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Review Paper

3D Printing in Medicine: Technologies, Materials, Applications, Challenges, and Future Directions

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ABSTRACT

3D printing manufacturing, is rapidly transforming the landscape of modern medicine and pharmaceutical sciences facilitating the design and creation of customized, patient-specific solutions. This review systematically explores the major 3D printing technologies-fused deposition modelling (FDM), stereolithography (SLA), selective laser sintering (SLS), and inkjet printing, particularly targeting their mechanisms, advantages, and drawback in medical applications. Emphasis is placed on pharmaceutical-grade substances including thermoplastics, polymeric gel like hydrogels, biodegradable polymers, and tissue compatible ink called as bioinks, which are essential for successful printability and biocompatibility. The article further highlights key applications in personalized drug delivery, regenerative medicine, custom prosthesis production, and surgical visualization, demonstrating the versatility and clinical relevance of this technology. Despite its promise, the field faces critical challenges, including regulatory barriers, material limitations, reproducibility, and scalability issues. This review also discusses emerging trends such as 4D printing, AI integration, and smart materials, offering insight into future directions for Research and Innovation. The integration of 3D printing into mainstream pharmaceutical practice holds significant potential to drive personalized medicine and improve therapeutic outcomes.

INTRODUCTION

Startups like Teva and Aprecia are investigating the use of digitally fabricated pharmaceuticals, with Aprecia pioneering the first FDA-approved one. Aprecia introduced Spritam (Levetiracetam) for epilepsy in 2015 using its patented Zip Dose technology.[1] 3D printing is a vital innovative approach in healthcare, used in dentistry, tissue

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engineering, regenerative medicine, medical devices, and drug formulation and development. It supports both commercial medical products and advanced research like tissue and organ printing. Though patented in 1986, 3D printing gained attention recently and is now revolutionizing the pharmaceutical industry. In the past decade, it has advanced drug delivery systems and medical device production.[2] Pharmaceutical development constantly evolves with new drug designs, improved manufacturing methods, and a deeper understanding of material properties. Patient-focused treatments are gaining attention, promoting personalized medicine and customized drug delivery. Among the latest innovations, 3D printing stands out a revolutionary technology, enabling precise, patient-specific drug delivery system and healthcare devices.[3]

❖ Material and Methods Used In 3d Printing Medicines

Emerging 3d Printing Techniques in Pharmaceutics: Fabrication Methods and Medication Delivery Perspectives:

1) Fused Deposition Modelling (FDM)

FDM is a 3D printing technique where a filament is melted and deposited layer by layer to create a structure. Its mechanical properties depend on factors like the type and ration of API, polymer, and excipients.[4] FDM is an additive manufacturing technique that builds structures layer by layer, similar to Stereolithography (SL) and Selective Laser Sintering (SLS). Widely used in prototyping and production, FDM was invested by S. Scott Crump in the late 1980s and commercialized by Stratasys in 1990.[5] FDM shows great potential for personalized drug delivery and medical implants but lacks market-approved products due to regulatory challenges. This study evaluates three FDM printers based on key parameters like accuracy, temperature, printing, speed, and material flow.[6]

2) Stereolithography (SLA)

SLA is high-precision 3D printing technique that uses light as its energy source. It has gained popularity in fields like tissue engineering, dentistry, and pharmacoprinting for creating intricate drug delivery systems and personalized medicines.[7] SLA is a high-resolution 3D printing technique that solidifies liquid resin using photopolymerization, making it valuable in tissue engineering and drug delivery. It enables precise drug incorporation with minimal heat exposure, though its use is limited by the availability of photocrosslinkable polymers and regulatory constraints.[8] Stereolithography (SLA) has been used to create drug loaded print lets, like paracetamol tablets and anti-acne masks, by solidifying a photopolymerizable solution with a laser. While it enables high-resolution printing at room temperature, concerns over the potential carcinogenicity of photopolymer materials require further investigation.[9]

3) Selective Laser Sintering (SLS)

This study explores the feasibility of Selective Laser Sintering (SLS) for fabricating drug-loaded oral dosage forms using high quality pharmaceutical excipients. Unlike Powder Bed (PB) technique, SLS employs a laser to fuse powder particles, offering a solvent-free, high -resolution, and faster alternative to Fused Deposition Modelling (FDM) and PB-based methods. SLS mainly utilizes high-temperature sintering of plastics, ceramics, and metals, limiting its pharmaceutical use due to potential drug degradation. As a result, it has been applied primarily during the development of systems for tissue regeneration and target-specific drug delivery mechanism, with no studies yet exploring direct drug-loaded formulation printing. [9]

4) Digital Light Processing (DLP)

Uses of DLP 3D printing technology in photocurable resins and projection lamp (UV or white) for rapid, layer-by-layer fabrication. Its customizable resin formulations allow for the development of structures with advanced characteristics and capabilities.[10] Our printing technology utilizes photopolymerization, where liquid photoreactive resins (photopolymers) are managed using ultraviolet (UV) light to form solid components. This process is widely used in stereolithography 3D printing, where a light source selectively hardens the resin to create a redefined shape. When a Digital Light Processing (DLP) projector is employed as the light source, the technique is known as DLP printing. In this method, the user-defined shape is projected as a 3D volume onto a vat of liquid photopolymer. During printing, the build platform moves incrementally, exposing this resin layers to light, which solidifies specific areas (white voxels), forming the object layer by layer.[11] DLP 3D printing shows promise for medical devices but remains unexplored for orally administered solid forms with the help of theophylline with PEGDA and PEGDMA, we optimized polymer content for robust tablets and varied surface areas to achieve diverse drug release profiles, analysing drug-polymer interaction FTIR spectroscopy.[12]

5) Binder Jetting (BJ)

In 2015, the FDA granted its first approval for a 3D-printed drug. which used binder jetting technology. This method is the only existing form of 3D printing technique officially authorized by the FDA for pharmaceutical use, and it stands out for its ability to produce tablets in full colour.[13] Binder jetting (BJ) 3D printing is derived from powder technique where a selective deposition of liquid binder binds powder particles, forming solid structures. It has been used to create various targeted delivery approaches, including individualized drug therapies, multi-release devices, and Oro dispersible formulations.[14]

Pharmaceutical and Biocompatible Materials For 3d-Printed Medicine:

Recent advancements have utilized melt mixing to integrate biologically compatible polycaprolactone (PCL) with polyvinyl chloride (PVC) for 3D printing via Fused Filament Fabrication (FFF). PVC-PCL blends exhibit excellent miscibility, enhanced mechanical properties, and a strong shape memory effect, with 10% PCL-PVC achieving 45 MPa tensile strength, 81% elongation, and 100% shape recovery.[15]

The predominantly utilized synthetic polymers for 3D printing include poly (lactic acid) (PLA), poly (glycolic acid) (PGA), polylactic-co-glycolic acid (PLGA), polyurethane (PU), and polycaprolactone (PCL). Polymers serve a vital function in organ 3D printing as integra parts of bioinks, primarily in the layered construction process. Bioinks, composed of cell-laden polymeric hydrogels, undergo physical, chemical, or biochemical crosslinking to influence cell behaviour. While natural polymers provide bioactive support for cell growth and differentiation, synthetic polymers offer superior mechanical strength and lower immunogenicity.[16]

Advances In 3d Printing Methods for Medicinal Applications: Fdm And Diw To Sls, Sla, And Beyond:

1) Extrusion-Based 3D Printing Methods in Fabrication

Material extrusion 3D printing is commonly used technique in additive manufacturing where material is extruded through a nozzle to form objects sequential layering.

➢ Two key extrusion-based methods are

a) Fused Deposition Modelling (FDM)

Extrusion-based 3D printing, especially Fused Deposition Modelling (FDM), works by melting thermoplastic materials like PLA, ABS, or Nylon pushing by directing them through a heated nozzle to generate objects in sequential layers. This method is commonly used in the pharmaceutical filed for making personalized drug tablets (Like Spritam), designing custom prosthetics, and developing controlled drug delivery systems.

b) Direct Ink Writing (DIW)

This technique involves extruding semi-solid paste through a nozzle using pneumatic or mechanical pressure, which solidifies via curing or gelation. It enables multi-material and bioprinting using polymers, ceramics, composites, and bioinks. Applications include tissue engineering, controlled drug delivery, and bone scaffold fabrication for regenerative medicine.

2) Powder-Bed Fusion (FBF) 3D Printing Methods in Fabrication

Powder-Bed Fusion (FBF) is an additive manufacturing technique that utilizes a heat source (such as a laser or electron bean) to selectively fuse fine powder particles layer by layer. It enables high-precision fabrication of complex structures, making it highly suitable for pharmaceutical, biomedical, and industrial applications.

➢ Two primary PBF methods are

a) Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS) is powder-based 3D printing technique where a laser selectively fuses fine layers of polymers, metals, or ceramics to build objects without the need for support structures. Materials like Nylon, PEEK, and elastomers are commonly used for medical implants, prosthetics, and drug delivery systems. In pharmaceutics. SLS empowers the creation of personalized devices with time-controlled drug release and biodegradable scaffolds for tissue engineering.

b) Selective Laser Melting (SLM)

This laser-based 3D printing technique, unlike SLS, fully melts metal or ceramic powders using a high-energy laser, resulting in dense parts with exceptional mechanical strength. Common materials include medically approved metals such as titanium, stainless steel, and cobalt-chromium alloys, as well as ceramics. It is widely used in medicine for custom orthopaedic and dental implants, high-precision surgical tools, and patient-specific prosthetics with elaborate geometries and exceptional strength.

3) Photopolymerization-Based 3D Printing Methods

Photopolymerization is an additive manufacturing technique employs light to specifically cure liquid photopolymer resins into solid structures. This method is highly precise and widely used in the medical, dental, and pharmaceutical industries for fabricating customized drug delivery systems, prosthetics, and bio-compatible implants.

➢ There are two primary photopolymerization-based 3d printing Techniques:

a) Stereolithography (SLA)

This technique employs a reservoir of UV-sensitive light sensitive resin, which is specifically cured by a ultraviolet (UV) laser to form solid layers, thereby constructing the object in a layer-by-layer manner. This method continues as the build platform lowers, and may require postcuring to improve mechanical properties. Materials used include UV-curable resins that can be customized for biocompatibility, flexibility, or strength. In medicine, it is applied in producing high-precision dental medical models, as well as drug delivery implants with controlled release profiles.

b) Digital Light Processing (DLP)

Digital Light Processing (DLP) is similar to SLA but uses a digital projector to cure an entire layer of resin at once, making it faster and more efficient. A light source projects each layer's pattern onto the resin surface, instantly hardening the exposed areas. Materials like UV-curable photopolymers and elastomers can be tailored for flexibility, strength, or biocompatibility. DLP is widely used in pharmaceutics and medicine for producing custom prosthetics, orthopedic supports. Drug-loaded implants with controlled release, and precise applications like crowns and aligners.[17]

3D Printing in Advanced Pharmaceutical Drug Delivery System: Innovations in Oral, Transdermal, Pulmonary, And Implantable Therapies:

1) Oral Drug Delivery System

3D printing has revolutionized oral drug delivery by enabling the precise tuning of drug release profiles to meet patient needs. This advancement has led to the development of immediate release, delayed- release, gastro-retentive systems, and polypills for complex regimens like diabetes and hypertension. Oral dosage forms remain the most convenient and patient-compliant route, benefiting from advancements in manufacturing and a diverse range of excipients. The investigation of drug loaded filaments confirmed mechanical robustness suitable for its application, with higher molecular grade PEOs increasing shear viscosity and hindering flow during printing. A radiator-like geometry with 1mm interplate spacing significantly enhanced drug release. 3D printing has overcome limitations of conventional multi-drug pills, enabling the fabrication of customized polypills with tailored release profiles. *Khaled et al.* developed a 3D printed polypill containing five drugs using a semisolid extrusion technique. In this formulation, aspirin and hydrochlorothiazide were released immediately, while pravastatin, atenolol, and ramipril showed sustained release. In another study by the same group, they designed a multi-drug pill targeting hypertension and diabetes. This included as osmotic pump system for captopril and sustained-release mechanisms for nifedipine and glipizide, resulting in controlled drug release profiles. A polypill was created using FDM-based 3D printing. Incorporating a PVA filament loaded with four different drugs: Lisinopril dihydrate, indapamide, rosuvastatin calcium, and amlodipine besylate. In a multilayer matrix, with drug release dependent on positioning. Water as a co-plasticizer reduced processing temperatures, minimizing thermal stress. 3D printing has also been applied for gastro-retentive drug delivery systems, such as floating tablets of itraconazole and theophylline-loaded shell, enhancing drug absorption in the stomach. Additionally, a SNEDDs-based 3D printed tablet of dapagliflozin improved solubility and immediate release. Inkjet-printed Oro dispersible films of enalapril maleate were also developed, allowing precise fixed-dose combinations.[18]

2) Transdermal Drug Delivery System

TDDS system provide a pain-free, self-administered alternative to traditional method, with 3D printing enabling personalized therapies in future. 3D printing makes it possible to create customized drug delivery system for transdermal application, such as implants, microneedles and patches, for personalized treatment. Kempin *et al*. created a 3D-printed implant with customizable geometry for targeted drug delivery, showing varying release rates of quinine with PCL, Eudragit RS, and ethyl cellulose. Allen *et al*. created soluble micro-needles using inkjet printing to encapsulate and stabilize a seasonal influenza vaccine for skin administration Goyanes *et al*. 3D-printed a custom acne fighting nose patch mask utilizing FDM, releasing under 187 µg/cm² of the drug in 3 hrs. Mowaffak *et al*. developed custom 3D- printed nose and ear-shaped wound dressing with antimicrobial metals for better adherence and enhanced treatment. He-Gyeong Yi *et al*. developed a 3D printed anticancer patch with polycaprolactone and PLGA, releasing 5-fluorouracil for up to 4 weeks for local drug delivery. The piezoelectric inkjet printing method was used to fabricate transdermal films containing indomethacin, improving drug penetration and anti-inflammatory effects at 600 DPI.[18 19]

3) Pulmonary Drug Delivery System

3D printing is emerging as a valuable tool in respiratory disease treatment, enabling the fabrication of medical devices and personalized inhaled medicines. Morrison et al. demonstrated its potential by developing 3D-fabricated bioresorbable airway splints, significantly minimizing airway collapse in paediatrics trachea bronchomalacia patients. Similarly, Zopf et al. a tracheobronchial airway splint was developed, which enhanced longevity in a porcine model by preventing severe bronchial collapse. 3D printing has significantly contributed to the creation of medical devices for asthma and respiratory issues. Researches created a ‘’Sneezometer’’ this technology is used to measure airflow and the speed of a sneeze more accurately than a traditional spirometer. It also aids in designing better inhalers for asthma patients. Additionally, an ergonomic asthma inhaler was developed using 3D printing developed to improve ease of use. In lung cancer treatment, Quinone’s et al. designed a 3D printed lung tumour movement simulator to track tumour shifts during during breathing, enhancing radiotherapy precision. The increasing focus on the impact of infectious respiratory disease, such as the Coronavirus, demonstrates the promise of 3D printing in medical research. 3D printing is a budget-free option approach to creating lung models to study airflow, aerosol deposition, and pulmonary interventions. Various models have been developed to replicate human respiratory structures and test inhalation conditions. However, existing studies have not extensively explored particulate drug distribution in a controlled flow environment. To address this, a model of human upper respiratory tract (HURT) was developed, incorporating the larynx, trachea, and bronchus, to aanayze inhaled drug particles deposition. This is the foundational model that mimics the anatomy of the respiratory pathways for in vitro testing of dry particle deposition. [18,20]

4) Implantable Drug Delivery System

Intrauterine drug delivery devices have been developed using 3D printing technology. enabling personalized structures for precise and controlled API release. A T-shaped contraceptive device was created employing FDM 3D printing process, demonstrating faster drug delivery due to the amorphous state of indomethacin in the device. The same researchers also developed EVA-based intrauterine and subcutaneous implants with sustained drug release over 30 days. Similarly, *Fu et al*. personalized vaginal rings were developed based on specific requirements in various shapes through FDM-based 3D printing technology, Additionally, a selective laser sintering technique was employed to fabricate an intrauterine device with a combination of progesterone and 5-fluorouracil demonstrated synergistic effects for the treatment of gynaecological cancers such as uterine(endometrial) and ovarian cancers. 3D printing facilitates the production of implantable drug delivery devices designed to match patient-tailored anatomies and hormone treatment regimens, as well as release durations, supporting personalized therapies. In contrast, traditional methods like injection molding and extrusion produce bulk implant with fixed doses and shapes, limiting customization.[21] Over the past two decades, two major challenges have been faced in controlled drug delivery: achieving sustained release of the drug at a zero-order rate and enabling pulsatile or staggered delivery. Various techniques, such as osmotic pumps, swelling matrices, diffusion control, and multi-layered systems, have addressed sustained release. Meanwhile, responsive delivery systems that react to environmental stimuli like light, temperature or magnetic fields have been explored for controlled, time-specific drug release.[22]

3d Bioprinting And Personalized Therapeutics: Advancements in Tissue Engineering, Drug Manufacturing, And Synthetic Organs:

1) Bioprinting And Implantable Tissue Engineering

3D bioprinting enables the fabrication of implantable tissues, offering groundbreaking applications in regenerative medicine. Notable examples include the 3D printing of synthetic skin, which can be transplanted onto burn victims to facilitate healing. Additionally, bioprinting serves as a platform for testing cosmetics, chemical, and pharmaceutical products, reducing the reliance on animal models. Another significant advancement is the creation of heart valves by integrating ells with biocompatible materials to regulate the valve hardness. Moreover, bioprinting technology has been used to create human-like ears by using scaffolds filled with a gel that contains cow cartilage cells mixed with collagen.

2) Personalized Drug 3D Printing

Three-dimensional printing technology is bringing a big change in pharmaceutical drug manufacturing by allowing the production of fast-dissolving pharmaceutical formulations. This approach enhances drug bioavailability and absorption compared to conventional tablets. Moreover, it facilitates precise dose customization based on individual patient needs, promoting personalized medicine.

3) Customizing Synthetic Organs

3D printing offers a breakthrough in organ transplantation by helping solve the lack of donar organs and cutting down patient waiting times. Additionally, bio printed organs hold great potential for pharmaceutical research, providing an ethical and effective replacement for animal models for drug toxicity assessments.[23]

Recent Advances and Innovative Uses Of 3d Printing in Medicine and Healthcare:

The Integration of 3D printing into pharmaceuticals applications is revolutionizing drug delivery by enabling personalized dosages, multi-layered release profiles, and patient-specific drug delivery devices. This advancement minimizes pill burden while improving treatment precision. With the significant impact of 3D printing on medicine, numerous reviews have examined various aspects, ranging from medical imaging to surgical applications. This review explores cutting-edge innovations in 3d printing in medicine from the past three years.[24]

Researchers at University College London used 3D bioprinting to fabricate nose-worn drug delivery devices for acne treatment with salicylic acid. Comparing Fused Deposition Modelling (FDM) and stereolithography (SLA), they found SLA more convenient. The dosage can be adjusted by modifying the polymer filaments during preparation. At the University of Nottingham used a low-cost 3D printer to fabricate Guaifenesin bilayer tablets achieving a drug release profile comparable to the commercial version. They also assessed weight, hardness and friability. *Goyanes et. al*. studied the impact of tablet shape on drug delivery, printing various geometries with paracetamol loaded PVA filaments. Their findings showed drug release of the drug was dependent on the ratio of surface area to volume, highlighting the advantages of 3D printing over traditional methods.

1) Surgical Planning

3D printing is increasingly used in surgical planning allowing surgeons to study complex organs and defects before operations. By creating detailed anatomical models, surgeons can explore different approaches, reducing operation time and improving patient outcomes.

2) Prostheses

Recent advancements in 3D-printed patient-specific prostheses, aided by high-quality imaging, enable precise anatomical reconstructions, benefiting individuals with disabilities and significantly impacting medical fields like dentistry.

3) Medical education and training

The use of cadaveric materials for training medical physicians faces ethical and cost challenges. 3D printing offers a novel alternative by replicating complex anatomical organs from high resolution CT imaging, providing scalable and precise models for medical training.

4) Medical research

The development of 3D printers capable of directly printing cells has enabled automated cell structure production to toxicity testing and disease treatment. With many drugs failing due to inaccurate preclinical models, 3D-printed tissues mimicking natural cellular arrangements offer a powerful tool to accelerate medical research.

5) Organ printing

3D printing is already designed to create human organ and living tissue structures intended for research, integrating with biocompatible microfluidics to mimics native organ function. The future lies in printing transplantable organs or even in-situ organ printing during surgery, potentially revolutionizing medicine and replacing traditional transplants.[24]

Fig. No. 1

The Implementation of Artificial Intelligence in Pharmaceutical Research Along With 3d Printing: From Machine Learning to Generative Models:

The pharmaceutical sector faces challenges like high cost, complex disease, and the need for personalized treatments. Innovation in AI, 3D printing, and nanomedicine are transforming drug development, improving precision, and enhancing delivery. Ai predicts drug effectiveness, 3D printing aids in compliance, and nanomedicine enhances solubility and targeting. Future trends focus nanotechnology, innovating the path forward in healthcare.[25] 3D printing innovated solid oral dosage forms by enabling precise control over drug dose, geometry, and release behaviour for personalized medicine. Despite advancements in polypill and controlled-release designs, traditional dosage form design struggles to keep pace in 3D printing's capabilities. Studies show drug release depends on surface area-to-volume ratios, allowing for the prediction of dissolution behaviour and creation of complex release profiles using multilayer and core-shell structures. However, designing dosage forms to achieve specific release profiles remains a complex optimization challenge. Artificial Intelligence (AI) enhance 3D printing in medicine by enabling automated design, formulation development, and cost-effective personalized drug manufacturing. Studies have integrated AI models like machine learning, self-organizing graphs, and generative adversarial networks(cGANs) to optimize materials, printing parameters, and dosage geometry. Tolls like M3DISEEN predict printability, while AI-driven approaches improve drug release behaviour and formulation innovation. Despite advancements, challenges remain, such as improving accuracy in dosage geometry predictions. Genetic algorithms further enhance 3D printed capsule design, ensuring dissolution consistency with target profiles for precise personalized medicine.[26]Structural heart disease (SHD) interventions rely on advanced imaging for procedural planning, as traditional methods focus on diagnosis rather than simulation and outcome prediction. The absence of a surgical visual field in transcatheter procedures increases dependence on imaging for guidance. 3D printing aids in procedural planning, reducing the learning curve for operators and enhancing preclinical device development. When combined with computational modelling, it accelerates research on fluid mechanics in device testing.[27] Artificial intelligence (AI) is transformative technology that is propelling progress throughout various fields, influencing both technological advancements and societal developments. Its core objective is to replicate human intelligence, enabling it to perform tasks at a significantly at a faster speed than humans. This ability helps address hurdles such as workforce shortages while also minimizing human exposure to hazardous environments. In drug discovery, AI facilitates virtual simulations, drastically reducing the time required to bring new molecules to market. Given the rising costs associated with product development and commercialization, the pharmaceutical industry is increasingly leveraging AI in its product development processes. Machine learning a branch of AI, enhances efficiency in complex processes like predicting 3D printing capabilities, drug-food interactions, and modelling long-acting injectables. Another AI subset, machine vision, plays a crucial role in real-time monitoring of oral film disintegration and optimizing tablet coating through process analytical technology additionally, AI advances robotics by effectively replicating human movements. Natural language processing, a lesser-used AI subset in pharmaceutics, enhances machine-human communication by replicating human conversion. Traditionally, coding was required to interact with machines, limiting AI's accessibility in pharmaceutical research. However, the advent of large language models has revolutionized NLP, enabling rapid, intelligent responses to queries. This advancement addresses the challenge of sifting through vast scientific literature, streamlining information retrieval and accelerating discoveries. LLMs utilize neural networks trained on vast amounts of text and images, enabling them to recognize patterns, generate text, and answer questions. Initially capable of executing tasks with minimal input, they evolved to process multi-modal data like sound and visuals. As a result, LLM are classified as generative AI, setting them apart from traditional ML models focused on prediction. LLMs utilize neural networks trained on vast datasets of text and images to identify patterns, relationships, and contextual meaning. Once trained, they can generate text, answer questions and assist with various tasks by recalling learned information. Initially, models like GPT performed tasks with minimal instructions, but advancements now enables them to process multi-modal data, including sound and visuals. This evolution classifies LLMs as generative AI, distinguishing them from traditional ML models focused on prediction.[28]

Diagrammatic Presentation Of ''Integration of Ai and 3d Printing for Automated Drug Formulation Development'': [29]

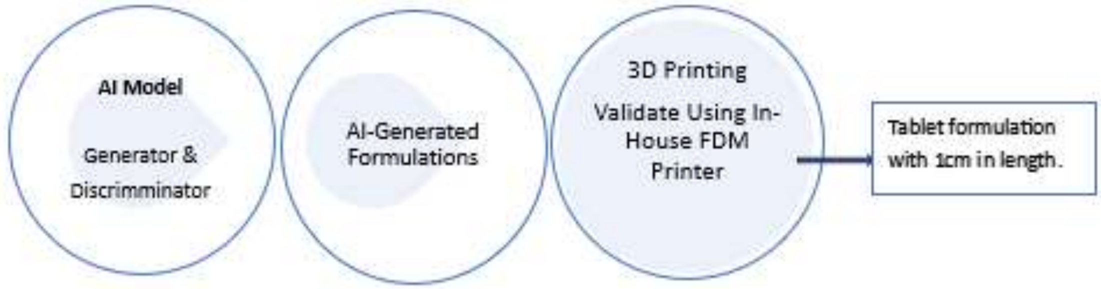

Fig. No. 2

Regulatory Frameworks and The Future Of 3d Printing in Pharmacotherapy:

1) Geometry Matters

The shape of print lets significantly affects drug dissolution rates. Goyanes et al. found that pyramid-shaped paracetamol tablets, with the highest surface area-to-volume ratio, dissolved fastest, while cylindrical and spherical shapes had slower dissolution. Hydrochlorothiazide tablets with embedded channels (≥0.6mm) enhanced drug release, meeting pharmacopoeia standards for immediate release. Arafat *et al.* designed tablets with bridged units and spacing gaps, influencing disintegration and dissolution, offering an alternative to conventional disintegrants.

2) Collaboration Leads to Better Results

Dual head extrusion enables 3D printing with two materials of different melting points allowing innovative drug formulations. Studies have demonstrated its use in delayed and modified-release tablets, dual-compartment dosage units and capsular devices enhancing drug release control and API separation. Additionally, improving dissolution rates, though filament aging may impact stability and mechanical properties.

3) Extrusion of Semisolids

Extrusion based 3D printing of semisolid or semi-molten materials enables high drug load formulations using compressed air, syringe plungers, or screws. While during is required post-printing, this method has been used for immediate-release paracetamol tablets and modified release systems like gastro-floating dipyridamole tablets. Multi-syringe printing further allows the fabrication of polypills with multiple APIs released at different rates.

4) Patient-Centric Therapy

3D printing offers vast applications in medicine and pharmacy, enabling the fabrication of tablets, capsules, implants and Oro dispersible films with personalized dosing. Its flexibility allows dose and dosage adjustments tailored to patient needs, particularly benefiting paediatrics, geriatric, and orphan drug formulations. The technology enhances pharmaceutical compounding, enabling on-demand production in hospitals and pharmacies, with additional advantages like taste masking and improved patient acceptability. Studies highlight that tablet shape like the shape of the tablet, whether spherical, toroidal, disc-like, capsule-shaped, or a tilted diamond, greatly affects how easy it is swallow and handle, with torus-shaped tablets being the most preferred. 3D printing allows the creation of tablets that contain multiple drugs with controlled dissolution profiles, reducing medication burden and allowing precise formulation adjustment. Beyond oral dosage forms, it has been applied for transdermal drug delivery via microneedles and for personalized vaginal rings, highlighting its potential for tailored drug delivery systems despite current industrial challenges.

5) From Patients-Specific to Large Scale Production

The integration of 3D printing in-patient facilities is widely debated, with concerns over drug quality and safety limiting its immediate adoption. While patient involvement in medicine printing could beneficial, risks like adverse effect mismanagement remain. However, pharmacy-based 3D printing particularly via fused deposition modelling, is more feasible, leveraging pharmaceutical-grate API-loaded filaments. This method also helps maintain drug stability by incorporating APIs in crystalline state, reducing issues associated with amorphous drug formulation during printing. The growing integration of 3D printing in the pharmaceutical manufacturing is hindered by the lack of specialized production equipment. While Aprecia pharmaceuticals pioneered the first marketed 3D-printed drug, further advancements, such as multi-head printing conveyors-based systems, are needed for efficiency. Without dedicated pharmaceutical 3D printers, the technology will remain in research, requiring collaboration among manufacturers, scientists, and regulators to drive its integration into pharmacotherapy.

6) Letter of Law

3D printing is an emerging technology in pharmaceutics, showing great potential, especially in personalized medicine. Despite its progress, industrial feasibility remains a challenge, with only on FDA-approved product available. Regulatory guidelines are essential to address quality, safety, and manufacturing standards, considering the diverse processes involved. As 3D printing advances into pharmacotherapy, training specialists in pharmaceutical 3D printing is essential, integrating additive manufacturing into medical and pharmacy education.[30]

Current Hurdles and Limitations:

The integration of 3D printing in wound care regenerative medicine faces technical, biological, economics, regulatory, and ethical challenges. Addressing this limitation is crucial to unlocking its full potential.

1) Technical and Biological Challenges

A key challenge in 3D printing for wound care is ensuring vascularization, as functional blood vessels are essential for effective healing. Additionally, immune responses to foreign materials and the degradation rate of biodegradable scaffolds impact biocompatibility and tissue integration. Researches are exploring bioactive factors, ECM-mimicking materials, and optimized degradation rates to overcome these hurdles.

2) Economics and Regulatory Challenges

The high costs of 3D printing technologies, materials and customization pose economic barriers to widespread adoption in wound care. Additionally, complex regulatory pathways require rigorous testing to ensure safety and efficacy, making streamlined approval processes essential for clinical integration.

3) Ethical Considerations and Patient Safety Concerns

Ethical concern in 3D printing for wound care include patient consent, privacy, and safety, requiring informed decision-making and continuous monitoring. A multidisciplinary approach is essential to address these challenges and ensure the safe integration of this technology into clinical practice.

4) Future Direction and Innovations

Advancements in 3D printing for wound care include 4D printing with smart materials that adjust to environmental conditions changes, boosting wound healing. Additionally, integrating bioelectronics and sensors into wounds dressings enables real-time monitoring and targeted therapies, improving patient outcomes and accelerating recovery.

5) Emerging Concepts of Personalize and On-Demand Wound Healing Therapies

3D printing enables personalized wound care by creating custom-sized dressings and scaffolds tailored to individual patient needs. On-demand therapies allow real-time production of wound care products, enhancing treatment precision. Innovations line 4D printing and bioelectronics promise to revolutionize wound healing with adaptive, patient-centric solutions.

6) Future Possibilities and Directions for Research Field

Future research in 3D printing for wound care focuses on 4D printing, bioelectronics, and personalized treatments for enhanced healing. Key challenges include standardizing protocols, ensuring long-term biocompatibility, and integrating adaptive, patient-specific solutions. Advancements in material, scalability, and clinical validation will drive further innovation.[31]

Navigating Ethical and Regulatory Pathways In 3d Printed Healthcare:

The integration of 3D printing in medicine demands strict regulatory oversight and adherence to ethical principles. Regulatory bodies like FDA, EMA, and NMPA evaluate the safety and efficacy of 3D-printed medical products through preclinical tests. Clinical trials, and post-market surveillance. Ethical concerns arise from patient consent, source materials, and equitable access. Sustainable and responsible practices are crucial to ensure both patient safety and societal well-being.[32] Although 3D printing is applied in certain medical fields its broader adoption is hindered by unclear EU legislation. An analysis of EU laws on approval before market release, legal responsibility, intellectual property issues, and data protection protocols highlighted limitations and a lack of flexibility, reflecting a cautious regulatory approach. While patient safety is vital, legal uncertainties and overregulation stifle innovation, underscoring the need for adaptive legislation to foster innovation and improve patient outcomes[33] The ICH is a global initiative uniting regulatory authorities and the pharmaceutical industry to create harmonized guidelines for drug development, manufacturing, and registration. This collaboration reduces regulatory barriers and duplication, streamlining global drug approvals while ensuring consistent quality and safety standards. Pharmaceutical manufacturing and 3D printing medicine is strictly regulated worldwide to guarantee the safety, effectiveness, and quality of medicines. Major authorities like the FDA, EMA, WHO, and ICH play an essential part in establishing and enforcing these guidelines. In the US, the FDA oversees drug regulations through frameworks like the Code of Federal Regulations (CFR), ensuring thorough clinical testing and monitoring.[34] In Europe, the EMA oversees medicine regulation across the EU, ensuring safety and effectiveness. Globally, the WHO sets standard, especially for low- and middle- income countries, while the ICH to harmonize pharmaceutical regulations across regions. Though these bodies share similar goals, companies must still adapt to each region’s unique rules and timelines. The FDA has made progress in regulating 3D printed medical Devices, but key challenges remain due to differences from traditional manufacturing. Current regulations are still largely based on conventional methods, lacking specific guidelines for 3D printing. Although guidance documents exist, they don't fully address the unique complexities of this technology. This highlights the need for a distinct regulatory framework tailored specifically to 3D printed medical devices.[35]

CONCLUSION:

3D printing has become the game-changing technology in today's medical field, bringing major advancement in how drug delivery system is developed and how treatments. offering unparalleled customization, precision, and innovation in pharmaceutical delivery systems, healthcare devices, and regenerative medicine. The diverse range of 3D printing techniques- such as FDM, SLA, SLS, DLP, and binder jetting- has expanded the possibilities for developing patient-specific therapeutics and personalized treatments. A wide spectrum of materials, from thermoplastics to biocompatible polymers and hydrogels, have been successfully employed to meet the complex requirements of medical applications. Despite advancements, challenges persist in regulatory approval, reproducibility, scalability, and material biocompatibility. Integrating real-time imaging, AI, and bio-fabrication offers promise but requires interdisciplinary research and harmonized regulations for clinical adoption. The evolution of 3D printing in medicine lies in personalized, on-demand production of drugs, implants, and tissues. Realizing its full potential will require close collaboration among engineers, material scientist, pharmacists, and clinicians.

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