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Review

Pharmaceutical 3D printing in Africa: A scoping review of trends, challenges, and implications for future adoption

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Pharmaceutical 3D Printing in Africa: Trends, Challenges, and Implications for Future Adoption

Abstract

Pharmaceutical 3D printing (3DP) is transforming global medicine manufacturing, enabling personalised therapies and fabrication of patient-friendly formulations. However, there is uneven adoption of this innovation across different regions. This scoping review evaluates pharmaceutical 3DP research in the low-and middle-income countries (LMICs), with particular focus on Africa, assessing progress, gaps, and challenges against global trends. The systematic search of literature generated a total of 205 studies, and six eligible studies were included for the review. Only 2 out of the 54 African countries produced the 6 studies, representing 3.7% of the continent. Four studies were conducted at three universities in Egypt, and two studies were conducted at one university in South Africa. The 3DP technologies explored from the continent were limited to Semi-solid extrusion, Fused deposition modelling, and Liquid crystal display, and 50% of the studies received no dedicated funding. Findings demonstrate a vast research-to-implementation gap on pharmaceutical 3D printing in Africa. There was no study on its clinical implementation to treat patients from the continent despite its dire need for digital health innovations to provide personalised treatments and mitigate healthcare emergencies. Enhanced funding, strategic global collaborations, and the development of regional policies through bodies such as the African Medicine Agency (AMA), the Africa Centre for Disease Control and Prevention (Africa CDC), and the African Union (AU) are crucial for supporting local healthcare innovations and building a resilient medicine supply chain, which is essential for the future adoption of the technology in Africa.

Keywords: Pharmaceutical three-dimensional printing in Africa, additive manufacturing of drug formulations, African Medicine Agency, personalised medications, printed pharmaceuticals, customised drug delivery systems and medicinal products, point-of-care manufacturing

Highlights

- Africa contributes minimally to global pharmaceutical 3D printing research, with activity confined to just 2 of its 54 countries, with only 6 original research studies from the continent.
- Despite its potential in personalised medicine and enhanced medicine supply chain resilience, no single study from Africa has advanced pharmaceutical 3D printing to clinical implementation for patient treatment at the point of care.
- Future adoption hinges on Pan-African funding, regulatory initiatives by the African Medicine Agency, and strategic global partnerships

1. Introduction

Pharmaceutical 3D printing (3DP) is a disruptive additive manufacturing process that creates customisable drug delivery systems in a layer-by-layer style to form 3D dosage forms from computer-aided design (CAD) models (Bendicho-Lavilla et al., 2024; Musazzi et al., 2018; Oh et al., 2025; Rodríguez-Pombo et al., 2024; Tracy et al., 2023). 3DP allows for precise, rapid, automated and flexible fabrication of different types of dosage forms such as hard tablets (Saydam and Takka, 2020), chewable tablets and/or gummies (Ganatra et al., 2024; Rodríguez-Pombo et al., 2024), dispersible tablets (Allahham et al., 2020), orodispersible films (Khalid et al., 2021; Musazzi et al., 2018; Selmin et al., 2021), mutable drug delivery systems (Oh et al., 2025), personalised rectal suppositories (Awad et al., 2023), among other innovative next-generation drug delivery systems. With pharmaceutical 3DP, most of these drug delivery platforms can be fabricated with customisable doses, shapes, drug release, and different formulation compositions (Dumpa et al., 2021; Kottlan et al., 2023; Raijada et al., 2021; Rodríguez-Maciñeiras et al., 2025; Deng et al., 2025). Moreover, pharmaceutical additive manufacturing has been proven to be a promising innovation for automated, rapid prototyping workflows, particularly for solid dosage forms such as tablets, tailored to individual patient needs, especially on demand at the point-of-care (PoC) (Denis et al., 2024; Oh et al., 2025; Ong et al., 2025).

There are several 3DP technologies in the pharmaceutical world for dosage form fabrication. Each technology possesses unique features utilising different feedstock materials that define their capabilities and potential applications in a specific setting (Gültekin et al., 2021). More suited to smaller batch manufacturing with rapid turnaround times, material extrusion 3DP involves the continuous flow of material via a nozzle and the deposition of material in a layer-by-layer arrangement to build a 3D dosage form. In most cases, this process relies on the thermo-plasticity of the polymer filament, which allows it to fuse while printing at elevated temperatures and harden at room temperature thereafter (Falcone et al., 2022; Jamróz et al., 2020, 2018a; Siddique et al., 2022). However, other 3DP technologies, such as inkjet and/or semi-solid extrusion (SSE), can extrude and print soft materials, also referred to as pharma-ink (mixture of drug and excipients) at room temperature, depending on the rheological properties of the pharma-ink (Falcone et al., 2022; Ganatra et al., 2024; Seoane-Viaño et al., 2021).

Historically, the concept of pharmaceutical 3DP can be traced back to additive manufacturing innovations in the 1980s, with its pharmaceutical application taking a major leap in 2015 when the U.S. Food and Drug Administration (FDA) approved the first 3D-printed drug, Spritam®, which contains levetiracetam as the main active pharmaceutical ingredient (API) (Goyanes et al., 2015). Developed by Aprecia Pharmaceuticals, Spritam uses ZipDose® technology to produce rapidly disintegrating tablets for the treatment of epilepsy (Auel et al., 2025; Mohammed et al., 2021).

Following the landmark success of ZipDose® 3DP technology, which uses a mass manufacturing approach, over the last decade, attention has been shifted toward decentralised, on-demand development of personalised 3D printed dosage forms to enhance medication adherence based on individual patients' unique therapeutic needs, tailoring dosages, which is especially beneficial in geriatric and paediatric patients, and rare diseases (Khalid et al., 2021; Mora-Castaño et al., 2025; Musazzi et al., 2018; Rodríguez-Pombo et al., 2024). Consequently, interest in clinical implementation of pharmaceutical 3DP has grown steadily, with regulatory bodies beginning to develop frameworks for broader adoption of the technology at the PoC. For instance, the United States Food and Drug Administration (FDA), European Medicines Agency (EMA) (European Medicine Agency, 2024; Pettersson et al., 2024), and the United Kingdom Medicines and Healthcare products Regulatory Agency (MHRA), have been engaging with experts in the field on advancing frameworks for decentralised manufacturing of medicines at the PoC to ensure suitable quality control of such products before they can be administered to patients (Jørgensen et al., 2025a). Therefore, the technology is fast advancing from incubation and exploration in the laboratories to the bedsides, exemplified by several clinical studies that administered the 3D printed medicines to patients (children) in Spain (Goyanes et al., 2019; Rodríguez-Maciñeiras et al., 2025; Rodríguez-Pombo et al., 2024), and China (Liu et al., 2023; Lv et al., 2025) in hospital settings. Moreover, our recent study also demonstrates, for the first time, the clinical application of

pharmaceutical 3D printing in a community pharmacy for personalised treatment of adult patients where available medicinal products do not meet their needs (Rodríguez-Maciñeiras et al., 2025).

Beyond applications in our world, pharmaceutical 3DP is so futuristic that NASA is considering the technology to print personalised medicines on demand for astronauts in space during long-duration space missions. This approach will ensure drug stability, reduce space requirements aboard, and enhance medicine sufficiency and safety for NASA's deep-space exploration missions (NASA, 2024; Jørgensen et al, 2025b; Seoane-Viaño et al., 2022).

Despite these enormous global advancements in pharmaceutical 3DP, in terms of basic research, R&D, and clinical implementation at PoC, published literature is scarce on research involving pharmaceutical 3DP in Africa, either from academia or research institutes on the continent. While global patent growth and investment in pharmaceutical 3DP manufacturing have surged, African applications of additive manufacturing remain largely limited to prosthetics, diagnostics, and medical devices (Alzhrani et al., 2024a).

Africa is the second-largest and second-most populous continent in the world, with over 1.4 billion people across 54 countries. It is rich in cultural diversity, languages, and traditions. Africa has vast natural resources, including gold, diamonds, oil, and fertile land (African Development Bank Group, 2025), making it one of the most resource-rich regions globally. Despite its richness, many African countries are listed among the low- and middle-income countries (LMICs) and some classified as low-income economies. Thus, many African countries face challenges like underdeveloped infrastructure, including poor healthcare infrastructure (Kobiane et al., 2024; Oleribe et al., 2019). With its potential to enhance healthcare resilience in emergencies situations such as, epidemics, pandemics, natural disasters, and the effects of climate change that could disrupt the medicine supply chain in the region, pharmaceutical 3DP in Africa is a promising solution for sustainable and eco-friendly medicine manufacturing that can be easily deployed to hard-to-reach and resource-limited healthcare facilities to manufacture small batches of medicines on-demand for personalised treatments (Van der Veen et al., 2025). This way, it is easy to use as a decentralised manufacturing platform (Beitler et al., 2022; Parramon-Teixido et al., 2025) to mitigate medicine supply chain hurdles, as seen to significantly affect the continent during the COVID-19 pandemic, due to reliance on the importation of medicines from other continents (Ejekam et al., 2023; Kamara and Essien, 2022).

Therefore, this review aims to identify, analyse and document original research on pharmaceutical 3DP in Africa to understand trends, gaps or challenges in the practical exploration of this innovation among African universities and research institutions. To the best of our knowledge, this is the first study to investigate trends in original research specifically on pharmaceutical 3DP in Africa. The outcomes of this review are expected to stimulate further research and investment in this field to nurture growth in disruptive digital health, high-quality healthcare, and pharmaceutical product development across Africa. Thus, the study recommends strategies to engage academics, pharmacists, clinicians, intergovernmental agencies, regional medicine regulatory agencies, the newly inaugurated unified medicine and allied healthcare products regulatory body in Africa, i.e., the African Medicine Agency (AMA), and private pharmaceutical industries on the continent to take bold steps and concerted actions toward exploring the potential of this technology to revolutionise drug development and medicine security on the continent.

2. Methods

2.1 Literature Search

A systematic search of the literature on pharmaceutical 3DP was conducted using PubMed, Scopus, Web of Science, and Google Scholar. To cover as wide publications as possible on the topic, we did not restrict the search to a specific duration. A search strategy was developed to include only research

articles on pharmaceutical 3DP conducted only within Africa. Information was retrieved using the following Boolean search terms: 'pharmaceutical 3D printing' OR 'pharmaceutical additive manufacturing' OR '3D printing' AND 'personalised medicine' AND 'Africa' OR 'name of specific African country'. Relevant information was also retrieved from Google Scholar using similar search terms. Based on previous recommendations, only the first 200 search results from the Google Scholar search were considered for screening (Bramer et al., 2017). Due to limited research on pharmaceutical 3DP/additive manufacturing, grey literature related to pharmaceutical 3DP in Africa was identified through Google searches, web pages of organisations such as the National Agency for Food and Drug Administration and Control (NAFDAC) in Nigeria, the South African Health Product Regulatory Authority (SAHPRA), the Egyptian Drug Authority (EDA) or the African Medicines Regulatory Harmonization (AMHR) initiative. Information from grey literature was evaluated for trustworthiness and relevance based on the AACODS (Authority, Accuracy, Coverage, Objectivity, Date, and Significance) checklist (Tyndal, 2010).

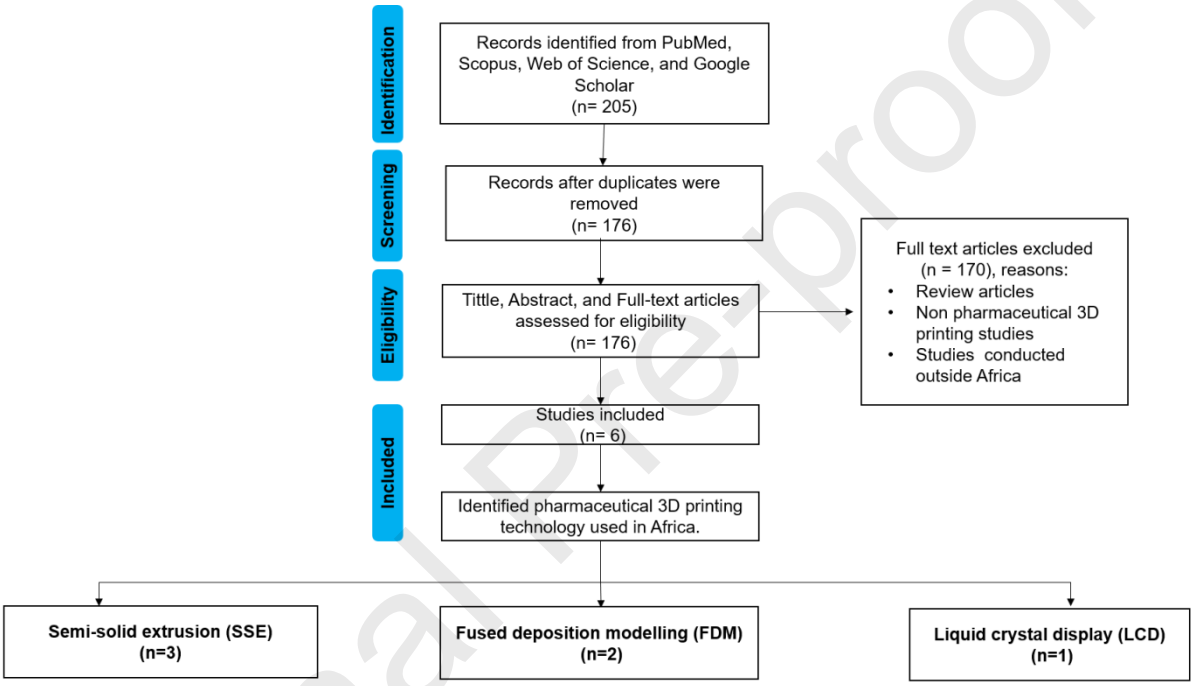

Figure 1. Flowchart for the study selection process

2.2 Study Selection

Studies were included based on the following criteria: Only articles written in the English language were included. Any peer-reviewed articles (Original research) on pharmaceutical 3DP from any region of Africa, published regardless of the period, were included. Articles with full text were included, as were studies conducted in Africa. Disputes between authors regarding the study selection process were resolved through discussion until an agreement was reached. Figure 1 demonstrates the study selection process, from identification through specific inclusion.

2.3 Data Extraction

Information extracted from the included studies highlights the following: country of the original study, region in Africa, university where the study was conducted, type of 3DP technology employed, API(s) and excipients used, dosage form/drug release manufactured, 3D printer used, external collaboration and any specific advantage offered by the technology.

2.4 Operational Definitions

PoC manufacturing refers to the on-site production of pharmaceutical formulations or medical devices at the location of patient care, such as hospitals, clinics, or pharmacies (Jamróz et al., 2018b). This model enables faster access, on-demand supply, and patient-specific customisation of medicines (Forbes et al., 2024).

Personalised medicine in the context of personalised dosing refers to the use of individual patient data (e.g., age, genetics, pharmacokinetics, and organ functions) to tailor drug dosages for optimal efficacy and safety. This approach departs from the 'one-size-fits-all' and relies on model-informed precision dosing (MIPD) strategies (Minichmayr et al., 2024).

Original research describes a structured programme of research that leads to new knowledge, new insights, or new understanding that contributes to the body of knowledge in a particular discipline. Contribution of research to the body of knowledge is essential; however, conditions to ordain the contribution as original should not be binary. For instance, a summary, survey, review, or fusion on the domain area or existing research cannot be considered as original research (Shaheen 2021).

2.5 Relative Cost of Pharmaceutical 3D Printer

To estimate the costs associated with each of the 3D printers used in the relevant studies, a quick search was conducted to determine the average price of each printer and summarised in Table 1. (Printlitic, 2025; Aniwaa, 2025a; Aniwaa, 2025b; De Beer et al., 2011)

2.6 African University Ranking involved in pharmaceutical 3DP

A comprehensive literature and database search was conducted using the AD Scientific Index, a reputable real-time ranking system for universities and scientists with bi-daily updates. Based on this index, which lists 1,258 accredited and globally ranked universities in Africa, we focused our search on identifying African institutions with documented evidence of research or activities in Pharmaceutical 3DP (AD Scientific Index, 2025). From the scoping review, a total of 4 accredited African universities that are globally ranked were identified to be involved in pharmaceutical 3DP research. Thus, from the information retrieved, the prevalence of pharmaceutical 3DP among African universities was calculated according to Equation 1.

$$\text{Prevalence}(/\%) = \frac{Accredited\ African\ universities\ with\ pharmaceutical\ 3DP\ research}{Total\ accredited\ universities\ in\ Africa} \times 100 \ldots [1]$$

3. Result and Discussion

Based on the analysis of pharmaceutical 3DP research data in Africa, this study identified several critical areas, including regional distribution of pharmaceutical 3DP research across Africa, APIs, excipient and dosage forms printed from the continent, funding patterns, 3DP technology, printer types and relative costs of the 3D printers, and regional and global collaboration patterns, which might collectively impact research take up of pharmaceutical 3DP technology across the continent. A summary of the findings from this review and characteristics of the included studies are presented in Table 1. The results are discussed under the following themes:

3.1 Regional Coverage of Pharmaceutical 3D Printing in Africa

Table 1 highlights the trends in the regional research utilising pharmaceutical 3DP in Africa, with the 6 identified studies showing different characteristics in terms of subregional representation. Figures 2A and 2B reveal a significant paucity of research and implementation of pharmaceutical 3DP in Africa,

with only 6 studies that actively showcase pharmaceutical dosage form development using 3DP technologies. Compared to the global trend, which demonstrates substantial growth in research within this domain (Anwar-Fadzil et al., 2022), pharmaceutical 3DP research in Africa is lagging behind. The study identified only two countries with active pharmaceutical 3DP research on the continent, Figure 2A. North Africa, represented solely by Egypt, leads the research landscape with four out of six studies (67%), while the Southern African region, represented exclusively by South Africa, accounts for the remaining two studies (33%), Figure 2B (Amin et al., 2023b; Bayoumi et al., 2022; El-Habashy et al., 2021; Kondiah et al., 2020; Naguib et al., 2021; Siyawamwaya et al., 2019). This distribution underscores the notable absence of advanced pharmaceutical 3DP technology adoption in West, East, and Central Africa, indicating that these regions are currently lagging substantially behind in embracing and implementing this innovative technology (Algahtani, 2021; Lebeau and Oanda, 2020; Teferra and Altbachl, 2004). This finding aligns with a 2023 comprehensive review examining general 3DP applications in Africa (Alzhrani et al., 2024b; Klenam et al., 2022) and a 2022 global perspective study analysing the relationship between global trends and African adoption of additive manufacturing in general (Algahtani, 2021; Huanbutta et al., 2023), both of which documented limited research output and implementation capacity across most of the African continent, with research activities predominantly concentrated in South Africa and some few North African countries.

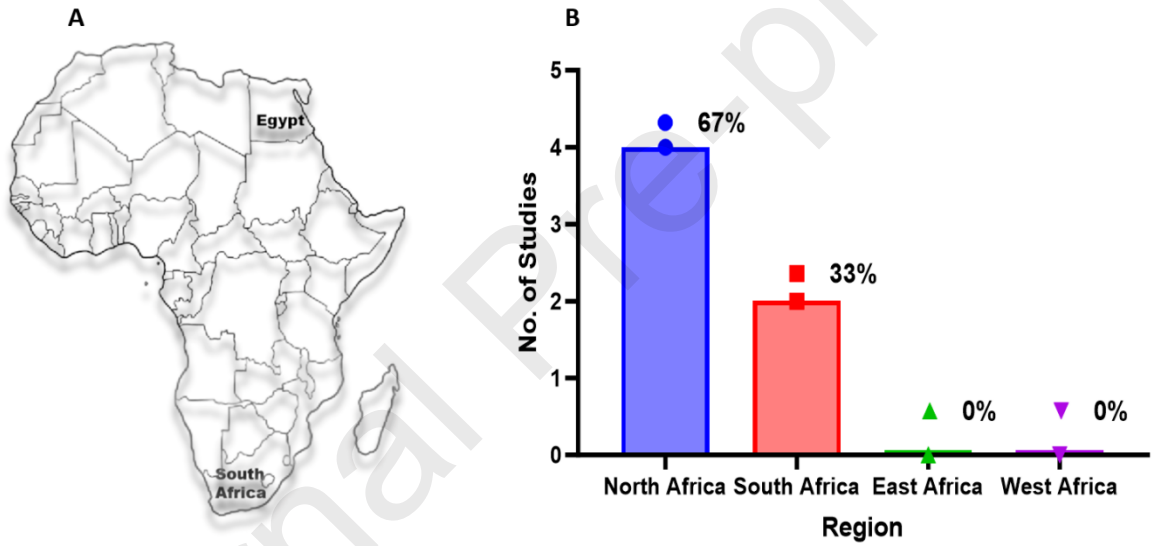

Figure 2. Map of Africa highlighting the only two countries (Egypt and South Africa) with a record of original pharmaceutical 3DP research (A); Regional distribution of the six identified peer-reviewed original research outputs, highlighting the complete absence of studies from West, East, and Central Africa (B).

The concentration of research in Northern and Southern Africa can be attributed to several factors including better-established university systems, greater access to funding, and more developed research infrastructure. Egypt's Al-Azhar University and South Africa's University of the Witwatersrand have emerged as key research centres, while Alexandria University and Cairo University have contributed significantly to the field. This regional concentration highlights the need for targeted capacity-building initiatives in the underrepresented regions to achieve more equitable technological development across the continent.

Table 1. Summary of peer-reviewed original research on pharmaceutical 3DP and their characteristics from Africa

Publication year	**Country of study**	**3DP technology**	**API(s) loaded**	**Excipients**	**Dosage form**	**3D printer**	**Relative cost of the 3D printer ($)**	**Funding**	**Remarks**	**References**
2023	Egypt	FDM 3DP	Mosapride citrate	Saccharin sodium Methocel K4M	Floating tablet	Regemat® 3D V1 printer, S.L (Spain)	23,100 - 34,600	Open Access Funds (STDF) Egypt Knowledge Bank	Floating tablets were developed using FDM 3DP and mosapride-saccharin co-crystals to enhance drug solubility and achieve gastric retention, with controlled and adjustable release profiles influenced by tablet configuration and wall thickness.	(Amin et al., 2023)
2019	South Africa	SSE 3DP	Efavirenz/Tenofevir/Emtricitabine	Humic acid Polyquaternium 10 (HA-PQ10)	FDC Tablet	3D-Bioplotter (Germany)	49,000 - 200,000	National Research Foundation of South Africa	A 3D bioprinted fixed-dose combination tablet integrating efavirenz,	(Siyawamwaya et al., 2019)

									tenofovir, and emtricitabine enables customizable, controlled intestinal drug release with enhanced bioavailability and pharmacokinetics, offering a potential personalised therapy for HIV management.	
2021	Egypt	SSE 3DP coupled crosslinking	Doxycycline	Calcium Chloride Sodium Bicarbonate Gelatin Polyvinyl alcohol	Scaffold	Robota 3D printer (Egypt)	-	No funding	An integrated doxycycline nanoparticle within 3D-printed bioinspired scaffolds was developed to enable controlled drug release and enhance bone regeneration in vivo.	(El-Habashy et al., 2021)
2022	Egypt	LCD 3DP	Ectoine	Carbopol 940 and Pluronic (F127).	Microneedle patches	Photon s Printer©	95 - 521.85	No funding	A 3D-printed microneedle array was designed for transdermal delivery of	(Bayoumi et al., 2022)

									ectoine gel, enhancing skin penetration and reducing melanoma severity in rats, with stable, non-irritant formulations that demonstrate the promising natural therapeutics for minimally invasive skin cancer treatment.	
2021	Egypt	FDM 3DP	Ganciclovir	Polylactic Acid Ultrafluidic Glycerosomes (UGF)	Ocular insert (Ocusert laden)	CoLiDo Plus 2.0 system (China)	989	No funding	A novel 3D-printed ocular insert was developed using polylactic acid and ultra-fluidic glycerosomes loaded with ganciclovir, which offers a non-invasive method for sustained CMV retinitis treatment with improved patient compliance.	(Naguib et al., 2021)

2020	South Africa	SSE 3DP	Simvastatin	Polypropylene FumaratePluroic -PEG-PCL-PEG	Bone scaffold	3D Bioplotter® (Germany)	49,000 - 200,000	National Research Foundation of South Africa	A 3D bioprinted simvastatin-loaded scaffold mimicking bone was optimised via neural networks to deliver sustained drug release and support personalised bone repair.	(Kondiah et al., 2020)

SSE: Semi-solid extrusion 3DP

FDM: Fused-deposition modelling 3DP

LCD: Liquid crystal display 3DP

CMV: Cytomegalovirus

3.2 Prevalence of Pharmaceutical 3D Printing Research among African Universities

Although Africa houses roughly 16% of the world population, it accounts for less than 10% of the world's higher education institutions, indicating a global disparity in educational resources and output as a recent data from the AD Scientific Index (2025), a frequently updated university and scientist ranking system, indicates that Africa is home to 1,263 accredited universities (AD Scientific Index, 2025). However, this review indicated that only four universities have been active in conducting original research on pharmaceutical 3DP technology in Africa, Table 1.

This represents a mere prevalence of 0.32% of the continent's accredited and globally ranked universities. This is relatively negligible compared to the global total of 6,737 original research articles retrieved from the Scopus database on pharmaceutical 3DP from inception to date. European universities are leading in research in this subject area. Moreover, in contrast to the rest of the world, research on pharmaceutical 3DP started in the last 4 decades (Meléndez et al, 2008; Deng et al, 2008), and research in pharmaceutical 3DP in Africa only appeared in 2019. The near-negligible prevalence of 3DP research among African universities underscores the limited penetration of advanced pharmaceutical technologies within African academia. Notably, all four pioneering institutions are public universities established between the early and mid-20th century. Their long-standing institutional history, coupled with sustained public funding, likely enabled the development of research infrastructure, academic reputation, and capacity necessary to adopt technologies like pharmaceutical 3DP. Consistent with this, Table 2 confirms their status among Africa's top-ranked research universities, a position facilitating early engagement in innovative fields such as pharmaceutical 3DP (AD Scientific Index, 2025). Within this context, only a handful of universities in Africa focus on advanced pharmaceutical manufacturing technologies such as 3DP. This constrained academic engagement impedes regional healthcare innovation, drug personalisation capabilities, and local pharmaceutical manufacturing development.

Table 2. Profiles and number of publications from African universities conducting pharmaceutical 3DP research with their 2026 ranking (AD Scientific Index, 2025)

University Name	Country	Year Established	Public/Private	Rank among African Universities	Global ranking	No. of Publications on Pharma 3DP
University of the Witwatersrand	South Africa	1922	Public	3	437	2
Cairo University	Egypt	1908	Public	7	669	1

Alexandria University	Egypt	1942	Public	17	1,109	1
Al Azhar University	Egypt	1961	Public	23	1,334	2

3.3 Trend of Original Research on Pharmaceutical 3DP in Africa

Table 1 reveals a consistently low output of original research on pharmaceutical 3DP from Africa between 2019 and 2023, with annual publications ranging from only one to two papers (Figure 3A). This analysis, which included all eligible studies from database inception to July 2025 with no year-wise exclusion criteria, highlights a critical finding: while foundational research in 3DP technology emerged globally over four decades ago, the first peer-reviewed original research on pharmaceutical 3DP from African institutions only appeared in 2019. A contrasting difference is evident in Figure 3B, which represents data from the Scopus database only. It shows the yearly incremental global trend in original research output with a total of 6,202 publications from 2018 to July 2025, and the data is still peaking.

Crucially, our data shows no original research publications in 2024 and up to July 2025 from Africa, indicating a stalling of research momentum and a recent decline in output. This is not an artefact of the current study, but a genuine reflection of the fragile and unsustainable state of research in this field on the continent. This stagnation and recent drop-off contrast sharply with the rapid growth of pharmaceutical 3DP research globally, which is marked by accelerating technological innovation and expanding clinical applications in Europe, North America, and Asia. (Wang, 2025). Furthermore, while these regions dominate global patent registrations and technology invention in this field, Africa remains absent from these metrics.

Despite this limited and faltering research activity, the pharmaceutical 3DP technologies adopted in Africa have proven capable of generating innovative drug delivery platforms. The included studies successfully developed floating tablets, fixed-dose combination tablets, microneedle patches, ocular inserts, and drug-loaded bone scaffolds. These systems demonstrated tangible benefits, such as enhancing drug solubility, achieving gastric retention, addressing polypharmacy to personalise HIV treatment, and providing a non-invasive ocular drug delivery platform. The fact that such promising proof-of-concept studies have not led to a sustained pipeline of publications or clinical translation further underscores the systemic challenges, such as funding gaps and infrastructural deficits, that we identified as major barriers to growth.

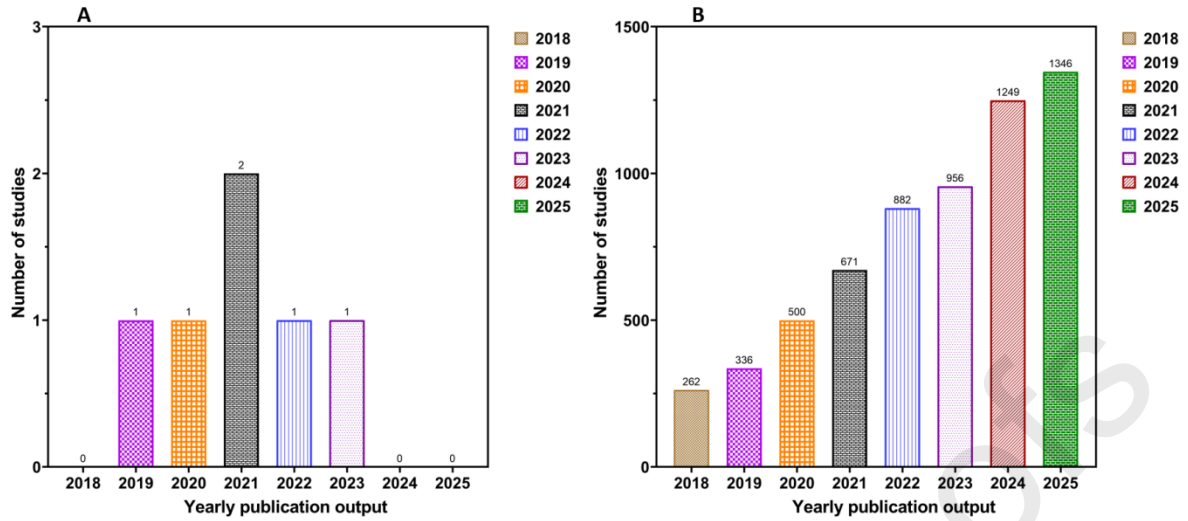

Figure 3. Yearly trend in original research publication output on pharmaceutical 3DP from Africa retrieved across different databases (A); Yearly global trend in original research publication output on pharmaceutical 3DP retrieved from Scopus database only (B). Search conducted up to July 2025.

3.4 Basic Principles of Pharmaceutical 3D Printing Technology used in Africa

The selection of appropriate 3DP technology depends on specific pharmaceutical application requirements, including drug characteristics, dosage form complexity, production volume, and regulatory considerations of the excipients to be used. Some of the technologies require extensive pre-formulation studies and development of suitable pharma-inks, such as filament used in FDM 3DP, while others require a simple drug and excipient mixture to print with or without heating the pharma-ink. Three pharmaceutical 3DP techniques were used frequently in Africa, namely; FDM, SSE, and Liquid Crystal Display 3DP (LCD). SSE being the most common among the six studies, accounting for 50% of all the studies included in this review. The FDM is ranked second with 2 studies, and only 1 study utilised LCD technique (Table 1). The dominance of SSE could be attributed to its simplicity, ability to print dosage forms of various shapes at room temperature, giving it the capability to print a wide range of APIs, including thermolabile actives and nutraceuticals, easy to clean and compliance with GMP specifications. Moreover, most of the clinical studies with pharmaceutical 3DP were done using the SSE 3DP technique, indicating its suitability for PoC manufacturing. In line with these trends, our recent study also highlights the potential of SSE 3DP technology to rapidly automate the extemporaneous compounding of solid oral dosage forms as dose-flexible crystalline solid dispersion (CSD) tablets, using celecoxib and acetaminophen as model APIs suitable for preclinical and phase 1 first-in-human studies. The study also explored the versatility of SSE 3DP for adoption at PoC and its adaptability for pharmaceutical industries and Contract Development and Manufacturing Organisations (CDMOs) to prepare small batches of personalised treatment on demand during clinical trials (Garba-Mohammed et al., 2025). FDM is the second most commonly used in Africa, attributable to its low cost and being the most commonly available 3D printer worldwide (Amin et al., 2023a; Fanous et al., 2021; Goyanes et al., 2016; Monteil et al., 2025; Saydam and Takka, 2020; Wang et al., 2025). Other extrusion-based 3DP technologies with practical applications in pharmaceutical formulation development include the Direct Powder Extrusion (DPE) 3DP, in which drug and excipient powder blends with a suitable plasticiser are directly melted and printed into a dosage form without the intermediary filament generation (Mendibil et al., 2021; Mora-Castaño et al., 2025). With these approaches, often multiple layers of drugs can be printed as a single pill, referred to as a polypill, to aid in reducing polypharmacy and enhance medication adherence in patients taking multiple drugs for different ailments at the same time. The LCD appeared to be the least explored for basic research on the continent can be related to

its limited resin pharma-ink choices due to weak biocompatibility with drugs, API stability concerns and complex post-processing curing process (Awad et al., 2018; Sautha et al., 2025).

The basic principles of commonly used pharmaceutical 3DP printing techniques in Africa are discussed below, while Table 3 details their comparative merits and limitations.

Fused Deposition Modeling (FDM)

FDM operates by feeding a polymer filament into a heated printhead and nozzle, where it melts into a semi-solid state. The melted material is then extruded onto the printer platform following a predetermined path along the x and y axes. After each layer is deposited, the stage lowers to accommodate the next layer, building the object along the z-axis (Figure 4A). The process is guided by Computer Aided Design (CAD) software that defines the shape and size of the printed object (Wang et al., 2023; Winarso et al., 2022).

Semi-solid Extrusion (SSE)

SSE is a 3DP technique that enables a layer-by-layer deposition of semi-solid materials—typically gels, pastes, or creams through a nozzle to fabricate customised objects under low-temperature conditions, making it ideal for formulating thermolabile drugs (Figure 4B). By precisely controlling the extrusion of pharma-inks, SSE allows for personalised medicine production, such as chewable tablets, fast-dissolving films, or rectal suppositories, directly at PoC locations like hospitals (Aina et al., 2025; Wang et al., 2023).

Liquid crystal display 3DP (LCD)

LCD, also known as masked stereolithography (mSLA), is a photopolymerisation-based technique that uses an LCD screen to selectively cure photosensitive resin layer by layer with UV light, enabling the fabrication of high-resolution objects at room temperature. This method is particularly advantageous for incorporating thermolabile APIs (Figure 4C). In pharmaceutical applications, LCD printing allows precise control over dosage form geometry, internal structure, and drug-release profiles, supporting the development of personalised tablets, multi-drug polypills, and drug-loaded implants. Its ambient printing conditions and pixel-level resolution make it particularly suitable for decentralised, patient-specific manufacturing at PoC settings such as hospitals (Awad et al., 2018; Sautha et al., 2025).

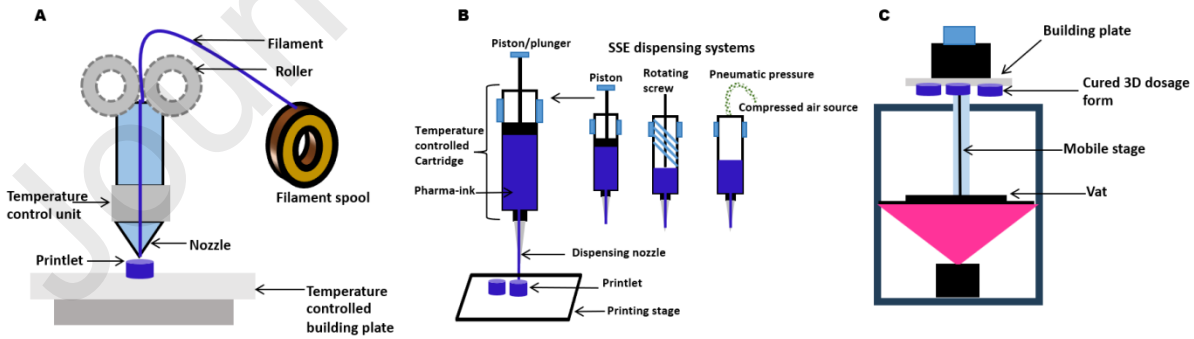

Figure 4. Schematic illustration of the key features of pharmaceutical 3DP technology used in Africa: FDM 3D printer (A); SSE 3D printer (B); LCD 3D printer (C).

Table 3. Merits and limitations of Pharmaceutical 3DP Technologies used in Africa

Technology	Merits	Limitations	Reference
FDM	-Low cost, widely available and budget-friendly. -Overcomes excess residual solvent issues. - Reusable filament.	-High temperature exposure (>120°C). -Potential drug degradation. -Not suitable for microneedle formulation development.	(Wang et al., 2023; Winarso et al., 2022)
SSE	-High precision and control. -Suitable for Thermolabile Ingredients. -Can avoid the use of heat.	-Dispersal of ingredients is challenging. -Requires long post-printing time, such as drying.	(Aina et al., 2025; Wang et al., 2023)
LCD	-Offers high resolution and layer precision at ambient temperature. -Wide variety of materials (thermoplastics, complex dosage forms like polypills). -Fine control of drug-release profile.	-Limited resin material choices (biocompatible resins). - May cause drug degradation at high temperatures. -Complex post-processing requirements, such as the curing process.	(Awad et al., 2018; Sautha et al., 2025)

3.5 Cost of Pharmaceutical 3DP as Economic Barrier

Figure 5 depicts the economic burden of acquiring and using a 3D printer as a substantial cost barrier that potentially impacts the implementation of pharmaceutical 3DP technology in African pharmaceutical research. This is in line with Algahtani's findings, who identified cost as the main barrier to the implementation of pharmaceutical 3DP in various hospitals across Saudi Arabia (Algahtani, 2021).

High-end bioprinters such as the 3D-Bioplotter, priced between $49,000 and $200,000, and the Regemat 3D VI Bioprinter, costing between $23,100 and $34,600, represent significant economic barriers due to their substantial investment requirements. These costs likely limit accessibility to advanced bioprinting technology primarily to well-funded institutions. In contrast, mid-range options like the ColiDo Plus 2.0, priced at approximately $989, offer a more affordable entry point for basic 3D applications, while

software solutions such as Metlab provide annual subscriptions ranging from $49 to $860, further lowering the financial threshold for engaging with bioprinting technologies. Together, these options illustrate a spectrum of affordability that influences the accessibility and adoption of pharmaceutical 3DP across different research and development settings.

However, recent developments in low-cost 3D bioprinter technology offer promising alternatives. Research indicates that functional bioprinters can be developed for as little as $250-260, with some prototypes using recycled materials costing under $120 (Gomes Gama et al., 2023).

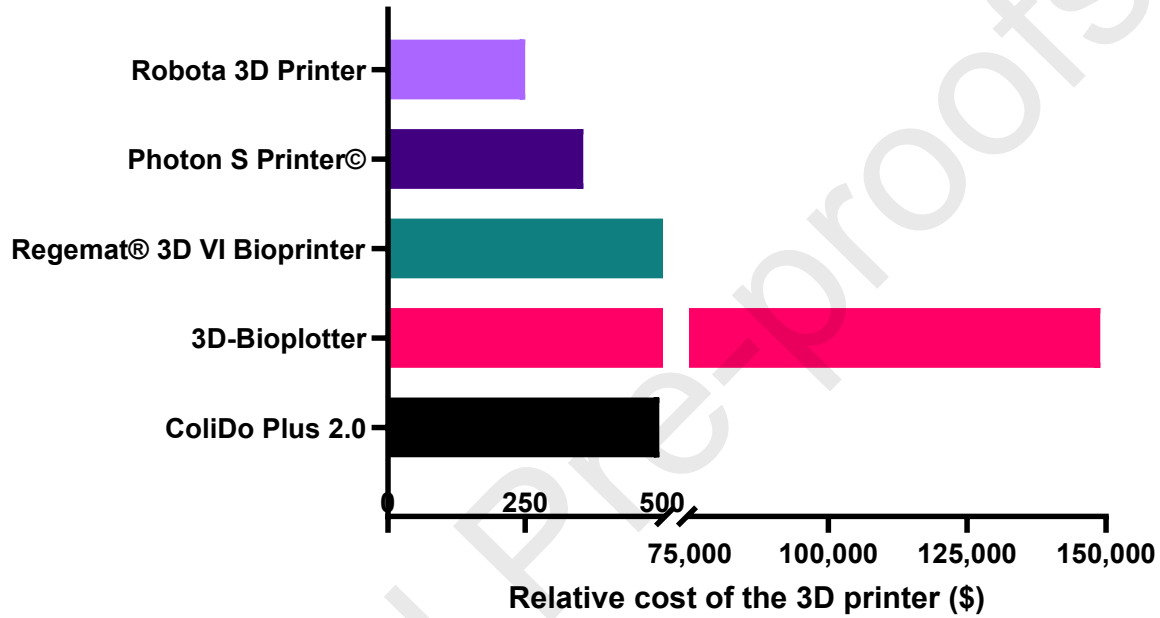

Figure 5. Relative cost of 3D printers used for pharmaceutical 3DP among African universities

3.6 Funding and External Collaboration Patterns

The funding analysis, Table 1, reveals a pronounced disparity in research support across Africa in relation to pharmaceutical 3DP, with only half of the pharmaceutical 3DP studies receiving funding and the other half operating without financial backing. Funded research primarily benefits from institutional support mechanisms such as Egypt's Open Access Funds through the Science and Technology Development Fund (STDF) and the Egypt Knowledge Bank, as well as South Africa's National Research Foundation, which consistently supports some of the select studies. Conversely, 3 of the 4 Egyptian studies report no external funding, relying instead on institutional resources or personal investment from the academics. This unequal funding split underscores the precarious nature of the funding landscape for 3DP research on the continent, emphasising that research capacity is heavily dependent on national science policies and the availability of government funding, which vary significantly between countries.

Furthermore, projects like South Africa's MedAdd demonstrate emerging local capabilities in 3DP medical devices, hinting at the potential for pharmaceutical applications to scale with appropriate investment and regulatory support (Central University of Technology, Free State, 2023). Additionally, the development of 3DP startups, such as AB3D in Nairobi (AB3D - African born 3D Printing, 2019) and Robota in Egypt (El-Habashy et al., 2021), showcases how university-industry partnerships can nurture local manufacturing and R&D capacity in this field on the continent.

Notably, none of the six studies reported external collaboration with international partners. This complete absence of international collaboration represents a significant concern for several reasons, including a lack of collaboration with established international research centres, which may slow the adoption of advanced 3DP techniques and constrain funding. In our opinion, this isolation may be attributed to several factors, including limited networking opportunities, language barriers, geographical barriers, and potentially inadequate international outreach by African institutions.

4. Challenges, Recommendations and Implications for Future Implementation

4.1 Challenges

Funding Issues

Pharmaceutical 3DP in Africa is critically hamstrung by an overwhelming funding crisis, representing the most fundamental barrier to harnessing this transformative technology. This deficit manifests in three crippling dimensions. Firstly, chronic research underfunding leaves half of all pharmaceutical 3DP studies without dedicated support, forcing reliance on scarce personal or institutional resources, as evidenced by three of Egypt's six projects proceeding unfunded. This scarcity leads to abandoned prototypes and stifles local innovation. Secondly, prohibitively high equipment costs create an insurmountable hurdle. Advanced bioprinters, priced between $49,000 and $200,000, dwarf most university research budgets. Even seemingly affordable alternatives like the $989 ColiDo Plus system represent a massive investment relative to local purchasing power, equivalent to over 1.5 million Nigerian Naira, for instance. Hidden expenses, steep import duties (up to 35%) (CustomsDutyFree, 2018), costly maintenance due to scarce expertise, and recurring import of premium materials further render sustainable operations economically unviable. Thirdly, Africa's funding ecosystem is fragmented and unsustainable. Existing grants often focus narrowly on equipment, neglecting critical needs like specialised training ($15,000–$30,000 per researcher), regulatory compliance ($50,000+ for GMP), and scaling pathways. Crucially, private investment is virtually absent, with less than 0.3% of African health tech startups targeting advanced manufacturing (Caelers and Okoth, 2023).

This funding vacuum fuels a debilitating brain drain, as ≥ 45% of contributing African researchers migrate abroad, and entrenches technological dependence on imported materials (Commodore-Mensah et al., 2019). Most tragically, it denies patients access to personalised medicines and prevents hospitals from realising significant savings through on-demand production. This crisis reflects a broader continental challenge: Africa, representing 18% of the global population, contributes only 1-2% of research output and invests a mere 0.42% of GDP in R&D, far below the global average (1.7%) and the AU's own 1% target for 17 years (Caelers and Okoth, 2023; Anyanechi et., 2023). Without urgent, concerted action such as establishing an AU 3DP Innovation Fund, leveraging regional procurement, and adopting phased implementation, Africa risks permanent exclusion from the $9.4B global 3DP medicine market (Data Bridge Market Research, 2023), forfeiting a vital tool for healthcare sovereignty.

Africa's Infrastructure Crisis

Pharmaceutical 3DP adoption in Africa faces critical infrastructure barriers extending beyond funding limitations. Erratic electricity supply fundamentally disrupts sensitive additive manufacturing processes requiring stable thermal control and uninterrupted power. Grid instability can cause equipment malfunctions, print failures, material wastage, and compromises drug stability. Reliance on backup generators introduces environmental variability that degrades material performance and final product quality. Severe facility deficiencies compound these challenges. Most African institutions lack GMP-compliant cleanrooms essential for sterility assurance and batch consistency (Chejor et al., 2024). Inadequate laboratory space, insufficient ventilation systems incapable of managing chemical emissions, and substandard storage for temperature-sensitive materials force researchers into

suboptimal improvisations. These conditions directly undermine product quality and prevent translation of research prototypes into clinically viable medicines.

Another barrier is critical dependency on imported pharmaceutical-grade excipients. Polymers and specialised additives face protracted customs delays, exorbitant shipping costs (5-8x global prices), and unreliable supply chains (Alfaouri et al., 2025). This scarcity causes project delays, necessitates experimental compromises with non-ideal substitutes, and precludes scaling of promising formulations. Import dependence stifles the development of formulations addressing Africa-specific disease burdens.

This infrastructure triad, unstable power, and material scarcity create a prohibitive operational environment. It escalates costs, jeopardises product quality and patient safety, and fundamentally impedes the deployment of 3DP for personalised medicine or resilient supply chains. Addressing these constraints requires substantial investment in grid stabilisation, construction of certified laboratories, pharmaceutical manufacturing facilities, and development of regional APIs and excipient production capacity to enable sustainable advancement of this technology.

Africa's Regulatory Void

Pharmaceutical 3DP in Africa faces a myriad of regulatory voids. Unlike regions with established pathways for PoC manufacturing, Africa lacks a cohesive continental strategy (Pharma Focus America, 2025; Department of Health and Social Care, 2025). This vacuum operates on two crippling levels: the absence of harmonised standards for 3D printed medicines and the acute technical incapacity of national agencies to oversee this technology. Despite its mandate, the African Medicines Agency (AMA) remains focused on conventional pharmaceuticals, offering no framework for validating novel "pharma-inks," ensuring decentralised quality, or managing patient-specific dosing risks (AUDA-NEPAD, 2025). This forces a fragmented national response; regulators in South Africa (SAHPRA), Nigeria (NAFDAC), and Egypt (EDA), and similar regulatory agencies across the continent lack dedicated units or protocols specific to pharmaceutical 3DP, leaving researchers navigating a perilous limbo where innovations remain trapped in laboratories.

Compounding this, national regulators lack the specialised expertise to assess unique 3DP risks: API stability during printing, resin toxicity, cross-contamination, or software validation. Their quality control relies on outdated "end-product testing," unsuitable for small-batch PoC production, and they lack resources for advanced techniques such as in-line process analytical technology frameworks, and/or real-time Raman spectroscopy (PharmaFocusAmerica, 2025; Stefaniak et al., 2025). Crucially, the essential hub-and-spoke oversight model, where a central authority certifies distributed manufacturing sites proposed by the new UK MHRA regulation on point-of-care decentralised manufacturing (Medicines and Healthcare products Regulatory Agency, 2025) remains theoretical if at all the regulators in Africa are aware of such development. Thus, making legal clinical implementation of the technology impossible.

This inertia deters research and investment and perpetuates Africa's $16 billion annual dependence on imported medicines, exposing health systems to dangerous shortages (Adebisi et al., 2022; Africa Imports 2025). Bridging this chasm demands urgent AMA action: forming a task force to draft continent-wide PoC guidelines (covering materials, non-destructive quality control, and licensing) coupled with massive investment in regulator training via global partnerships. Until this regulatory frontier is mapped, 3DP's life-saving potential remains inaccessible to African patients.

Knowledge Isolation Hinders African 3DP Advancement

Another major barrier rooted in the academic and professional ecosystem, with significant knowledge gaps and systemic isolation. From our findings, only a fraction (0.32%) of African universities engage in this research, reflecting a continent-wide deficit in awareness and technical familiarity. For most institutions, 3DP remains a theoretical concept rather than a practical tool integrated into research or

clinical discourse, creating a fundamental disconnect between innovation potential and on-ground healthcare realities.

This knowledge vacuum fuels scepticism among clinicians and pharmacists. Without visible, locally validated success stories such as PoC production of 3DP for chronic diseases, the technology will often be perceived as experimental and misaligned with Africa's immediate medication access challenges. Healthcare professionals, already navigating resource constraints, understandably prioritise familiar manual compounding methods over unproven solutions. Educational systems exacerbate these gaps. Pharmacy and medical curricula across Africa overwhelmingly neglect additive manufacturing, digital formulation design, and decentralised production regulation. Graduates enter the workforce without foundational literacy in 3DP, perpetuating cycles of unfamiliarity.

Critically, zero international collaborations in existing African studies on the topic isolate researchers from global knowledge networks. This absence denies access to mentorship, prevents access to advanced techniques and shared resources, forcing scientists to "reinvent the wheel" on calibration, optimisation, and quality control challenges. Such isolation stifles innovation, delays adoption, and confines Africa to the periphery of pharmaceutical 3DP advancement. Breaking these invisible walls requires integrating 3DP into academic curricula, showcasing local pilot successes, and forging strategic global partnerships to accelerate contextually relevant implementation of 3DP innovation.

4.2 Recommendations and Future Implementation

Strategic Roadmap for Africa's Pharmaceutical 3DP Revolution

To transform pharmaceutical 3DP from isolated research to a systemic healthcare solution, Africa must implement a coordinated continental strategy. The AU and AMA must spearhead regulatory modernisation through a dedicated Technical Working Group on pharmaceutical 3DP. This group should develop harmonised PoC manufacturing guidelines inspired by global frameworks like UK MHRA 2025 (Medicines and Healthcare products Regulatory Agency, 2024), while activating the Pharmaceutical Manufacturing Plan for Africa (PMPA) through a Pan-African 3DP Fund. This fund should provide competitive grants for equipment, research, and pilot programs, moving beyond fragmented national efforts. Simultaneously, Africa CDC must integrate decentralised PoC medicine production into pandemic preparedness plans, recognising 3DP's role in mitigating supply chain vulnerabilities exposed during COVID-19. National governments should catalyse adoption through tax incentives for 3DP imports and strategic infrastructure investments in stable electricity and digital-ready research hubs.

Building human capital is equally critical. The AU must establish immersive training programs: researcher exchanges at global centres of excellence, e.g., the UK's Centre for Additive Manufacturing, and other institutions with global recognition on pharmaceutical 3DP and clinical fellowships at pioneering PoC 3DP hospitals like Gustave Roussy in France. These should focus on practical PoC skills such as pharma-ink development, 3DP formulation development, printer operation, and non-destructive quality control techniques. Complementing this, continent awareness campaigns must showcase localised successes (Egypt's floating tablets, South Africa's HIV polypills) through healthcare professional-targeted workshops. Demonstrating tangible benefits of personalised paediatric dosing, chronic disease polypills, and drug shortage mitigation can convert scepticism into advocacy.

Regulatory harmonisation requires adopting a model with AMA as the central hub setting standards, certifying pharma-inks, and authorising control sites. Empowered pharmacists and technicians would produce medicines under AMA oversight with practical quality protocols: handheld NIR/Raman spectrometers for non-destructive testing and adaptive GMP requirements focused on critical control points rather than factory-scale compliance. These paradigm shifts must happen now if Africa is willing to align with the global landscape on pharmaceutical 3DP.

Securing Africa's Medicine Future through Pharmaceutical 3DP

Pharmaceutical 3DP offers Africa three interconnected pathways to achieve medicine sovereignty. First, localised mass production of complex generics, such as fast-dissolving tablets like Spritam®, could slash import dependency by 30-50%, insulating health systems from global supply shocks while redirecting billions toward primary care. During epidemics, pandemics, conflicts, and/or natural disasters, decentralised manufacturing at PoC using 3DP capability would prevent catastrophic drug shortages. Second, PoC is a precision automated compounding that empowers hospitals to print tailored medications with exact doses, eliminating dangerous off-label dosing. This directly addresses the 35% treatment failure rate in children linked to manual compounding errors, replacing uncertainty with engineered accuracy (Cohen, 2006; Conn et al., 2019).

Third, a pharma-ink ecosystem redistributes manufacturing: industries produce certified drug-excipient cartridges while pharmacies handle final printing. This minimises waste of scarce APIs (like oncology drugs), enables micro-dosing for rare diseases, and seeds high-value jobs in advanced materials science. Together, these strategies form a resilient triad: mass production stabilises supply chains, PoC printing personalises treatment, and pharma-ink innovation builds industrial capacity. If these approaches can be integrated, Africa can transform patients from passive recipients into empowered partners in care, fulfilling the African Union's vision of healthcare self-reliance while ending chronic medicine insecurity. Figure 6 highlights the challenges hindering the full adoption of pharmaceutical 3DP in Africa, along with our recommended action plans to establish a roadmap for a prosperous future of pharmaceutical 3DP on the continent.

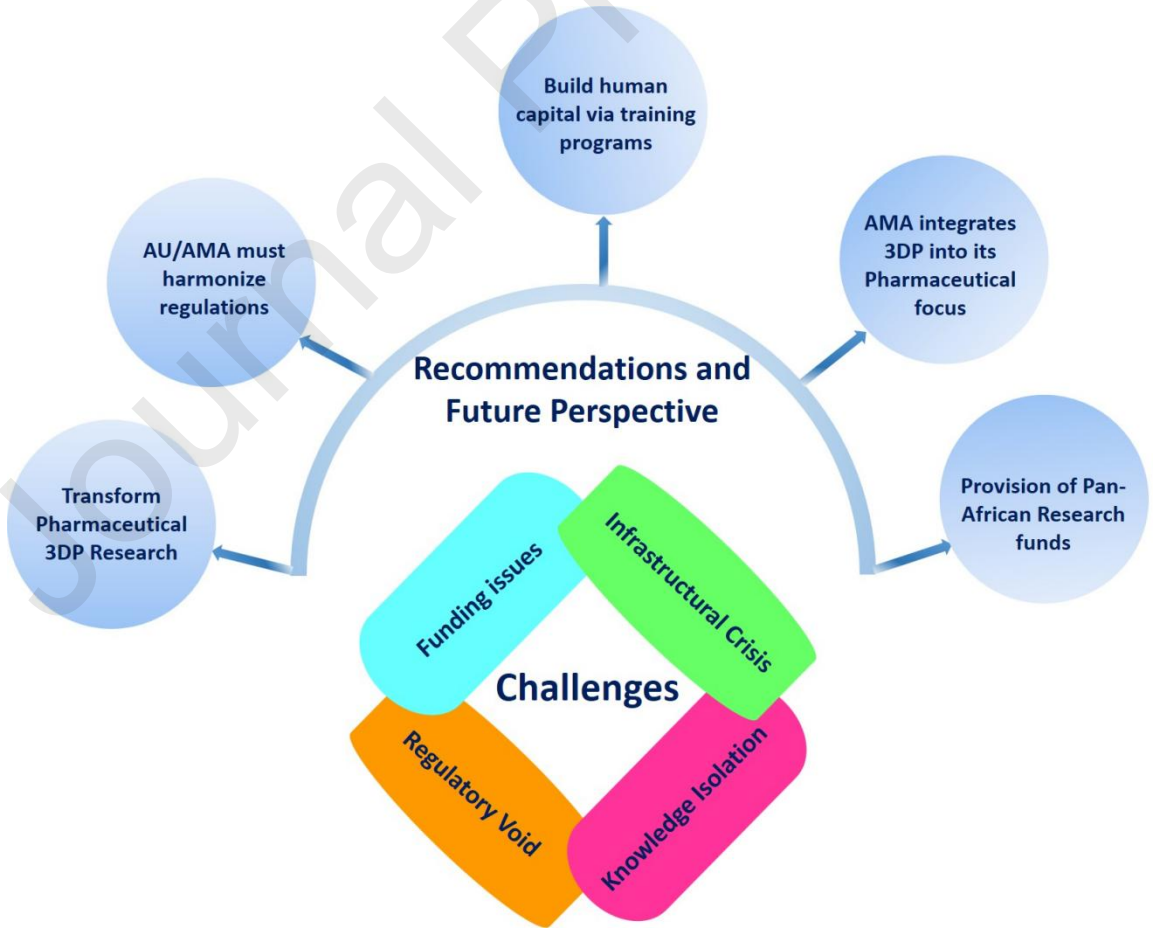

Figure 6. The challenges and future prospects of pharmaceutical 3DP in Africa**.**

5. Conclusion

Pharmaceutical 3DP is transforming the global landscape in medicine manufacturing from early-stage formulation development through clinical implementation at the PoC for personalised therapies. However, Africa is lagging behind in adopting this innovation, even at the basic institutional research levels. Undoubtedly, due to limited awareness of the technology in the region, relative to the rest of the world. Poor funding, inadequate infrastructure, and the absence of specific policies on pharmaceutical 3DP also top the list of challenges that impede the take-up of the technology in Africa. To bridge this gap, Africa must invest in its local research facilities, forge international collaboration that brings African scientists into global innovation networks, and establish regulatory and research financing models tailored towards homegrown solutions to the African healthcare challenges. Future efforts should prioritise building Africa's research capacity and integrating its scientists into global networks to advance pharmaceutical innovations. Thus, for the first time, this review highlights the key features and trends of pharmaceutical 3D printing in Africa. Moreover, with the official inauguration of the African Medicine Agency (AMA) in 2025, as the first unified medicine regulatory authority on the continent, this review provides baseline scientific evidence, along with succinct recommendations, that can guide the AMA in developing regulatory specifications for pharmaceutical 3D printing in Africa. This will undoubtedly influence the future adoption and regulation of the technology on the continent.

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583 **CRediT authorship contribution statement**

584 **Khalid Garba Mohammed:** Conceptualisation, Investigation, Methodology, Writing – review &
585 editing, Data curation, Software, Supervision. **Musa Sulaiman Muhammad** and **Muhammad**
586 **Abubakar Bello:** Writing – original draft, Methodology, Data Curation, Resources. **Mubarak G.**
587 **Bello:** Resources, Visualisation, Writing – review & editing, Supervision. **Carlos Bendicho-Lavilla**:
588 Writing – review & editing, Visualisation, Validation. **Alvaro Goyanes:** Writing – review & editing,
589 Visualisation, Validation, Supervision, Resources. **Abdul W. Basit:** Writing – review & editing,
590 Validation, Supervision, Resources.

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600 Alvaro Goyanes and Abdul W. Basit are cofounders of FABRX Ltd

601

602 **Data availability**

603 Data will be made available on request.

604

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