in Computer Science & Technology (IJARCST)*, *8*(3), 12207-12216. https://doi.org/10.15662/IJARCST.2025.0803010

Kumar Gupta, D., Ali, M. H., Ali, A., Jain, P., Anwer, M. K., Iqbal, Z., & Mirza, M. A. (2022). 3D printing technology in healthcare: applications, regulatory understanding, IP repository and clinical trial status. *Journal of Drug Targeting*, *30*(2), 131-150. https://doi.org/10.1080/1061186x.2021.1935973

Kurien, R. A., Kannan, G., Thanawut, K., Suttiruengwong, S., & Sriamornsak, P. (2025). Building the next frontier: Artificial intelligence in 3D-printed medicines. *Biomaterials Translational*, *7*(1), 55. https://doi.org/10.12336/bmt.25.00043

Li, C., Jiang, W., Shen, A., Li, Y., Wu, J., Tao, H., ... & Zhao, Z. (2025). International expert consensus on hospital intelligent pharmacy. *Intelligent Pharmacy*. https://doi.org/10.1016/j.ipha.2025.06.001

Malheiro, V., Duarte, J., Veiga, F., & Mascarenhas-Melo, F. (2023). Exploiting pharma 4.0 technologies in the non-biological complex drugs manufacturing: innovations and implications. *Pharmaceutics*, *15*(11), 2545. https://doi.org/10.3390/pharmaceutics15112545

Muhindo, D., Elkanayati, R., Srinivasan, P., Repka, M. A., & Ashour, E. A. (2023). Recent advances in the applications of additive manufacturing (3D printing) in drug delivery: a comprehensive review. *Aaps Pharmscitech*, *24*(2), 57. https://doi.org/10.1208/s12249-023-02524-9

Navaei, O. (2025). Personalized medicine: tailoring treatment plans based on genetic profile. *Eurasian Journal of Chemical, Medicinal and Petroleum Research*, *4*(2), 129-151.

Niazi, S. K. (2025). Continuous manufacturing of recombinant drugs: comprehensive analysis of cost reduction strategies, regulatory pathways, and global implementation. *Pharmaceuticals*, *18*(8), 1157. https://doi.org/10.3390/ph18081157

Pandey, A., & Gupta, S. P. (2024). Personalized Medicine:(A Comprehensive Review). *Oriental Journal Of Chemistry*, *40*(4). https://dx.doi.org/10.13005/ojc/400403

Patel, H., Raje, V., Maczko, P., & Patel, K. (2024). Application of 3D printing technology for the development of dose adjustable geriatric and pediatric formulation of celecoxib. *International Journal of Pharmaceutics*, *655*,

123941. https://doi.org/10.1016/j.ijpharm.2024.123941

Pethappachetty, P., Kumar, B., Govindaraj, A., Prakash, M., Kumari, B. V., Venkatesan, K. B., & Srinivasan, M. K. (2025). 3D Printing in Personalized Medicine: Revolutionizing Drug Delivery and Healthcare Applications. *Biomedical Materials & Devices*, 1-22.

Prajapati, B., Malviya, R., Patel, R. J., & Sundram, S. (Eds.). (2026). *Personalized Medication for Pediatric and Geriatric Patients*. CRC Press.

Salvador-Carulla, L., Woods, C., de Miquel, C., & Lukersmith, S. (2024). Adaptation of the technology readiness levels for impact assessment in implementation sciences: The TRL-IS checklist. *Heliyon*, *10*(9). https://doi.org/10.1016/j.heliyon.2024.e29930

Serrano, D. R., Kara, A., Yuste, I., Luciano, F. C., Ongoren, B., Anaya, B. J., ... & Lalatsa, A. (2023). 3D printing technologies in personalized medicine, nanomedicines, and biopharmaceuticals. *Pharmaceutics*, *15*(2), 313. https://doi.org/10.3390/pharmaceutics15020313

Tegegne, A. M., Ayenew, K. D., & Selam, M. N. (2024). Review on Recent Advance of 3DP-Based Pediatric Drug Formulations. *BioMed Research International*, *2024*(1), 4875984. https://doi.org/10.1155/2024/4875984

Wang, S., Chen, X., Han, X., Hong, X., Li, X., Zhang, H., ... & 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

Zhang, J., Vo, A. Q., Feng, X., Bandari, S., & Repka, M. A. (2018). Pharmaceutical additive manufacturing: a novel tool for complex and personalized drug delivery systems. *AAPS PharmSciTech*, *19*(8), 3388-3402. https://doi.org/10.1208/s12249-018-1097-x