IJPSR (2026), Volume 17, Issue 1 **(Review Article)**

INTERNATIONAL JOURNAL OF PHARMACEUTICAL SCIENCES AND RESEARCH

Received on 04 July 2025; received in revised form, 16 August 2025; accepted, 25 August 2025; published 01 January 2026

ASPECTS OF 3D PRINTING IN PHARMACEUTICAL TECHNOLOGY: CURRENT SCENARIO AND ITS FUTURE PERSPECTIVE

Manami Dhibar [1], Santanu Chakraborty [* 1] and Bishal Sarkar [2]

Formulation Development Research Unit, Department of Pharmaceutics [1], Dr. B. C. Roy College of Pharmacy & AHS., Durgapur - 713206, West Bengal, India.
Department of Pharmaceutics [2], Mata Gujri College of Pharmacy, Kishanganj - 855107, Bihar, India.

Keywords:

3D printing, Polypills, Bioprinting, Reprap Movement, .STL file

Correspondence to Author:
Santanu Chakraborty

Formulation Development Research Unit, Department of Pharmaceutics, Dr. B. C. Roy College of Pharmacy & AHS., Durgapur - 713206, West Bengal, India.

E-mail: santanu_nil@rediffmail.com

ABSTRACT: The use of 3D printing in the pharmaceutical industry is a relatively recent development that has attracted a lot of attention since it has many advantages over more conventional pharmaceutical manufacturing methods. The design of an appropriate 3D printing system that can produce formulations with the desired drug release may be made possible by technological advancements. The ability of printing technology to develop potentially innovative oral dosage forms is a significant feature in the field of drug delivery. Additionally, it makes it possible for production processes to evolve quickly, safely, and affordably. As a result, this innovative technology is applied widely in the pharmaceutical industry. Also improving patient convenience through 3D printing will increase drug compliance. The pharmaceutical sectors is particularly interested in fused deposition modelling, powder-bed fusion and inject printing processes, which are briefly covered in this paper among other technical advances for creating 3D objects. This innovative technique has great potential for creating different delivery systems and offering polyp ills with individualized patient-compatible formulations. The potential for this technology to offer 3D printing systems that can produce customized doses will determine its future. In summary, 3D technology can potentially advance drug delivery systems to a new level.

INTRODUCTION:

Three-Dimensional Printing: As the fourth industrial revolution begins, we are living through a technological revolution in the manufacture of finished goods. The fourth industrial revolution, or Industry 4.0, has the greatest impact on human-machine interfaces because it overrides fundamental limitations, according to this concept [1].

QUICK RESPONSE CODE

DOI: 10.13040/IJPSR.0975-8232.17(1).99-112

This article can be accessed online on www.ijpsr.com

DOI link: https://doi.org/10.13040/IJPSR.0975-8232.17(1).99-112

With the implementation of automation-promoting digital technologies, such as the Internet of Things (IoT) as well as artificial intelligence (AI), manufacturing strategies will be continued as personalized approaches emerge in a variety of public and private domains [2].

Three-dimensional (3D) printing will play a crucial role in the manufacturing and mass customization of complex and highly customized products as part of Industry 4.0 [3, 4]. There is a relatively new concept in the pharmaceutical industry known as 3D printing, also known as additive manufacturing (AM), solid freeform technology, or rapid prototyping (RP). 3D printing is associated with the process of preparing objects by preserving the material using the printed head, nozzle or other printing method [5, 6]. The 3D printing includes a complex structure and a modified industry, such as construction, prototyping, and biotechnology. Despite their strengths, construction families remain slow. Performance and expiration patents in the material field are promoted by innovation and application for education, housing and laboratory. At first, it was desirable for fast and inexpensive prototypes, but it is important for design and architecture [7].

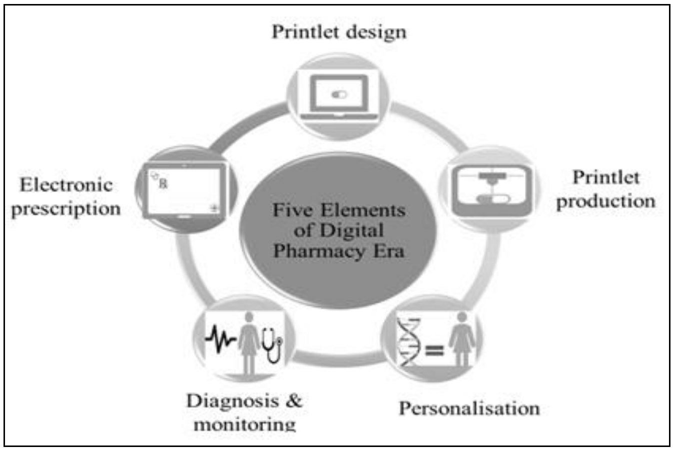

FIG. 1: FIVE ELEMENTS OF DIGITAL PHARMACY ERA

There are many technologies of additive production (AM), including bioprinting, DLP, FDM, HME, JET 3D, SLS, SSE, SLA, etc. In 3D printing, one layer of the substrate is surrounded by CAD, the nozzle builds the base of the object at the X-Y level and sets the thickness along the Z axis. Recent achievements in the field of non -invasive observations for diseases, including development, personalized drug guarantee and real -time treatment supervision [9]. Researchers have shown that with artificial intelligence, 3D printing technology can provide various advantages, including the possibility of determining printing and guaranteeing the quality and safety of complete drugs [10].

Personalized medical care can be presented in real time by sending a microbial recipe to the central management environment of 3D printing **Fig. 1.** This can be an innovative concept for digital pharmacy.

Timeline of Historic Inventions of Three-Dimensional Printing: Charles Hull invented 3D printing in 1984, calling it stereolithography [11]. With a background in engineering physics, Hull developed the method while working at Ultra Violet Products, using photopolymers to create plastic objects. The .STL file format, which stores CAD data like shape, color, and texture, guides the 3D printer. Hull founded 3D Systems, launching the first 3D printer, the "stereolithography apparatus." By 1988, their SLA-250 became the first commercial model. Later, firms like DTM Corporation and Z Corporation further refined the technology. Today, 3D printing revolutionizes industries, including manufacturing and medicine [12]. **Fig. 2** Demonstrates how 3D printing has developed throughout the years.

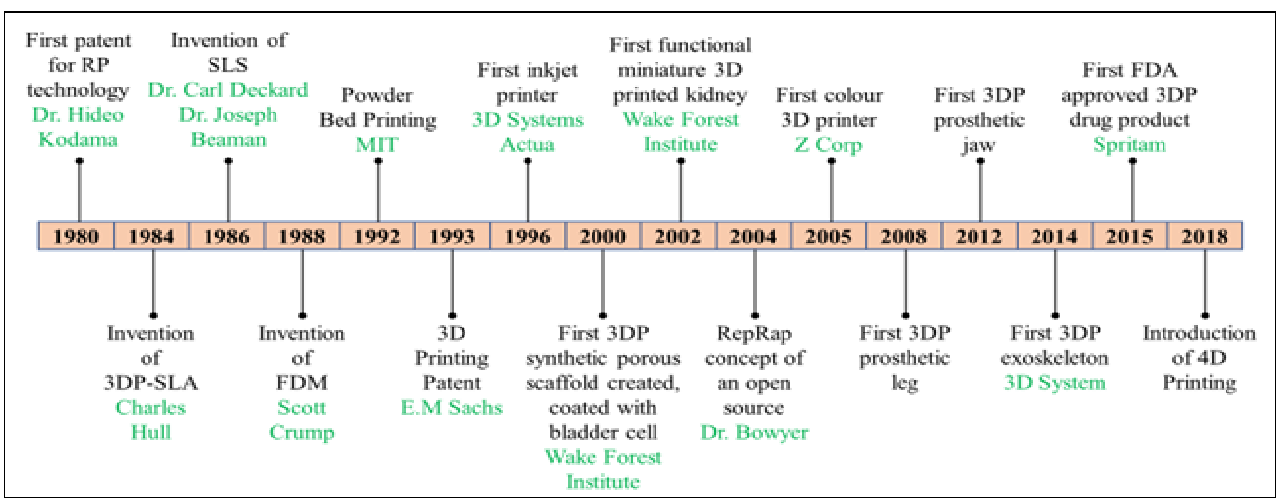

FIG. 2: A FRAMEWORK OF 3D PRINTING'S HISTORICAL DEVELOPMENT

Positive and Negative Aspects of three-dimensional printing [13]: Three-dimensional printing possesses various positive and negative aspects, which are outlined briefly in **Table 1.**

TABLE 1: POSITIVE AND NEGATIVE ASPECTS OF 3D PRINTING

Positive Aspects	Negative Aspects
3D printing accelerates idea development, cutting the process from months to days and enabling same-day concept production to keep companies competitive.	3D technology simplifies replica creation, sparking concerns over intellectual property rights.
3D printing reduces costs by enabling affordable part and tool production compared to expensive injection mold prototyping and machining.	3D printing is limited by size constraints, preventing the production of very large objects.
3D-printed prototypes offer a cost-effective way to validate designs before investing in expensive molding tools.	With only about 100 materials available, 3D printing lags behind traditional manufacturing. More research is needed for stronger, more durable products.
Mass production creates identical parts, while 3D printing enables custom designs, revolutionizing industries like medicine and innovation.	Automation may reduce manufacturing jobs, posing economic risks for developing nations like China, which rely on low-skilled labor.
Digital art and design have surged beyond expectations, and 3D printing now turns virtual ideas into tangible products quickly.	

Basic Working Procedures of Three-Dimensional Printing [12]: With this technology, concepts are turned into prototypes with the help of 3D computer-aided design (CAD) files, thereby allowing digitally controlled and customized products to be produced. Using this technology, layers of materials such as living cells, wood, alloys, thermoplastics, metals, etc., are layered on top of each other in order to build a 3D object. Aside from 3D printing, terms such as layered manufacturing, additive manufacturing, computer-assisted manufacturing, rapid prototyping, or solid freeform technology (SFF) are also used to describe the process. The procedure for 3D printing is demonstrated graphically in **Fig. 3.**

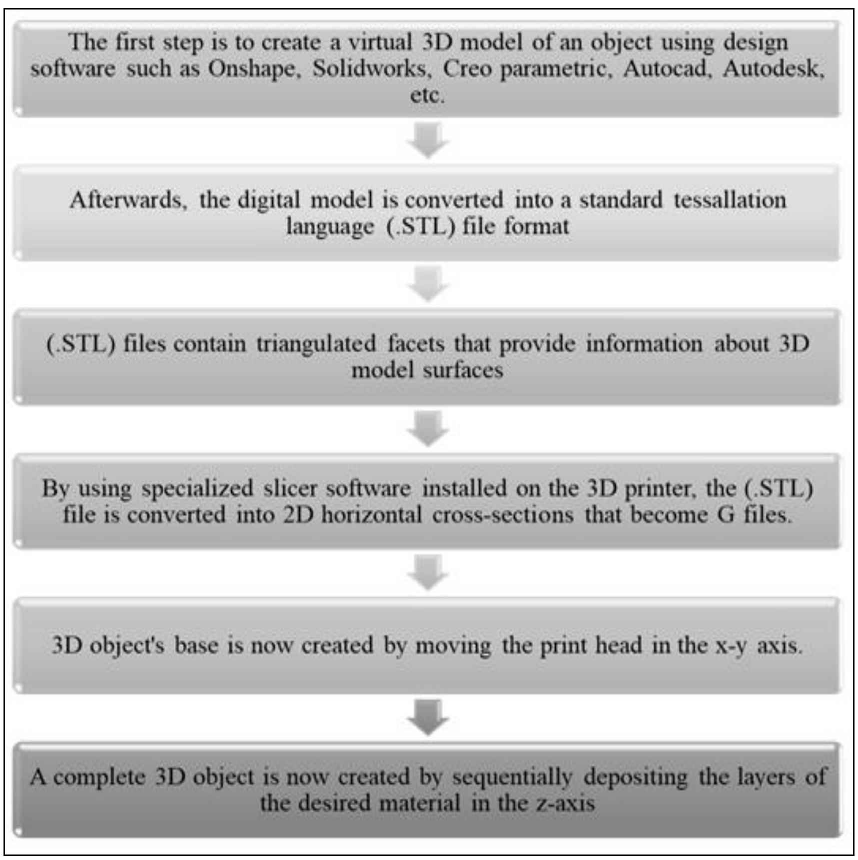

FIG. 3: A GRAPHICAL REPRESENTATION OF THE BASIC 3D PRINTING PROCEDURE

Comparisons between Two, Three, & Four-Dimensional Printing [14]: 2D printing creates flat images or texts on surfaces like paper, while 3D printing builds solid objects layer by layer using materials such as plastic or metal. 4D printing adds smart materials that transform over time when triggered by external factors. Though 4D is more advanced, it still shares its foundation with 3D printing, showing how additive manufacturing continues to evolve and influence fields like healthcare, engineering, and construction **Fig. 4.**

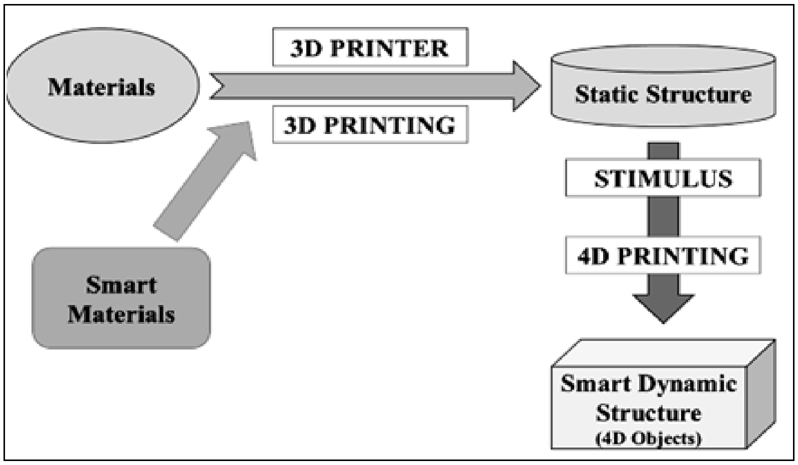

FIG. 4: FUNDAMENTAL PROCESS STEPS FOR 3D PRINTING & 4D PRINTING

3D and 4D printing share the same foundational process designing with 3D modeling software and printing with 3D printers. The key difference lies in 4D printing's use of smart materials that react to triggers like heat, light, moisture, or electricity, allowing printed objects to change over time. Effective 4D printing relies on suitable responsive materials, external stimuli, and time-based transformation. Advances in polymer science have made it possible to create materials that adapt or reshape under specific conditions **Fig. 5.**

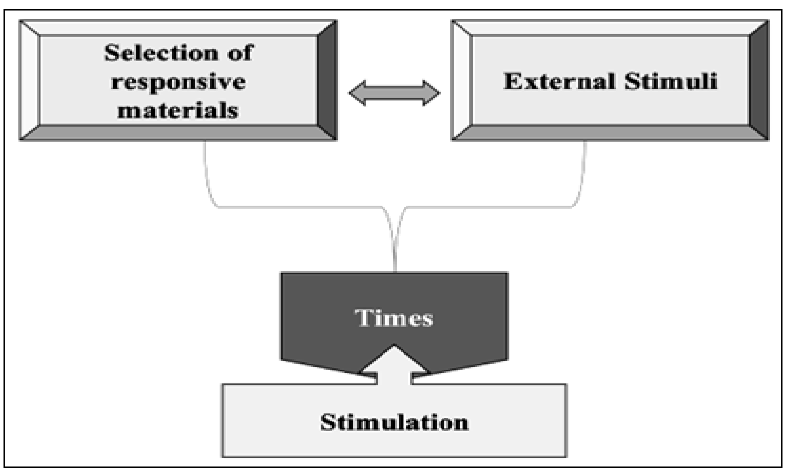

FIG. 5: THE KEY CHARACTERISTICS ASSOCIATED WITH 4D PRINTING

The Development of Crowd Funding [16]: After 2009, the 3D printing market divided into industrial firms with exclusive tech and a growing open-source community using RepRap and filament printers. Kickstarter, also launched in 2009, played a major role by helping fund open-source printer projects, offering printers as rewards to supporters. Success stories include the Form 1, which raised $3 million in 2012, and the Buccaneer, which earned half that a year later. Numerous other campaigns also secured significant funding, boosting progress in consumer and post-processing 3D printing.

An Overview of Various Additive Manufacturing Techniques used in Pharmaceutical Industry: Additive manufacturing (AM) methods were developed to meet the need for printing complex structures with high precision.

These technologies aim to enable larger builds, minimize errors, and enhance mechanical strength. Fused Deposition Modeling (FDM), which uses polymer filaments, is among the most popular 3D printing methods. Other key AM techniques include stereolithography, direct energy deposition, selective laser sintering and melting, inkjet printing, liquid binding, laminated object manufacturing, and contour crafting **Fig. 6** [17].

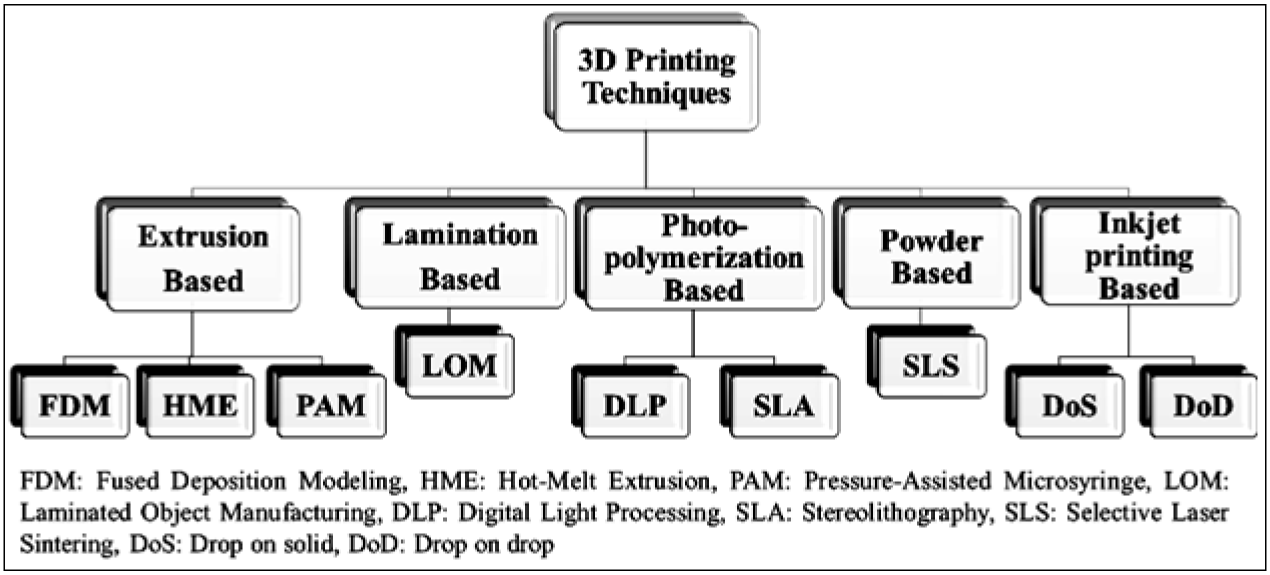

FIG. 6: DIFFERENT ADDITIVE MANUFACTURING TECHNIQUE

Elementary 3d Printing Technologies Employed Within the Pharmaceuticals Sector, Along with a Description of the Materials, Benefits, and Drawbacks:

Fused Deposition Modelling (FDM): For 3D printing, FDM uses thermoplastic filaments that melt when heated and are layered to form solid structures as they cool. The melted material bonds with previous layers and hardens at room temperature. Adding fiber-reinforced composites has enhanced the strength of printed parts, though challenges remain with fiber alignment, bonding quality, and voids in the material [18, 19]. Further summarises in **Table 2.**

TABLE 2: SUMMARISES THE VARIOUS MATERIALS, ADVANTAGES AS WELL AS DISADVANTAGES, APPLICATIONS AND RESOLUTION OF FDM [24]

Fused Deposition Modelling	**Materials**	Continues filaments of thermoplastic polymers Continuous fibre-reinforced polymers
	Advantages	Cost-effective Speedy Simplicity
	Disadvantages	Poor mechanical qualities Limited materials (only thermoplastics) Layer-by-layer finish
	Applications	Rapid prototyping Toys advanced composite parts
	Resolution (µm)	50-200 µm

Powder Bed Fusion (PBF): Powder bed fusion builds 3D objects by layering fine powder and using a laser or binder to fuse it.

After printing, leftover powder is cleared and the part may undergo steps like sintering.

Selective Laser Melting (SLM) fully melts metals for stronger parts, while Selective Laser Sintering (SLS) partially fuses materials like polymers and alloys [21, 22]. Further summarises in **Table 3.**

TABLE 3: SUMMARISES THE VARIOUS MATERIALS, ADVANTAGES AS WELL AS DISADVANTAGES, APPLICATIONS AND RESOLUTION OF PBF [24]

Powder Bed Fusion	**Materials**	Compacted fine powders Metals, alloys and limited polymers (SLS or SLM) ceramic and polymers
	Advantages	Fine resolution Superior quality
	Disadvantages	Slow printing Costly High porosity in the binder method (3DP)
	Applications	Biomedical Electronics Aerospace Lightweight structures (lattices)
	Resolution (µm)	80-250 µm

Inkjet Printing & Contour Crafting: Inkjet printing is a widely used method for creating ceramic structures, especially in tissue engineering.

It involves depositing ceramic suspensions, like zirconia oxide in water [24], through a nozzle onto a surface, forming solid layers that support further printing.

Ceramic inks are either wax-based, which solidify on a cool surface, or liquid suspensions that harden as the liquid evaporates. The quality of printed parts depends on factors like particle size, ink viscosity, extrusion speed, nozzle size, and solid content [25]. Further summarises in **Table 4.**

TABLE 4: SUMMARISES THE VARIOUS MATERIALS, ADVANTAGES AS WELL AS DISADVANTAGES, APPLICATIONS AND RESOLUTION OF INKJET PRINTING & CONTOUR CRAFTING [32]

Inkjet printing and contour crafting	**Materials**	Concentrated dispersion of particles in a liquid (ink or paste) Ceramic, concrete and soil
	Advantages	Being able to print massive structures Quick printing
	Disadvantages	Maintaining workability Coarse resolution Lack of adhesion between layers Layer-by-layer finish
	Applications	Biomedical Large structures Buildings
	Resolution (μm)	Inkjet: 5–200 μm Contour crafting: 25–40 mm

Stereolithography (SLA): Stereolithography (SLA) was one of the first additive manufacturing methods [27]. It uses UV light or electron beams to solidify resin layer by layer through polymerization. After printing, excess resin is removed, and post-curing processes like heating or light exposure improve strength. SLA can also print ceramic-filled resins, enabling advanced material applications [30].

It delivers high-resolution parts (≤10 μm) but is relatively slow, costly, limited in material options, and involves complex curing dynamics influenced by light intensity and exposure time [27]. Further summarises in **Table 5.**

TABLE 5: SUMMARISES THE VARIOUS MATERIALS, ADVANTAGES AS WELL AS DISADVANTAGES, APPLICATIONS AND RESOLUTION OF SLA [24]

Stereolithography	**Materials**	Resin with photo-active monomers Hybrid polymer-ceramics
	Advantages	Fine resolution Supreme quality
	Disadvantages	Very limited materials Slow printing Costly
	Applications	Biomedical Prototyping
	Resolution (μm)	10 μm

Direct Energy Deposition (DED): Direct energy deposition (DED) is a technique used to produce high-performance super alloys. Also known by names like laser engineered net shaping and direct metal deposition, it involves focusing a laser on a small area of a surface while simultaneously melting and adding material. As the laser moves, the feedstock melts, bonds to the surface, and solidifies in place [30]. Further summarises in **Table 6.**

TABLE 6: SUMMARISES THE VARIOUS MATERIALS, ADVANTAGES AS WELL AS DISADVANTAGES, APPLICATIONS AND RESOLUTION OF DED [24]

Direct Energy Deposition	**Materials**	Metals and alloys in the form of powder or wire Ceramics and polymers
	Advantages	Decreased production costs and time Superior mechanical qualities Controlled microstructure Accurate composition control
	Disadvantages	Low precision Poor surface quality, need for a dense support structure Complex shapes with fine details cannot be printed
	Applications	Aerospace Retrofitting Repair Cladding Biomedical
	Resolution (μm)	250 μm

Numerous Materials Are Employed for the 3D Printing Process in the Pharmaceutical Domain:

Metals and Alloys: In 2016, 97 firms sold AM systems, up from 49 in 2014, with nearly half focusing on metal AM. The aerospace industry uses this technology for prototyping, testing, and advanced parts like Boeing's F-15 Pylon Rib [32, 33]. It also serves automotive, defense, and biomedical sectors. Metal AM creates intricate, multifunctional parts for structural, protective, and insulation needs. Processes like Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) melt metal layers using lasers or electron beams. Emerging methods include binder jetting [34], cold spraying [35], friction stir welding [36], direct metal writing [38], and diode-based techniques [39].

These methods achieve high precision or speed. The PBF-based AM process can produce parts from metals like stainless steel, tool steel, aluminum alloys, titanium alloys, and nickel-based alloys. However, they are mainly used for small components due to slower speeds (up to 105 cm^3/h with four lasers). Research is exploring femtosecond lasers for high-melting-point materials (above 3000°C) and high thermal conductivity metals (over 100 W/mK), such as tungsten, rhenium, and certain ceramics. AM is optimized for titanium, steel, cobalt, magnesium, aluminum, and nickel alloys [40].

Polymers and Composites: Polymers dominate 3D printing due to their adaptability across various techniques. They are used as filaments, resins, powders, or monomers in processes like stereolithography and selective laser sintering (SLS). Industries such as aerospace, medicine, and consumer goods benefit from 3D-printed polymers, which enable precise, cost-effective customization compared to traditional methods like molding. However, pure polymer parts often serve only as prototypes due to limited strength. Research continues to enhance their mechanical properties, leading to advanced composites [24, 42]. Photopolymers, cured by UV light, account for nearly half of industrial 3D printing prototypes. Yet, their thermomechanical performance requires improvement, as layer thickness and UV exposure affect molecular structure. SLS, another key method, processes materials like polyamides and thermoplastic elastomers [43].

Ceramics: Additive manufacturing is revolutionizing ceramic production, particularly for biomedical applications such as bone and dental scaffolds [46]. However, ceramic 3D printing faces material limitations and visible layer lines that affect part quality [30]. While sintering printed ceramics enables complex geometries, the process remains time-intensive and costly. The technology excels in creating porous, lattice-structured ceramics that outperform traditional methods in speed and design flexibility for tissue engineering applications [30].

Key ceramic AM techniques include powder bed fusion, inkjet printing (optimal for large, post-process-free parts), paste extrusion, and stereolithography. Inkjet printing requires precisely formulated suspensions to ensure proper flow and drying [47], though printed filaments may experience cracking and shrinkage due to viscoelastic ink properties [48]. While selective laser sintering (SLS) is widely used for ceramic powders, thermal stress often causes cracking - a challenge addressed by the emerging selective laser gelation (SLG) method that integrates sol-gel chemistry with SLS for improved composite fabrication [49].

Concrete: Additive manufacturing is rapidly transforming construction practices, with emerging techniques like contour crafting - an inkjet-inspired method using large nozzles and high-pressure concrete extrusion [50]. This innovative approach incorporates a smoothing tool that eliminates visible layering, creating finished surfaces. While still in early development, 3D printing for buildings shows promise despite undetermined long-term performance characteristics. Recent research highlights the critical importance of fresh concrete properties, particularly extrudability for complex shapes and immediate strength (buildability) to support layered deposition [51].

Compared to traditional methods, 3D-printed fiber-reinforced concrete offers superior control over fiber alignment, demonstrated by a 30 MPa flexural strength increase when carbon fibers were strategically oriented during parallel line deposition. Current studies continue to refine both materials and methods for this groundbreaking construction technology [52].

Application of Three-Dimensional Printing Technology:

Three-dimensional Printing Methodology in Drug Delivery: In order to achieve customized drug delivery profiles, unique, novel, and specific geometries have been fabricated in 3D printing to achieve tailored drug release characteristics. With the arrival of three-dimensional printing, API can be delivered in different dosage forms [53], including immediate-release tablets [54], sustained-release tablets [55], modified-release tablets [61], immediate-release films [56], and controlled-release transdermal patches [53]. Simultaneously hydrophobic as well as hydrophilic drugs have been delivered using 3D printing technology. Additionally, 3D printing technology is used to fabricate drugs that fall underneath BCS classifications II and also IV, to enhance their solubility and bioavailability [57]. Various approaches to drug delivery using 3D printing will be discussed in this section.

Three-Dimensional Printing Technology in Oral Drug Delivery: 3D printing offers a promising alternative to traditional methods for producing solid oral medications. Unlike conventional manufacturing, this technology enables customized formulations that address common limitations. It allows for personalized dosages with varied sizes, complex shapes, and tailored drug release profiles. Extrusion-based 3D printing is widely used in oral drug development, facilitating immediate-release, delayed-release, polypills (combining multiple drugs), and gastro-retentive systems. Oral drug delivery remains the most convenient and patient-compliant route. However, traditional production restricts shape and design flexibility, whereas 3D printing's layer-by-layer approach enables unique geometries. Fuenmayor *et al.,* 2019, compared fused deposition modeling (FDM), injection molding (IM), and direct compression (DC) to produce identical tablets [54]. Results showed differences in physical properties and drug release, highlighting 3D printing's potential for innovation in pharmaceutical manufacturing.

Three-Dimensional Printing Technology in Transdermal Delivery of Drugs: 3D printing enables precise fabrication of transdermal drug delivery systems, including implants, microneedles, and patches, allowing localized or systemic API administration.

Kempin *et al.* developed customized 3D-printed implants using FDM-based hot-melt extrusion, incorporating drugs like quinine into polymer filaments for tailored release. Meanwhile, Allen et al. employed piezoelectric inkjet printing to produce dissolvable microneedles encapsulating a stabilized influenza vaccine, demonstrating controlled percutaneous delivery. These innovations highlight 3D printing's potential for personalized and advanced transdermal therapies [58].

Three-Dimensional Printing Technology in Pulmonary Drug Delivery: Printed prototypes of the lungs help to better understand the progression of the disease and to provide individual suction drugs. Morrison *et al.* In the case of pediatric organ bronocco -call, obstacle life reduces the life of obstacles [59]. Zopf *et al.* used 3D printing in a pig model to achieve similar success. This method optimizes the ergonomics of the inhaler by improving asthma treatment [60]. Quinones *et al.,* 2018, the respiratory movement, a 3D printed tumor simulator, continues to increase the accuracy of the radiation therapy plan for cancer patients [61].

Three-Dimensional Printing Technology in Intrauterine Drug Delivery: This technique allows you to use the form and dimensions of TaylorMade for the topic or control of the API of the whole body. Hollander *et al.,* developed a T-shaped uterus device using FDM-3D printing using polycaprolacton. Compared to the extruded filament, indomethacin, which has a 3D printing device, was freely released in the form of a print due to the amorphous state of the drug, and the resolution was increased compared to the crystalline charging drug room. This technology has allowed the production of various biological structures, including bones, vascular networks, organs and individual fabrics.

Three-Dimensional Printing Technology in Bio-Medical Sector: 3D printing has altered the medication since the early use of prosthetics and dental implants in the 2000s [14, 64]. This technology has allowed the production of various biological structures, including bones, vascular networks, organs and individual fabrics. The current application includes surgical models, personal implants, drug supply systems and drug inspections, and shows amazing universality in medical innovation [13, 65, 66, 67]. Then, in **Table 7**, we follow a brief expression of the application of biological medical application of 3D pressure.

TABLE 7: SUMMARISATION OF BIO-MEDICAL APPLICATIONS OF THREE-DIMENSIONAL PRINTING

Bioprinting	Cartilage
	Organ-on-chip
Implants & Prostheses	Limbs
	Craniofacial implants
	Casts
	Stents
Surgical models	Organs
	Vasculature
	Tumor models
	Disease models
Materials	Silicon
	Titanium
	Nanocellulose
	PCL
	PEG
	Alginate
Advantages	High resolution
	Good stability
	More effective treatment
	Increased surgeons skills
	Multipurpose materials
	Design of precise shapes

Application of Three-Dimensional Printing in Organ & Tissue Bioprinting: Tissue and organ failure caused by aging, disease, or trauma presents a critical healthcare challenge. While transplantation remains the primary treatment, donor shortages and compatibility issues significantly limit its effectiveness [11, 64].

These limitations have spurred the development of regenerative medicine approaches using patient-derived cells, which could reduce rejection risks and eliminate the need for lifelong immunosuppressants. Traditional organizational methods include cultivation of stem cells in biological frames, but the new 3D bio -printing method provides accuracy and excellent accuracy of cell placement compared to the tissue structure [64, 68, 69]. This improved method uses biosensation containing cells and biomaterials to build a layer of alternative lifestyles, and hydrogel is particularly effective in producing soft tissue. Current bioprinting systems (inkjet, lasers and extrusions) can produce multiple types of cells and complex structures, including vascular networks. The entire process of bio printing includes digital design, cell preparation, accurate precipitation and biological reactors. Although this technology is still developing, it has already succeeded in the production of various functional tissues from heart valve to artificial ears and has been a great success in solving the crisis of organ deficiency [12, 69, 70].

Application of Three-Dimensional Printing in Customised Prostheses and Also Implants: A prosthesis and surgical implant that produces standards and complex structures within 24 hours [12, 65, 67, 69, 71].

This innovation has revolutionized in the application field of dentistry, spine and orthopedic applications that traditional implants do not meet the anatomical requirements of certain patients. Unlike traditional production that requires manual formation of materials, 3D tape can provide especially useful accurate adjustments for brain implants after skull -brain damage [65, 79]. This method has achieved considerable clinical perception. This has been proven by the same breakthrough as a titanium nominal prosthesis developed in Belgium and was made by laser melting of titanium powder. This approach relates to significant restrictions on standardized implants when strengthening production time plans [67].

Application of Three-Dimensional Printing in Anatomical Models for Surgical Strategy: 3D-printed patient-specific models provide superior surgical planning tools compared to traditional 2D imaging, offering tactile, three-dimensional representations of complex anatomy. These customized models enable surgeons to practice intricate procedures and identify optimal surgical pathways with greater precision than MRI or CT scans alone [12, 67].

Particularly valuable in neurosurgery, they accurately display delicate structures like cranial nerves and blood vessels, reducing operative risks. Beyond cadavers, which lack pathological specificity, 3D models serve as cost-effective training tools that replicate actual patient anatomy [65]. The technology also extends to biomedical education, where printed molecular structures enhance understanding of complex biological systems through hands-on interaction. Recent innovations include dynamic models capable of simulating molecular interactions, demonstrating the versatility of 3D printing in both clinical and educational applications [12, 67].

Application of Three-Dimensional Printing in Unique Dosage Forms: 3D printing allows unprecedented marks in the field of drug doses, which leads to a system based on ink beams as a common method of pharmaceutical production. This technology can promote innovative configuration such as polypills using multiple drugs, allowing users to perform customized binding methods using one mode. In particular, these achievements are helpful for various diseases by improving drug compliance due to simplified doses. This technology successfully produces a variety of drug delivery systems, including hyaluron salt base, antibiotic micro -stacker, biological active glass scaffolds and nanosa pensions, and have excellent diversity for constraints [68, 70]. **Table 8** indicates an overview of the ingredients used in 3D printing. This additional production technology revolutionizes the medical system due to the progress of materials and resolution, increasing accuracy.

TABLE 8: SUMMARY OF INGREDIENTS THAT ARE UTILISED IN 3D PRINTING

Active pharmaceutical ingredients	Inactive pharmaceutical ingredients
Vancomycin	Glycerine
Ofloxacin	Methanol
Folic acid	Acetone
Dexamethasone	Surfactants (like Tween 20)
Theophylline	Kollidon SR
Acetaminophen	Ethanol-dimethyl sulfoxide
Paclitaxel	Propylene glycol
Tetracycline	Cellulose

Recent Advances and Developments: The latest achievements and development of pharmaceutical interventions obtained using 3D printing methods are listed in **Table 9**.

This technology is very beneficial because it allows digital distribution of pharmaceutical compositions in local pharmacies for production and can innovate traditional production and supply chains.

TABLE 9: RECENT ADVANCES AND DEVELOPMENTS IN PHARMACEUTICAL INTERVENTIONS MANUFACTURED BY EMPLOYING THREE-DIMENSIONAL PRINTING TECHNOLOGIES

Sl. no.	Remedies	Dosage Form	3DP Technique	References
1.	Caffeine	Tablet	FDM and injection modeling (IM) technique	[59]
2.	Ropinirole hydrochloride	Tablet	3DP-UV inkjet printing	[71]
3.	Dronedarone & ascorbic acid	Super-H & Can-capsule	FDM	[72]
4.	Paracetamol and 4-aminosalicylic acid	Modified-release tablets	SLA	[73]
5.	Quinine	Implants	FDM coupled with hot-melt extrusion	[74]
6.	Deflazacort	Nanocapsules	FDM	[75]
7.	Progesterone	Vaginal rings	FDM	[60]
8.	Irbesartan	Multilayered polypill	SLA	[76]
9.	Acetaminophen	Controlled release tablets	Inkjet printing	[77]
10.	Riboflavin and Ibuprofen	Hydrogels	SLA	[78]
11.	Progesterone and 5-fluorouracil	Intrauterine device (IUD)	SLS	[61]
12.	Paclitaxel	Tablet	Extrusion printing	[79]
13.	Insulin	Polymeric needle patches	SLA	[80]
14.	Levofloxacin	Implants	Inkjet 3DP	[81]
15.	Isoniazid	Implant	Inkjet 3DP	[82]
16.	Chlorpheniramine maleate	Delayedrelease tablets	FDM	[83]
17.	5-Fluorouracil	Bio-degradable patch	Extrusion-based three-dimensional printing	[84]

FDM = Fused Deposition Modeling; SLA = Stereolithography; SLS = Selective Laser Sintering.

Future Perspectives: 3D printing changes personalized drugs due to the ability of drugs, functional tissues and in some cases, and in some cases. This technology gains great advantages because the digital distribution of pharmaceutical compositions in local pharmacies revolutionizes on customized production and traditional production and supply. These changes were combined with several drugs at once, leading to individual polypill and greatly improved compliance with the patient. While still in early development, 3D printing offers unprecedented flexibility in drug manufacturing, facilitating novel delivery systems such as hyaluronan-based microcapsules, bioactive scaffolds, and precision-controlled release formulations.

The most groundbreaking applications may emerge in bioprinting, where researchers anticipate creating functional organs within two decades. Current progress includes successful skin regeneration using layered cell printing, with future applications targeting complex organs like livers and kidneys. Patient-specific tissue strips could serve as testing platforms for medication efficacy, while stem cells from biological sources like dental pulp may enable personalized organ regeneration. Surgical applications are advancing through *in-situ* bioprinting techniques, where portable printers could directly repair damaged tissues during procedures, aided by robotic surgical systems. Emerging developments like 4D printing - where biocompatible materials adapt post-production - demonstrate the field's innovative potential. While technical and regulatory challenges remain, ongoing research continues to refine these methods, positioning 3D printing as a future standard for personalized, on-demand medical solutions that could fundamentally transform patient care across multiple specialties.

CONCLUSION: The world could be revolutionized by 3D printing technology. Technological progression for three-dimensional printing can significantly improve and change how we manufacture products throughout the world. Computer Aided Design software scans or designs objects, then slices them into thin layers that can be printed later to produce solid three-dimensional products.

Research activities on personalized treatment approaches have been significantly influenced by 3D printing technology. Pharmacy, industry, and even household sites are now actively engaged in real-time manufacturing of pharmaceuticals, largely benefiting from the long-standing trend of on-demand manufacturing in central facilities. It is crucial for healthcare professionals and patients to address practical issues ranging from safety-first (from the patient's perspective) to everyday practices (from the healthcare professionals' perspective) before even considering implementing these scenarios. There must be significant changes, taking into account current regulations and the mentality of all relevant professionals and members of the public. Although three-dimensional printing has changed everything how we perceive medicines, major steps must be taken in a timely manner in order to realize the leap from current pharmaceutical strategies towards the future pharmaceutical manufacturing concepts.

ACKNOWLEDGEMENTS: Authors are grateful to Dr. B. C. Roy College of Pharmacy & A.H.S., Durgapur and Mata Gujri College of Pharmacy, Kishanganj, Bihar for providing all the facilities for this work.

CONFLICT OF INTEREST: The author(s) confirm that this article content has no conflicts of interest.

REFERENCES:

1. Ćwiklicki M, Klich J and Chen J: The adaptiveness of the healthcare system to the fourth industrial revolution: A preliminary analysis. Futures 2020; 122: 102602.
2. de Castro Sobrosa Neto R, Maia JS, de Silva Neiva S, Scalia MD and de Andrade Guerra JB: The fourth industrial revolution and the Coronavirus: A new era catalyzed by a virus. Res Glob 2020; 2: 100024.
3. Peng T, Kellens K, Tang R, Chen C and Chen G: Sustainability of additive manufacturing: An overview on its energy demand and environmental impact. Addit Manuf 2018; 21: 694-704.
4. Govender R, Abrahmsén-Alami S, Larsson A and Folestad S: Therapy for the individual: Towards patient integration into the manufacturing and provision of pharmaceuticals. Eur J Pharm Biopharm 2020; 149: 58-76.
5. Mancilla-de-la-Cruz J, Rodriguez-Salvador M and Ruiz-Cantu L: The next pharmaceutical path: determining technology evolution in drug delivery products fabricated with additive manufacturing. Foresight STI Gov 2020; 14(3): 55-70.
6. Yeh CC and Chen YF: Critical success factors for adoption of 3D printing. Technol Forecast Soc Change 2018; 132: 209-16.
7. Berman B: 3-D printing: The new industrial revolution. Bus Horiz 2012; 55(2): 155–62.
8. Mathew E, Pitzanti G, Larrañeta E and Lamprou DA: 3D printing of pharmaceuticals and drug delivery devices. Pharmaceutics 2020; 12(3): 266.
9. Awad A, Trenfield SJ, Gaisford S and Basit AW: 3D printed medicines: A new branch of digital healthcare. Int J Pharmaceu 2018; 548(1): 586-96.
10. Elbadawi M, McCoubrey LE, Gavins FK, Ong JJ, Goyanes A, Gaisford S and Basit AW: Harnessing

artificial intelligence for the next generation of 3D printed medicines. Adv Drug Del Revi 2021; 175: 113805.
11. Schubert C, van Langeveld MC and Donoso LA: Innovations in 3D printing: a 3D overview from optics to organs. Br J Ophthalmol 2014; 98(2): 159–61.
12. Gross BC, Erkal JL, Lockwood SY, Chen C and Spence DM: Evaluation of 3D printing and its potential impact on biotechnology and the chemical sciences. Anal Chem 2014; 86(7): 3240–53.
13. Gokhare VG, Raut DN and Shinde DK: A review paper on 3D-printing aspects and various processes used in the 3D-printing. Int J Eng Res Technol 2017; 6(06): 953-8.
14. Zhang Z, Demir KG and Gu GX: Developments in 4D-printing: a review on current smart materials, technologies, and applications. Int J Sma Nano Mater 2019; 10(3): 205-24.
15. Choi J, Kwon OC, Jo W, Lee HJ and Moon MW: 4D printing technology: a review. 3D Print Addit Manuf 2015; 2(4): 159-67.
16. Berns JP, Jia Y and Gondo M: Crowdfunding success in sustainability-oriented projects: An exploratory examination of the crowdfunding of 3D printers. Tech Soc 2022; 71: 102099.
17. Bhushan B and Caspers M: An overview of additive manufacturing (3D printing) for microfabrication. Microsys Techno 2017; 23: 1117-24.
18. Parandoush P and Lin D: A review on additive manufacturing of polymer-fiber composites. Compos Struc 2017; 182: 36-53.
19. Wang X, Jiang M, Zhou Z, Gou J and Hui D: 3D printing of polymer matrix composites: A review and prospective. ComposB Eng 2017; 110: 442-58.
20. Mazzanti V, Malagutti L and Mollica F: FDM 3D printing of polymers containing natural fillers: A review of their mechanical properties. Polym 2019; 11(7): 1094.
21. Utela B, Storti D, Anderson R and Ganter M: A review of process development steps for new material systems in three-dimensional printing (3DP). J Manuf Proce 2008; 10(2): 96–104.
22. Lee H, Lim CHJ, Low MJ, Tham N, Murukeshan VM and Kim YJ: Lasers in additive manufacturing: a review. Int J Precis Eng Manuf-Green Technol 2017; 4(3): 307–22.
23. Huber F, Rasch M and Schmidt M: Laser powder bed fusion (Pbf-lb/m) process strategies for *in-situ* alloy formation with high-melting elements. Met 2021; 11(2): 336.
24. Dou R, Wang T, Guo Y and Derby B: Ink-jet printing of Zirconia: Coffee staining and line stability. J Am Ceram Soc 2011; 94(11): 3787–92.
25. Travitzky N, Bonet A, Dermeik B, Fey T, Filbert-Demut I, Schlier L, Schlordt T and Greil P: Additive manufacturing of ceramic-based materials. Adv Eng Mater 2014; 16(6): 729–54.
26. Elkaseer A, Schneider S, Deng Y and Scholz SG: Effect of process parameters on the performance of drop-on-demand 3D inkjet printing: Geometrical-based modeling and experimental validation. Polymer 2022; 14(13): 2557.
27. Kazemian A, Yuan X, Cochran E and Khoshnevis B: Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture. Construct Build Mater 2017; 145: 639–47.
28. Melchels FPW, Feijen J and Grijpma DW: A review on stereolithography and its applications in biomedical engineering. Biomater 2010; 31(24): 6121–30.
29. Eckel ZC, Zhou C, Martin JH, Jacobsen AJ, Carter WB and Schaedler TA: Additive manufacturing of polymer-derived ceramics. Sci 2016; 351(6268): 58–62.
30. Fernández-Francos X, Konuray O, Ramis X, Serra À and De la Flor S: Enhancement of 3D-printable materials by dual-curing procedures. Mater 2020; 14(1): 107.
31. Gibson I, Rosen D and Stucker B: Directed energy deposition processes. Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. 2nd ed. New York: Springer 2015; 245–68.
32. Arias-González F, Rodríguez-Contreras A, Punset M, Manero JM, Barro Ó, Fernández-Arias M, Lusquiños F, Gil FJ and Pou J: *In-situ* laser directed energy deposition of biomedical Ti-Nb and Ti-Zr-Nb alloys from elemental powders. Met 2021; 11(8): 1205.
33. Wohlers T: 3D printing and additive manufacturing state of the industry Annual Worldwide Progress Report Wohlers Report 2017.
34. Council NR: Accelerating technology transition: bridging the valley of death for materials and processes in defense systems. National Academies Press 2004.
35. Bai Y and Williams CB: An exploration of binder jetting of copper. Rapid Prototyp J 2015; 21(2): 177–85.
36. Sova A, Grigoriev S, Okunkova A and Smurov I: Potential of cold gas dynamic spray as additive manufacturing technology. Int J Adv Manuf Technol 2013; 69(9–12): 2269–78.
37. Sharma A, Bandari V, Ito K, Kohama K, Ramji M and BV HS: A new process for design and manufacture of tailor-made functionally graded composites through friction stir additive manufacturing. J Manuf Process 2017; 26: 122–30.
38. Chen W, Thornley L, Coe HG, Tonneslan SJ, Vericella JJ, Zhu C, Duoss EB, Hunt RM, Wight MJ and Apelian D: Direct metal writing: controlling the rheology through microstructure. Appl Phys Lett 2017; 110(9): 094104.
39. Matthews MJ, Guss G, Drachenberg DR, Demuth JA, Heebner JE, Duoss EB, Kuntz JD and Spadaccini CM: Diode-based additive manufacturing of metals using an optically-addressable light valve. Optic Express 2017; 25(10): 11788–800.
40. Herzog D, Seyda V, Wycisk E and Emmelmann C: Additive manufacturing of metals. Acta Mater 2016; 117: 371–92.
41. Nie B, Yang L, Huang H, Bai S, Wan P and Liu J: Femtosecond laser additive manufacturing of iron and tungsten parts. Appl Phys A 2015; 119(3): 1075–80.
42. Takezawa A and Kobashi M: Design methodology for porous composites with tunable thermal expansion produced by multi-material topology optimization and additive manufacturing. Compos B Eng 2017; 131: 21–9.
43. Ligon SC, Liska R, Stampfl J, Gurr M and Mülhaupt R: Polymers for 3D printing and customized additive manufacturing. Chem Rev 2017; 117(15):10212–90.
44. Gundrati NB, Chakraborty P, Zhou C and Chung DDL: First observation of the effect of the layer printing sequence on the molecular structure of three-dimensionally printed polymer, as shown by in-plane capacitance measurement. Compos B Eng 2018; 140: 78–82.
45. Gundrati NB, Chakraborty P, Zhou C and Chung DDL: Effects of printing conditions on the molecular alignment of three-dimensionally printed polymer. Compos B Eng 2018; 134: 164–8.
46. Wen Y, Xun S, Haoye M, Baichuan S, Peng C, Xuejian L, Kaihong Z, Xuan Y, Jiang P and Shibi L: 3D printed porous ceramic scaffolds for bone tissue engineering: a review. Biomater Sci 2017; 5(9): 1690-8.
47. Derby B: Additive manufacture of ceramics components by inkjet printing. Eng 2015; 1(1): 113–23.

48. Bienia M, Lejeune M, Chambon M, Baco-Carles V, Dossou-Yovo C, Noguera R and Rossignol F: Inkjet printing of ceramic colloidal suspensions: filament growth and breakup. Chem Eng Sci 2016; 149: 1–13.
49. Liu FH, Shen YK and Liao YS: Selective laser gelation of ceramic–matrix composites. ComposB Eng 2011; 42(1): 57-61.
50. Khoshnevis B: Automated construction by contour crafting - related robotics and information technologies. Autom Con Struct 2004; 13(1): 5–19.
51. Le TT, Austin SA, Lim S, Buswell RA, Gibb AGF and Thorpe T: Mix design and fresh properties for high-performance printing concrete. Mater Struct 2012; 45(8): 1221–32.
52. Hambach M and Volkmer D: Properties of 3D-printed fiber-reinforced Portland cement paste. Cement Concr Compos 2017; 79: 62–70.
53. Park BJ: Pharmaceutical applications of 3D printing technology: current understanding and future perspectives. J Pharm Investig 2019; 49(6): 575–85.
54. Gioumouxouzis CI: A 3D printed bilayer oral solid dosage form combining metformin for prolonged and glimepiride for immediate drug delivery. EJPS 2018; 120: 40–52.
55. Algahtani MS, Mohammed AA, Ahmad J and Saleh E: Development of a 3D printed coating shell to control the drug release of encapsulated immediate-release tablets. Polym 2020; 12(6): 1395.
56. Ehtezazi T, Algellay M, Islam Y, Roberts M, Dempster NM and Sarker SD: The application of 3D printing in the formulation of multilayered fast dissolving oral films. J Pharm Sci 2018; 107(4): 1076–85.
57. Tsintavi E, Rekkas DM and Bettini R: Partial tablet coating by 3D printing. Int J Pharm 2020; 581: 119298.
58. Allen EA, O'Mahony C, Cronin M, O'Mahony T, Moore AC and Crean AM: Dissolvable microneedle fabrication using piezoelectric dispensing technology. Int J Pharm 2016; 500(1−2): 1–10.
59. Morrison RJ: Mitigation of tracheobronchomalacia with 3D-printed personalized medical devices in pediatric patients. Sci Transl Med 2015; 7(285): 285-364.
60. Zopf DA, Flanagan CL, Wheeler M, Hollister SJ and Green GE: Treatment of severe porcine tracheomalacia with a 3-dimensionally printed, bioresorbable, external airway splint. JAMA Otolaryngol Neck Surg 2014; 140(1): 66–71.
61. Quinones DR: Open source 3D printed lung tumor movement simulator forradiotherapy quality assurance. Mater 2018; 11(8): 1317.
62. Fu J, Yu X and Jin Y: 3D printing of vaginal rings with personalized shapes for controlled release of progesterone. Int J Pharm 2018; 539(1−2): 75–82.
63. Cui X, Boland T, D'Lima DD and Lotz MK: Thermal inkjet printing in tissue engineering and regenerative medicine. Recent Pat Drug Deliv Formul 2012; 6(2): 149–155.
64. Banks J: Adding value in additive manufacturing: Researchers in the United Kingdom and Europe look to 3D printing for customization. IEEE Pulse 2013; 4(6): 22–26.
65. Hoy MB: 3D printing: making things at the library. Med Ref Serv Q 2013; 32(1): 94–99.
66. Klein GT, Lu Y and Wang MY: 3D printing and neurosurgery—ready for prime time?. World Neurosurg 2013; 80(3–4): 233–235.
67. Bartlett S: Printing organs on demand. Lancet Respir Med. 2013; 1(9): 684.
68. Mertz L: Dream it, design it, print it in 3-D: What can 3-D printing do for you?. IEEE Pulse 2013; 4(6): 15–21.
69. Lipson H: New world of 3-D printing offers "completely new ways of thinking:" Q & A with author, engineer, and 3-D printing expert Hod Lipson. IEEE Pulse 2013; 4(6): 12–14.
70. Gu Y, Chen X, Lee JH, Monteiro DA, Wang H and Lee WY: Inkjet printed antibiotic-and calcium-eluting bioresorbable nanocomposite micropatterns for orthopedic implants. Acta Biomaterialia 2012; 8(1): 424-431.
71. Clark EA, Alexander MR, Irvine DJ, Roberts CJ, Wallace MJ, Sharpe S, Yoo J, Hague RJ, Tuck CJ and Wildman RD: 3D printing of tablets using inkjet with UV photoinitiation. Int J Pharm 2017; 529(1-2): 523-30.
72. Gioumouxouzis CI: A 3D printed bilayer oral solid dosage form combining metformin for prolonged and glimepiride for immediate drug delivery. Eur J Pharm Sci 2018; 120: 40–52.
73. Wang J, Goyanes A, Gaisford S and Basit AW: Stereolithographic (SLA) 3D printing of oral modified-release dosage forms. Int J Pharmaceutics 2016; 503(1-2): 207-12.
74. Algahtani MS, Mohammed AA, Ahmad J, Abdullah MM and Saleh E: 3D printing of dapagliflozin containing self-nanoemulsifying tablets: formulation design and *in-vitro* characterization. Pharm 2021; 13(7): 993.
75. Beck RC, Chaves PS, Goyanes A, Vukosavljevic B, Buanz A, Windbergs M, Basit AW and Gaisford S: 3D printed tablets loaded with polymeric nanocapsules: An innovative approach to produce customized drug delivery systems. Int J Pharm 2017; 528(1-2): 268-79.
76. Xu X, Robles-Martinez P, Madla CM, Joubert F, Goyanes A, Basit AW and Gaisford S: Stereolithography (SLA) 3D printing of an antihypertensive polyprintlet: Case study of an unexpected photopolymer-drug reaction. Addit Manufac 2020; 33: 101071.
77. Yu DG, Branford-White C, Ma ZH, Zhu LM, Li XY and Yang XL: Novel drug delivery devices for providing linear release profiles fabricated by 3DP. Int J Pharm 2009; 370(1-2): 160-6.
78. Martinez PR, Goyanes A, Basit AW and Gaisford S: Fabrication of drug-loaded hydrogels with stereolithographic 3D printing. Int J Pharm 2017; 532(1): 313-7.
79. Gospodinova A, Nankov V, Tomov S, Redzheb M and Petrov PD: Extrusion bioprinting of hydroxyethylcellulose-based bioink for cervical tumor model. Carb Poly 2021; 260: 117793.
80. Pere CP, Economidou SN, Lall G, Ziraud C, Boateng JS, Alexander BD, Lamprou DA and Douroumis D: 3D printed microneedles for insulin skin delivery. Int J Pharm 2018; 544(2): 425-32.
81. Huang W, Zheng Q, Sun W, Xu H and Yang X: Levofloxacin implants with predefined microstructure fabricated by three-dimensional printing technique. Int J Pharm 2007; 339(1-2): 33-8.
82. Wu G, Wu W, Zheng Q, Li J, Zhou J and Hu Z: Experimental study of PLLA/INH slow release implant fabricated by three dimensional printing technique and drug release characteristics *in-vitro*. Biomed Eng 2014; 13: 1-11.
83. Rowe CW, Katstra WE, Palazzolo RD, Giritlioglu B, Teung P and Cima MJ: Multimechanism oral dosage forms fabricated by three dimensional printing™. J Cont Rel 2000; 66(1): 11-7.
84. Yi HG, Choi YJ, Kang KS, Hong JM, Pati RG, Park MN, Shim IK, Lee CM, Kim SC and Cho DW: A 3D-printed local drug delivery patch for pancreatic cancer growth suppression. J Cont Rel 2016; 238: 231-41.

How to cite this article:
Dhibar M, Chakraborty S and Sarkar B: Aspects of 3D printing in pharmaceutical technology: current scenario and its future perspective. Int J Pharm Sci & Res 2026; 17(1): 99-112. doi: 10.13040/IJPSR.0975-8232.17(1).99-112.