"Artificial Intelligence -Driven 3D Printing in Pharma: Innovations and Future Directions"

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ABSTRACT

The technology of three-dimensional printing which was applied in a new way to a medication production facility is an extremely impactful process that is now making things like drug delivery and the medicine became personalized a reality on a scale that has never existed before. The primary objective is to produce through a low-cost method the personalized products that are very complex and created on-demand. This review will provide an analysis of many different 3D printing technologies, including the Powder Bed Fusion (PBF) methods such as the Selective Laser Sintering (SLS) and the Direct Metal Laser Sintering (DMLS), which give the ability to produce the drug delivery systems that are accurate and have the controlled release profiles. Techniques like Nozzle-based and Fused Deposition Modeling (FDM) makes it possible to extend the versatility of 3D printing to create individual dosage forms and the implants thus, tailor treatment for the patient. The synergy of artificial intelligence and 3D printing robustly enhances the pharmaceutical industry, as a well as a creation of a newfound era of innovation and precision is brought into the medical world. The text you read educates people on the ways that the combination of AI 3D printing and pharma can advance. Major steps comprise personalized pharmaceuticals and drug delivery systems, which are developed for unique patient needs, drug formulation, which has been saved by rapid prototyping, and one of the main achievements was bioprinting the tissues for regeneration and regenerative medicine. AI is the end-point of 3D printing interactions as long as it speeds up the interface and makes the process more accurate and efficient. The possible patterns denote the forward development of AI algorithms, the inevitable of the availability digital health tech, as well as the necessity for government regulation development. Regard to the future, the existing research is focused on these technologies that are to be bettered/optimized in order to give a chance for hi-tech therapeutic treatments through direct pharmaceutical solutions.

Keywords: 3D printing, Drug delivery systems, Types of 3d printing, AI Technology in 3D Printing, Dosage forms.

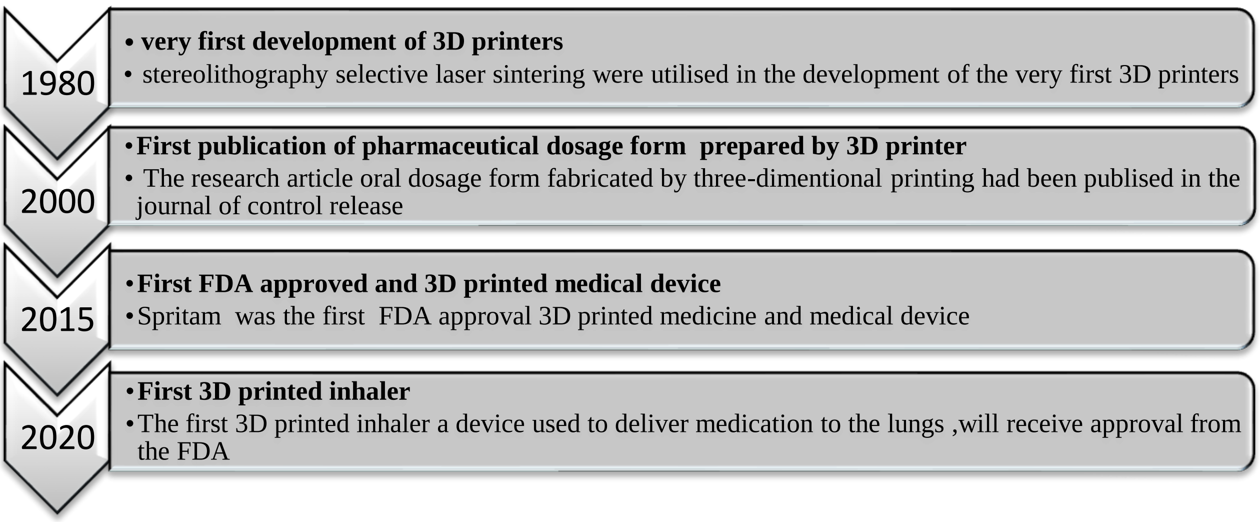
INTRODUCTION

In recent years, 3D printing, also known as additive manufacturing has emerged as a transformative technology with profound implications across various industries. One such sector where 3D printing is making significant strides is the pharmaceutical industry. Three-dimensional printing is attractive for several reasons. First, the cost of a 3D printer is affordable, making it accessible to a large number of end users[1]. Second, several printing techniques can be used for a variety of applications and printing materials. The manufacturing period and printing quality are now superior to those of the past .Traditionally; pharmaceutical manufacturing has relied on conventional methods that are often time-consuming, costly, and limited in customization. Three-dimensional printing is matchless method which uses computer aided drafting technology and programming to make three dimensional objects by layering material onto a substrate. It is a process of making three dimensional solid objects from a digital file. Now a day, 3D printing could be extended throughout the drug development process, ranging from preclinical development and clinical trials to frontline medical care. Different types of drug delivery systems for instance oral controlled release systems, micro pills, microchip, drug implants, fast dissolving tablets and multiphase release dosage forms have been developed using three-dimensional (3D) printing technology. It has been applied in several fields, including aerospace, automotive, food, healthcare, architecture, construction, and electronic industries In a range of medical uses, including dentistry, anatomic models, medical instruments, tissue models and engineering skins, and medication formulations, 3DP technology is currently employed. To date, 3DP has been most commonly used for the dental market and the hearing aid industry.[2] The complex applications of AI robot technology and 3D printing in the drug market are the leading forces that make this revolution possible. Combining advanced technology and modern biopharmaceutical manufacturing is the foundation of the revolution of AI and 3D printing in the pharmaceutical sector. AI uses complex algorithms to analyze data and make predictions, and 3D printing builds precise, customized objects layer by layer. Thesetogether are changing the way drugs are designing, producing, and delivering. The AI-driven 3D printing will definitely introduce new frontiers such as personalised medications tailoring for different individual needs and advanced drug delivery systems creation also they will be developed. This synergy also provides the possibility to speed up the suffering of drug discovery and improve the efficiency of production. The article will examine the full range of the application of AI and 3D printing to the pharmaceutical landscape by focusing on the most important innovations, as well as the discussion of future likely developments[3].This may be because finished goods are small and need to be designed for patients, rendering these industries receptive to 3DP. The review article begins with an overview of 3D printing technology. We describe the most common 3D printing methods applied to drug product manufacturing and discuss recent advances in 3D printing technology that affect drug product development and challenges that are associated with this technology, as well as its future potential [4].

HISTORY

3D Printing is a platform for personalized medicine from the beginning of 1990 There are major successes in 3D printed medical device, FDA's Center for Device and Radiological Health (CDRH) has revised and cleared 3DP medical devices. The first 3D printing method used in pharmaceutics was attained by inkjet printing, a binder solution onto a powder bed, therefore the particles bind together. Initial experiments focused on custom dosage forms and drug delivery. In 2015, Inkjet printing was the technique used to manufacture Spritam tablets (levetiracetam) for oral use, the first 3D printed drug approved by the Food and Drug Administration (FDA) in 2016 by Aprecia Pharmaceuticals. 3D printing is most advanced technique in the fields such as automobiles, aerospace, biomedical, tissue engineering and now in the pharmaceutical industry (initial phase). FDA motivates the development of advanced manufacturing technologies such as 3D-printing and by means of risk-based approaches. Since then, researchers have been developing personalized medicine and novel drug delivery systems using 3D printing. Ongoing clinical trials and research aim to evaluate safety and efficacy, while future advancements hold promise for revolutionizing drug development and manufacturing[5].

Journey of 3D Printing in Pharmaceutical Application:



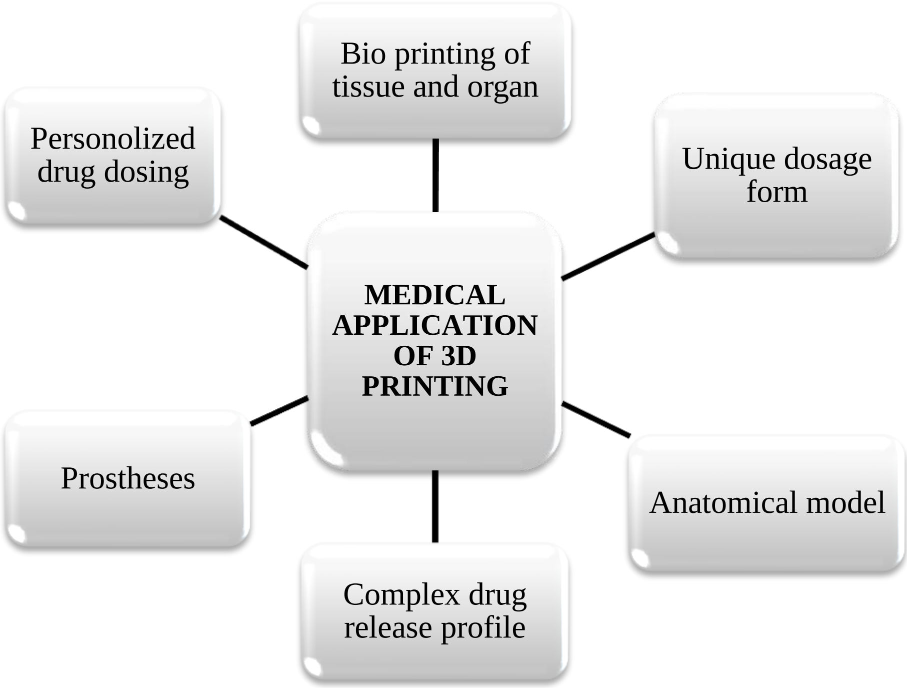
Advantages of 3D Printed Drug Delivery

- High drug loading capability compared to conventional dosage forms.
- Accurate and Precise dosing of potent drugs, which are administered at small doses for activity.
- Reduced production cost due to less wastage of materials.
- Medication can be tailored to a patient in particular based on age, gender, genetic variations, ethnic differences and environment.
- Treatment can be customized to improve patient adherence in case of multi-drug therapy with multiple dosing regimen.
- 3D printers capture minimal space and are affordable.

Disadvantages

- Problems related to nozzle are a major challenge as stopping of the print head, which affects the final products structure.
- Powder printing clogging is another hurdle.

- Possibility of modifying the final structure on to mechanical stress, storage condition adaptions and ink formulations effects.
- Printer related parameters and these effects on printing quality and printer cost.[6]



TYPES OF 3D PRINTING TECHNOLOGY

The processes traditionally used by the pharmaceutical industry such as milling, grinding, granulation, and compression often give rise to inconsistent finishing quality in accordance with factors such as drug packing, drug release, drug stabilisation and pharmaceutical dose stability. In contrast, 3DP has strategic advantages as a powerful tool technology such as increased efficiency of R&D, enhanced security, effectiveness and accessibility of medicines. 3DP technologies are the most widely used in medical applications. A short discussion continues on each of these technologies:

I. Powder Bed Fusion (PBF)

Powder bed fusion technologies, such as Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS), have been adapted for pharmaceutical use. In SLS, powdered materials are selectively fused together by a laser to create solid structures. This method has been explored for producing drug delivery systems, such as implants and oral dosage forms, with precise control over drug release rates.[7]

II. Bio printing

Bioprinting technologies, which use bioinks containing living cells and biomaterials, hold potential for tissue engineering and regenerative medicine applications in the pharmaceutical industry. Bio printed tissues and organs can be used for drug testing, disease modeling, and personalized medicine approaches.[8]

III.Nozzle Based Printing

This system has advantages over the drawbacks such as utilisation only in case of lower dosage of therapeutics, not upto the mark rigidity, issues in various layer printing of inkjet printing system. Binder in solution form is assorted with solid constituents such as drugs and polymers in case of this technique. A three-dimensional object is formed upon transferring the assortment through a nozzle and following layers are transferred.

Fused Deposition Modeling (FDM)

FDM, also known as Fused Filament Fabrication (FFF), was first commercialized in 1991 is currently one of the most commonly used low-cost techniques in 3D printing. Fused deposition modelling (FDM) is commonly used method in 3D printing; the materials are softer or melt by heat to create objects during printing. Fused deposition modeling 3D printing helps in manufacturing delayed release print lets without an outer enteric coating and also provides personalized medicines doses. This 3D Printing indicates some limitations for system like lack of suitable polymers, slow and often incomplete drug release, because of the drug remain trapped in the polymers; miscibility of drug and additives with the polymers used was not valued.

Pressure-assisted Micro syringes (PAM)

In this case, fluid matter of appropriate resistance to flow is forced out by micro syringe. Similar to inkjet system, micro syringe is able to proceed and fluid is ejected with assistance of pressurised air. Sophisticated drug delivery systems are made possible by PAM.[Akin system in which piston is utilised has emerged which delivers the printing component not by pressurized air but by stepper motor.[9]

IV. Inkjet Printing

Inkjet printing has emerged as a promising 3D printing technology for pharmaceutical applications. In this process, liquid formulations containing drug compounds are deposited onto substrates in precise patterns using inkjet printheads. Inkjet printing enables the fabrication of multi-layered dosage forms, such as oral films and tablets, with customizable drug compositions and release profiles. It further is classified into continuous inkjet (CI) and drop-on-demand (DOD) printing.

Continuous Inkjet (CI) printing

In this case, ink circulates via opening of size fifty to eighty µm diameter continuously in availability of pump with greater pressure. Fluid ink gets deranged into drops at already decided pace, dimensions and particular intermissions by application of piezoelectric crystal.

Drop-on-demand (DOD) printing

Drops of dimension 10-50µm in diameter are produced in DOD printing. Similar to CI printing piezoelectric crystal is applied and thermal heads are also utilized as printing heads in this kind. Fluidized ink temperature gets raised to 300 degree Celsius which leads to build up of bubbles that leads to forcing of ink to print. Usage of this technique is only for vaporous fluids.[10]

V. Laser Based Writing System

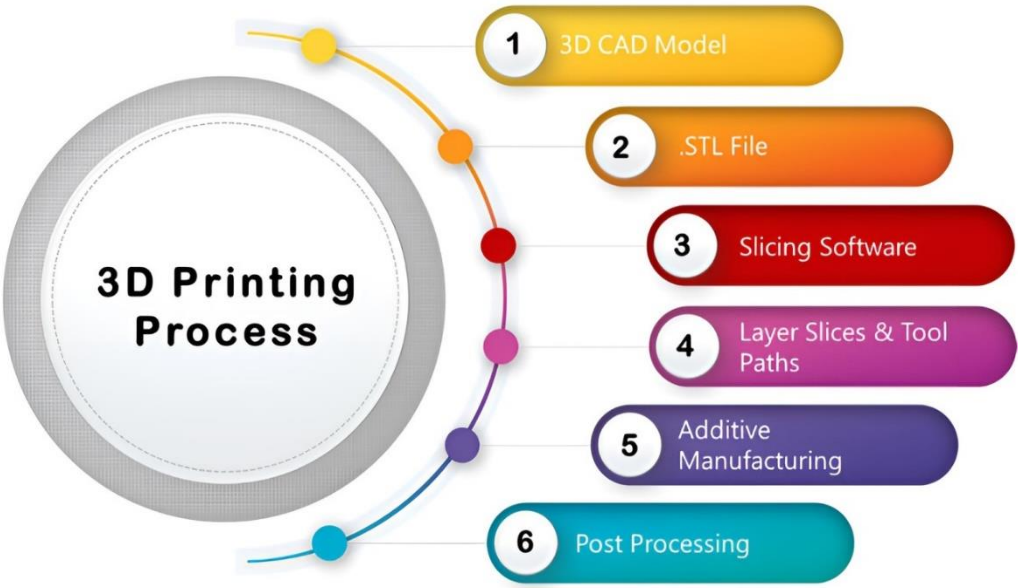
Hypothesis of photo polymerization is applied in this system which involves interplay of photo initiator and ultraviolet light that in turn leads to formation of free radicals.

Stereolithography (SLA) and Digital Light Processing (DLP)

Stereolithography is the method of computer regulated laser beam is used to make liquid polymer/resin as solid, by this means creating a 3D structure. Stereolithography has several advantages over former types of other 3DP, predominantly it’s astonishing resolution and dodging of thermal practices can be harmful for specific drug molecules.[11] SLA and DLP technologies, which use photopolymer resins cured by UV light, have been investigated for fabricating drug-eluting implants, transdermal patches, and microneedles. These methods offer high resolution and surface finish, enabling the precise control of drug dosage and release kinetics.[12]

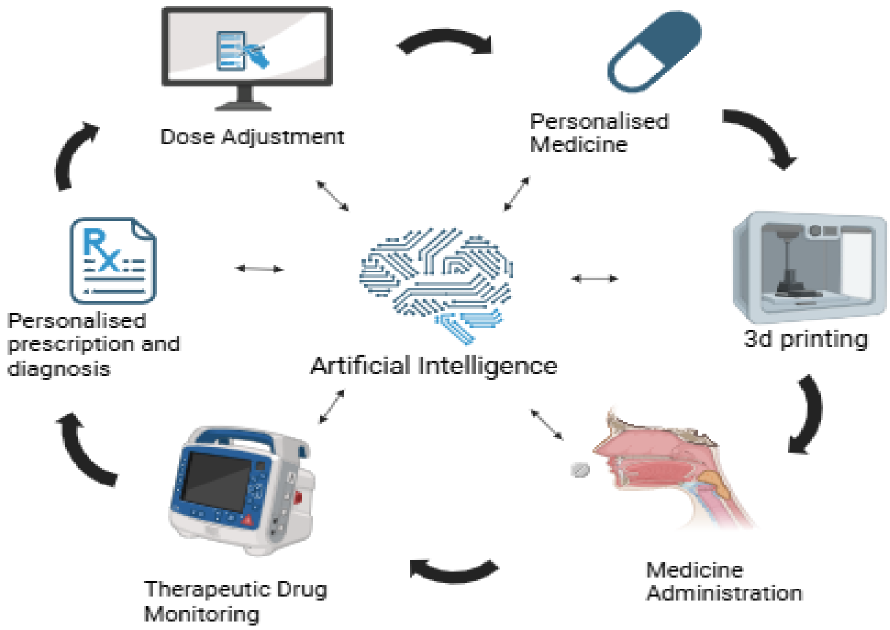
Selective Laser Sintering (SLS)

The crushed material for printing new items is used in an SLS printer. A laser pulls the object outline into the powder and fuses it. Then a new powder layer is formed and the procedure is repeated one by one and builds each layer to create the product. Varied drug delivery systems have been formed with assistance of SLS. For instance, miniprintlet of anti-pyretic drug paracetamol[13].



AI TECHNOLOGY IN 3D PRINTING

Recently, artificial intelligence (AI) has appeared as a new way of living the future, and it can even be found in the most advanced devices. 3D printing technology can use artificial intelligence technology. It is a progressive and state-of-the-art technology. At present, individuals are making new innovations such as AI in 3D printers. The blend of the 3D printing and artificial intelligence will improve the functionality of 3D printing at a rapid pace. Artificial intelligence is the way of agent behavior in machines that is intelligent, also commonly named machine intelligence. Those machines of this kind are able to get information on their own and then do their own reasoning and analysis to draw conclusions (imitation of human learning thinking) that allow them to do advanced missions. Machines that are like humans in their behavior are said to be the AI[14]. The automation process of artificial intelligence can be carried out in a large number of different ways. The operation of the 3D printer itself is quite a complicated process, and the use of artificial intelligence could assist it greatly in improving, hence, making the new technology to operate with higher efficiency. At present, 3D printing (3DP) is one of the recent techniques in manufacturing industries where analog materials are being used in layers to create a 3D object from the digital description. This is a device that has an intelligent extruder that can recognize if there are any issues. It can choose to make the response on its own. It is a big 3D printer that is operated by robots and machine learning software. The employment of robotic manipulators and the use of robotic manimulators to print functioning parts without any trouble by themselves are the real revolution[15].



Additive Manufacturing (AM)

Additive manufacturing is the ‘Cinderella of the modern era’ thus being the most promising and highly recognized technological field. 3D printing (3D) is bodied out of the stereolithographic printing method such as in 1984 . Additive manufacturing (AM) is being utilized to fabricate elements that generally are too complex for the traditional approach. The AM should be developing along the digital era by means of rapid prototyping and additive manufacturing. In medicine, the basic materials such as various polymer, metal, and biomaterials are commonly used to make the prototypes and finished products with unique shapes, multifunctional compositions, reliability, and high quality. This development of AM technologies will bring about radically changed scenarios. One of the changes that will come as a result of innovations are that the supply chain will be shortened meaning that buyers will be able to print anything they want at home and remotely. The digital manufacturing era has just started, not yet reached maturity. Thoughts are made from 3D models and then sent to the 3D printing machine that starts and finishes the production without human control. The main thing that people will worry about is the use of different food production materials, toolers, the necessity to produce spare parts, etc[16].

Artificial Intelligence (AI)

The principle coordinates where workers and users are needed is artificial intelligence and software creation. In modern times, transportation and logistic systems worldwide are switching to digital transportation model efficiently. There is a technology race that is to be witnessed among local additive maufacturers in the near future. They will compete at the local level of production and they will also cooperate on the global level that is aimed at making the economy of each country sustainable. Currently, the UK, USA, and a few other European countries are witnessing a tremendous technological transformation in the manufacturing of digital products. For instance, the company "Airbus" employs AM for most of the airplane parts that are neither made nor manufactured[17].

Machine Learning (ML)

The current machine learning industry is on the rise almost at an exponential pace as it has more sources of data (i.e. from other channels). This process is achieved through machine learning, a sub-discipline of artificial intelligence, by studying algorithms that can perform tasks similar to those of human. Machine learning works on the basis of algorithms to search for patterns in large data volumes and deliver valuable knowledge to the user. It is increasingly a big challenge in society today, and it is spreading to all sorts of science, industry, and market applications, such as big data, Internet of Things (IoT), Web, psychology, health care, etc[18].

METHODOLOGY

This paper uses the case study method in determining the trend of artificial intelligence and 3D printing technology in construction. The data used secondary information collected from published research, related studies, journals, and available news report on the web[19].

Ethical Impacts of the Artificially Intelligent System

a) Unemployment:

The construction industry has a great impact on employment in the Philippines particularly where human labor remains a significant source of income to construction workers. Government is obliged to formulate laws that will protect the employment in the construction industry. The new invention of 3D production, however, can decrease labor costs to practically 50%, which eventually benefits the countries, where foreign labor is widely used in the building industry. In countries where the building industry is the major economic sector and where labor is cheaper, 3D printing may not be the best alternative.

b) Humanity:

Legal issues will be faced with the use of 3D printers in the construction industry by the owners, contractors, manufacturers, and software developers. It has a major effect on the income generation of construction workers at the workplace. The growth of the additive manufacturing field is what hit the construction sector, and the project management would definitely be changed as well. As 3D printers will be automated and self-sufficient, there will be a few workers on the building sites. Because 3D printers can work nonstop for 24 hours and do not need overtime, the projects will be finished earlier than scheduled.

c) Security and intellectual property:

Users' safety when it comes to structural capacity are 3D printing technologies would always be a major problem. Besides, a designer's intellectual property may suffer. The future-wide distribution of home manufacturing thus raises two ethical matters. For one thing, security is an issue. Our present security legislations are centered on this idea, resulting in the fact that it is very hard to use them for a new manufacturing concept. Later there are disagreements with copyright. It is now doable to use a 3D scanner to scan objects and make their replicas; a lot of objects are simply not included in these rules as per the now-present intellectual property laws[20].

IMPACTS ON MACHINE

a) AI bias:

In modern-day instances, three-D cement printing (3DCP) has come to be famous as a technological method of lowering the big carbon footprint of cement manufacturing. Research indicates that 3DCP's capability to enhance automation and address the modern-day loss of professional people in the building quarter is what encourages organizations the most to put money into the technology—now not the environmental advantages. Present government shopping regulations do no longer safely well known sustainability perks to inspire the use of 3DCP.

b) Global regulations:

Regulatory groups need to cope with the design and creation processes along with fitness and safety necessities in 3-d printing creation technology. The want for creating a regulatory framework to establish the bar for the performance of 3-D published gadgets is driven with the aid of the lack of ability to tolerate structural screw ups and compromises at the health and safety of both people and the overall public. Based on the studies, a subsidiary piece of regulation for 3D printing in buildings turned into recommended to balance the inherent risks of this new technology without sacrificing public protection at the grounds of fine, health, and safety.

c) Accelerated hacking:

The consequences additionally reveal that 3D printing has been negatively and definitely impacted via the hacking culture. It has actively aided inside the democratization of 3D printing by making participation and benefits similarly available to every body. However, via allowing the use of three-D printers in places outdoor of institutional authority in which ethical approval isn't always necessary, it has additionally by chance fostered societal troubles.

Integration of AI Technology in 3D Printing: Enhancing Efficiency, Quality, and Innovation"

Design Optimization:

• **Generative Design:** AI algorithms can generate and optimize designs based totally on unique parameters and constraints. This capability allows for the introduction of complicated geometries that maximize performance at the same time as minimizing cloth utilization.

• **Topology Optimization:** AI can analyze structural requirements and propose best material distribution within a layout. This improves the energy-to-weight ratio of revealed gadgets[21].

Process Monitoring and Control:

• **Real-time Monitoring:** AI-powered sensors and cameras display the 3-d printing procedure in real-time. They locate deviations, defects, or mistakes as they occur, enabling instant adjustments and decreasing waste.

• **Predictive Maintenance:** AI algorithms examine data from printers to predict maintenance desires based totally on utilization styles and overall performance metrics. This proactive approach minimizes downtime and guarantees consistent operation[22].

Quality Assurance:

• **Computer Vision:** AI-driven computer vision systems inspect printed objects for excellent control. They can locate surface defects, deviations from design specs, or structural weaknesses that can compromise overall performance or protection[23].

Material Development:

• **Material Simulation:** AI models simulate fabric properties and behaviors below different conditions. This allows in the improvement of recent materials especially tailor-made for 3-d printing, optimizing their performance and compatibility with printing processes.

• **Material Selection:** AI algorithms help in deciding on the most appropriate substances for precise packages based on favored characteristics along with energy, flexibility, or biocompatibility.

Customization and Personalization:

• Parametric Modeling: AI allows parametric modeling that allows for personalisation of 3-d-revealed items primarily based on individual specifications or consumer alternatives. This is specifically precious in industries like healthcare for personalised medical gadgets and prosthetics.

Supply Chain Management:

• **Demand Prediction:** AI algorithms examine records to expect demand for 3D-published products and components. This facilitates in optimizing stock management and making sure well timed availability of materials.

• **Logistics Optimization:** AI optimizes supply chain logistics with the aid of identifying the most efficient routes for distributing substances and completed products, reducing costs and delivery times[24].

The integration of AI (Artificial Intelligence) with 3D printing in the pharmaceutical industry offers several significant benefits:

Post-Processing Optimization:

Surface Finishing: AI algorithms can recommend superior submit-processing strategies based totally on the kind of cloth and favored floor finish. This enhances the aesthetic appeal and practical performance of three-D-revealed gadgets.

Personalized medicine: AI algorithms can analyse patient data to develop drug formulations and dosing agents. 3-d printing then allows these customized medications to be precisely manufactured, based on the preferences of the affected gender.

Complex drug delivery systems: AI can optimize complex drug delivery systems that are then displayed in 3D. This includes controlled delivery of drugs or devices that focus on specific areas in the wood, improving treatment outcomes[25].

Rapid drug development: AI-pushed simulation and modeling for rapid testing of systems and recent tablets. 3-D printing allows for faster prototyping of these drugs, faster reproducibility, and certainly faster time-to-market

Manufacturing on demand: AI can anticipate manufacturing processes and optimize 3-D drug display. This manufacturing flexibility ensures that pharmaceutical products are produced to order, reducing waste and establishing a distribution chain more efficiently.

Cost efficiencies: By optimizing materials and manufacturing processes, AI helps reduce the costs associated with drug development. 3D printing further increases costs by reducing waste and improving manufacturing efficiency[26].

Improved regulatory compliance: AI technology can help ensure that 3D printed drugs meet regulatory standards for safety, efficacy and quality. This includes real-time monitoring of printing and quality controls.

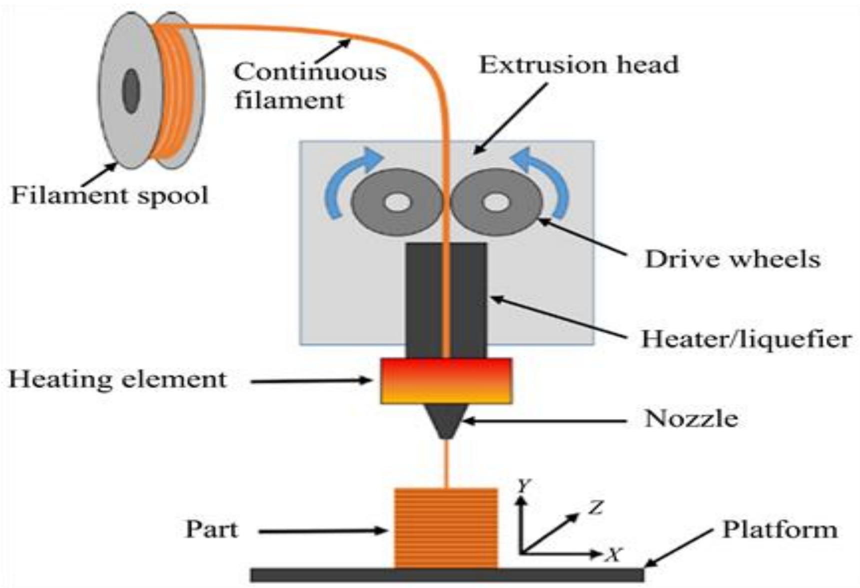
Optimization and patient compliance: AI-driven optimization of drug dosage and form improves patient care in treatment regimens. 3D printing enables the development of drug delivery systems that are easier to deliver and more likely to be accepted by patients[27].

CHALLENGES IN 3D PRINTING TECHNOLOGY

- Although proved promising results are there in drug delivery, still under the developing stage[28].
- Several challenges such as versatile use, appropriate excipient selections, post treatment method to advance the enhancement of 3D printed products and to magnify the application scope in novel drug delivery systems.
- The primary parameters are to be modified to improve quality of 3DP such as printing rate, passes, print heads line velocity, printing layers interval time, nozzles and powder layer distance etc[29].
- 3DP technologies will result in a massive loss of work for a vast range of manufacturing processes. As well as this drastic reality, it will establish a great work opportunity for qualified specialists in CAD technology, materials engineering, computer technology, mathematics, and technology automation[30].

3D PRINTING OF DRUG DELIVERY SYSTEMS

This section will highlight the range of dosage forms prepared using 3D printing technologies, specifically highlighting studies conducted over the last 10 years, 2006–present.



3D Printing in Medical Implant Fabrication

Smarting from securing the rights and showing off 3D powder bed inkjet printing via academic publication, the MIT researchers developed the biodegradable implants to demonstrate that it is possible to administer the drug through them at the same time as improving implant Osseo integration. 3D printing has greatly simplified the process of medical implant production, as it allows the production of Implants to be tailor-made according to the patient's anatomy[31]. This technology is such that precise geometrically variant implants are made which not only have better biomechanical properties but also reduce errors during treatment of patients. By incorporating a layer-by-layer depositing of materials, besides production of metal or polymer components with complex geometries, 3D printing promotes unprecedented control of various forms and the indie fabrication of parts with a multi-material composition. With 3D printing, ideas can be realized quickly and tailored to the needs of the user, thus the manufacturing cycle as well as costs can be minimized. The structuring of these patient-specific instruments will enable the surgeon to perform pinpoint placement surgeries as part of their operations, an act that may lead to the complete elimination of the need for an anesthesia[32]. Each material shows different properties, covering if needed the specific requirements and biocompatibility limits for implant usage in the human body. All in all, the presence of three-dimensional reproduction in the production of the medical devices signifies the move towards individually crafted health management[33].

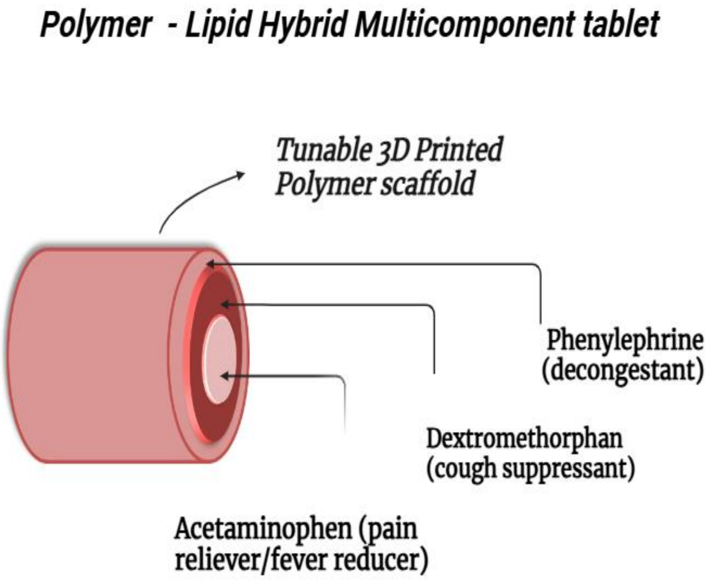
3D printing of capsules

The first 3D-printed capsular devices were manufactured in 2015 by Melocchi et al. For the manufacturing, hydroxypropyl cellulose-containing filaments were created by hot-melt extrusion and then the filament was 3D printed. The manufactured samples were swellable erodible capsules for oral pulsatile drug release[34]. Fused deposition modeling and inkjet printing were used to fabricate capsules from different polymer formulations.

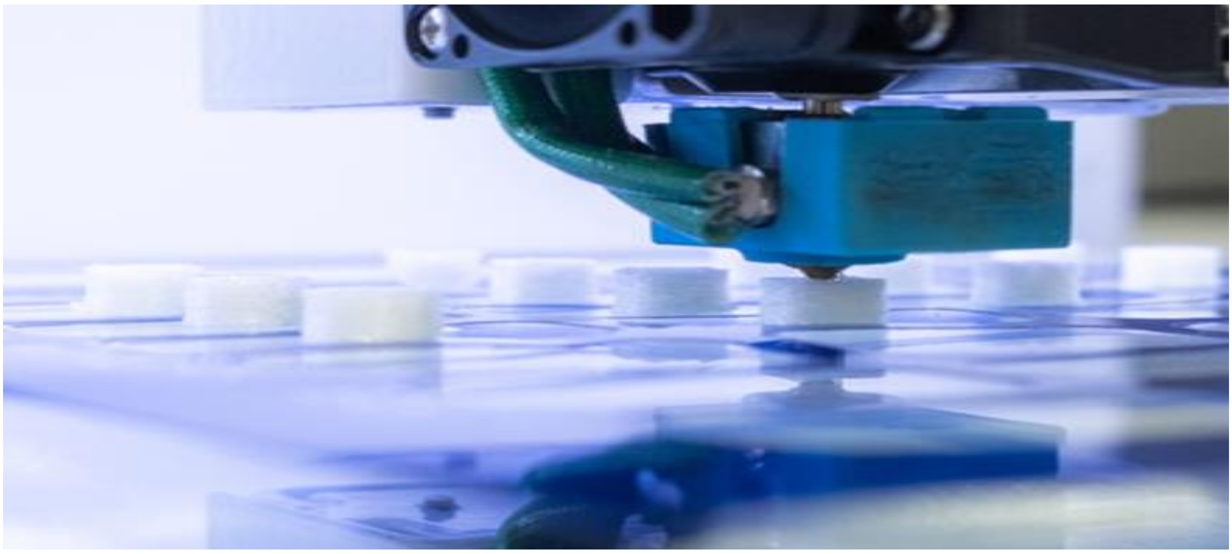
The capsules were formed by three parts: two hollow parts which had a cylindrical closed end and a rounded open end; the middle part acted like a joint and a partition, The hollow parts differed in geometry and wall-thickness. The samples were filled with model APIs and the results showed that the device was able to successfully release the model APIs in pulses within 2 h. The main benefits of this device were that the release could be modulated simply by modulating the inner geometry of the PLA capsule and as the API did not undergo heating a wide range of APIs could be used[35].

3D printing of tablets

Nowadays 3D printing technology is starting to find its use in the pharmaceutical industry when it comes to the production of drugs. 3D printing is an advantageous, accurate, and simple method where the deposition of materials (active pharmaceutical ingredients (APIs) is done layer by layer to customize the dosage form. This concept gives several benefits, e.g. by individually creating tailored drug-release profiles or devising targeted therapies, and, therefore, greater patient compliance. In fact, 3D printing technique also contributes to incorporating several active pharmaceutical ingredients into one affordable tablet, which, in turn, also approve the combination therapies along with the cost-effective solutions for patients[36].



Several 3D printing methods, including physical deposition modeling (FDM), photocuring (SLA), and selective laser sintering (SLS), have been adopted for tablet-scale production. Notably, methods of making tablets are re-defined: the various shapes, particle sizes, porosities, and release kinetics which once had to be produced, can now be pre-programmed and thus, their batch production can be reduced to less than half of the originally required amount of time[35]. Though the application of tablets 3D printing in the pharmaceutical industry is highly promising it still faces a set, like having regulatory approval, materials identification, and scalability among others, of challenges that have to be dealt with. By the same token, developing work together with a manufacturing process that has integrated this cutting-edge technology is paving the way for its universal spread in drug manufacturing and personalized medicine[36].



3D Printing of Transdermal Delivery Systems

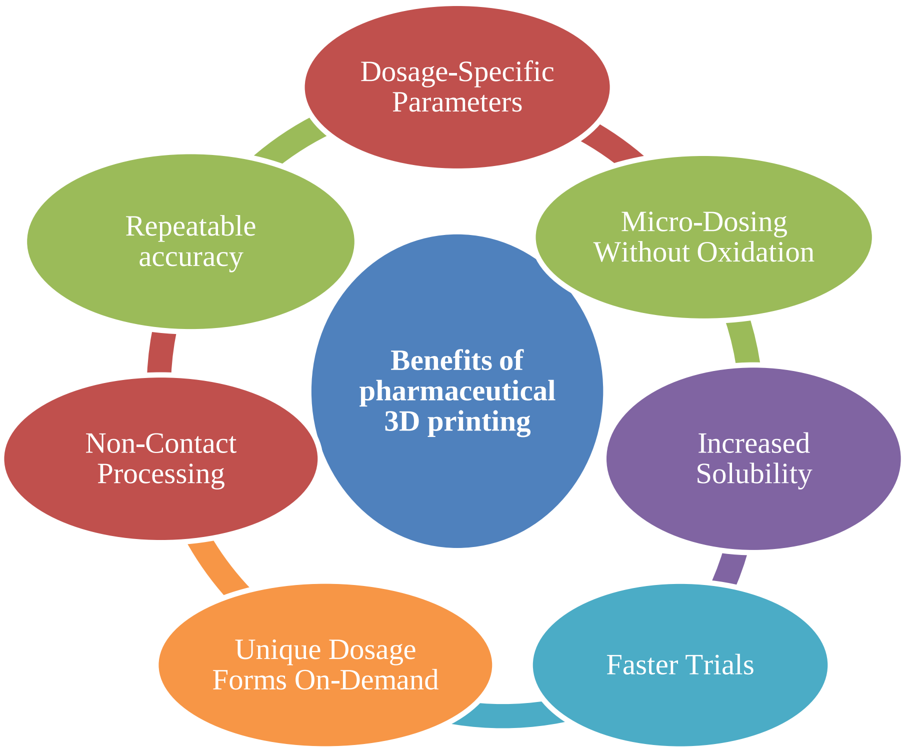
Transdermal drug delivery systems are one of the methods that recognize the kin as a non-invasive route for the administration of drugs granting advantages such as increased patient compliance and slow sustained release of therapeutic agents. The rise of 3D technology has unlocked the chances of creating the transdermal delivery system with the accuracy and customization quality never seen before. Adding the mores of 3D printing technology, inkjet printing, or fused deposition modeling (FDM), the professionals can assure the deposition of the drug-loaded substances on flexible substrates to fabricate transdermal patches or films with high resolution and reproducibility (flexible substrates are those flexible materials which are used as the base of digital devices e.g lenses). For that purpose the design of the optimal drug release profiles, which are perfectly matched to the needs of the patient, is possible[37]. Moreover, development of 3D printing grants the combination of few or numerous of active ingredients, the control over thickness of the patch, and on the another note, it enables the integration of microneedles or other surface modifications to the skin to accelerate drug permeation. The use of 3D technology for the generation of transdermal drug delivery systems is not widespread but still there are also disadvantages such as the material selection, formulation optimization, and regulatory approval which are the major issues in the process. In contrast, ongoing research and technological developments in this area are set to deliver the new generation of transdermal drug delivery procedures which could have a ground breaking effect in healthcare delivery and patient treatment vis-à-vis traditional substances and methods[38].

3D Printing of Microneedles Delivery Systems

Microneedles, with the 3D printing technology integrated, are a new level of drug delivery systems that are exceptionally useful in effective and safe treatment of patients with the help of their power to increase therapeutic efficacy and patient compliance. Micron-scale needles, the one which were developed as painless means for the breaking of the skin's outer layer to enable targeted administration of medicaments or vaccines directly into the dermis or epidermis. 3D printing technology, which is capable of exact control, makes it possible to use the precise length of the needles, the number of needles on the array, and the amount of drug in order to suit the specific needs of ideal treatments. In the biomedical sector, microneedles that are 3D printed can store drugs, peptides, or vaccines inside the bio-degradation or nonbio-degradation copolymers or hydrogels if required[39]. This way not only does more stability of sensitive drugs but tailored release profiles (like sustained or pulsatile delivery) are also made. The versatility of 3D printing design also allows the blending of the agent into a multiple microneedle array, thus promoting the use of combination therapies and solving the medical problems pertaining to complex illnesses with a great output[40].

3D-printed microneedles are a hope for personalized therapy. The user wanted to make the article more informative so the content got a little longer in the process. This capability is especially important for the creation of customized treatments that take into account the individual differences in the skin thickness, drug dosage, and treatment schedules. Besides, 3D printing technology that provides the option of outsourcing the stable core and printing around it, is a key factor in achieving low-cost manufacturing of microneedle arrays that in turn promotes large-scale production of clinical applications. However, the development of approval procedures, biocompatibility tests, and increasing production quantities need the resolution of the challenges for obtaining the full advantages of 3D printing technology and creating microneedles in healthcare[41].

3D Medical applications in the Pharmaceutical Industry



Benefits of pharmaceutical 3D printing

1) Dosage-Specific Parameters

Zip Dose era is merging the implant and drug shipping worlds, and this has, at last, made site-unique colon targeted drugs a truth. Drop-on powder has also been used for the anti-cancer drug, fluorouracil. Researchers lately examined a number of polymer answers to acquire just the right dosages via fused deposition modelling FMD. This studies proved that optimised powder-primarily based printing should produce excipients with out thermal processing, thereby allowing thermo-touchy drugs to be produced in specific dosages. The take a look at's printing parameters blanketed binder volumes, jet dispenser speeds, and the variety of drops fired. Production saved temperatures under 50 degrees Celsius. Drop on call for techniques in the long run produced a homogenous coating that required nothing extra than the right provider powders[42].

2) Micro-Dosing Without Oxidation

Breaking up capsules can oxidise substances. When tablets want to be quartered, accurate dosages are nicely-nigh impossible to obtain. 3-d-revealed alternatives can provide precise dosage forms that supply microdoses with out oxidation threat.

3) Increased Solubility

Thermal inject printing TIJ has been used to fabricate Miconazole, which has notoriously low solubility in aqueous environments. TIJ micromolding makes use of lined microneedles as drug-loaded coatings. 3-d-printed drug delivery gadgets like microchips and polymeric nanoparticles have end up cheap enough for mass consumption. Vat photopolymerization is used in a comparable way by using relying on light-activated polymerization for precise drug-shipping programs. Zip Dosing takes solubility to an entirely new level by achieving a rapidly-disintegrating formulation. Researchers are currently looking into what hot-melt extrusion and drug geometry changes will do for drug release.

4) Faster Trials

Medical engineers have used 3D technologies such as VAT and photopolymerization to develop preclinical drug products for testing purposes. This process is faster than before. As research accelerates, so does the development of new drugs. Pharmacists edit drug plans directly from a CAD file on the go. This enables the final link in the supply chain to perform additional iterations in different salts, quantities and ancillary materials when needed[43].

5) Unique Dosage Forms On-Demand

Special volume forms can be obtained through licensed blueprints. This gives physicians the ability to reduce dosing. Thus, distribution and logistics costs can be eliminated and clinicians can treat multiple diseases in a single dose[44].

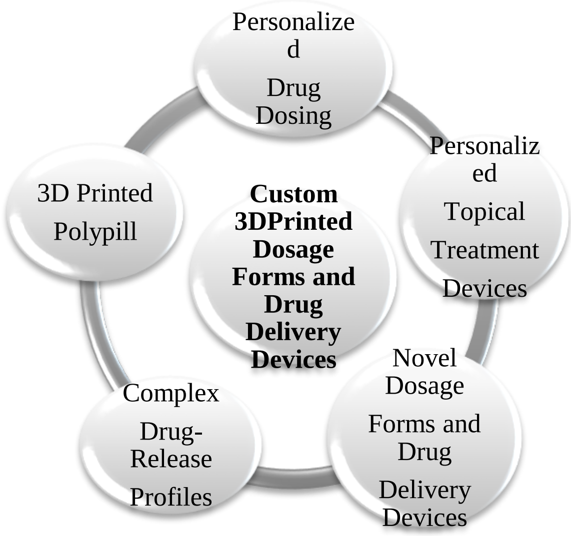
6) Non-Contact Processing

Inkjet printing can process droplets of up to 100 pl into 3D structures using a micrometer-scale nozzle. The water can be heated to boiling temperature or charged. Dirt and heat damage can be reduced in this way, but ink technology can do more than just layering. It can also be used to print magnetic nanoparticles, purified proteins, and other biological materials. Drug release profiles can be tightly controlled by stability, filtration and pH levels. This technology has been used to produce stable doses of prednisolone using heat and various other excipients.

7) Repeatable Accuracy

3D printing techniques provide great resolution, accuracy and repeatability even for small-scale production lines. This will be more of an equality in the pharmaceutical industry as small businesses will have the ability to produce complex products within tight budgets. Unnecessary features can be eliminated, and that is felt in the final consumption value. Even better, when the complexity of drug delivery data leads to greater control over drug delivery. This, in turn, can increase the effectiveness of some drugs[45].

Recent Progress of 3D Printing Technology In Drug Delivery Application



I. Personalized Drug Dosing

Personalized drug dosing, as the name of the procedure tells, is the changing of drug regimens to individual patients according to their genetic profile, metabolism, and the stage of their disease. This method acknowledges the point that patients can have different reactions and side effects with a standard dose of a drug because of factors such as genetic variations, age, weight, liver function, and other medical conditions[46]. The functions of the electronic health records, pharmacogenetic testing, and therapeutic drug monitoring together with more patient information provided to healthcare providers lead the personalized dosing process to success. Also, novel drug delivery technologies like 3D printing enable the craft of custom drug forms that are unique to each patient. Regardless of its potential, personalized drug dosing still has obstacles before it becomes widely accepted, related to cost, accessibility, and regulatory approval. Most of the time, new developments and the establish pharmaceutical companies, and regulatory authorities are the drivers of change and the paths to more personalized and effective medication therapies in the future[47].

II. Complex Drug-Release Profiles

The drug release process can vary in several ways, which are together termed as complex drug-release profiles. Instead of being released all at once, many profiles are designed to release medicine on a controlled, prolonged or even discontinuous basis. These profiles aim at ensuring proper medication works like that of a valve with the same medicine staying in the body for a longer time or only releasing when it is in call. The different kinds of technology that are employed to treat various diseases by giving the patients the right amount of medication at the right time are utilized to create these profiles[48].

III. Personalized Topical Treatment Devices

Personalized topical treatment devices are peculiar medical tools that are used to administer drugs in a person's skin. These are personalized to serve your needs like applications of specific skin problems or different skin types. These devices might be in any of several forms, with some that have used patch releases to drugs, others that are in the form of sprays or foams, and some that are special applicators for precise dosage. They're very beneficial not only because they make treatments more efficient but also because they're easier to use and fewer cases of side effects occur. Even though they are still not as widely available as people would like, ongoing research is geared towards achieving this[49].

IV. Novel Dosage Forms and Drug Delivery Devices

New approaches to administer drugs are being through inhalers, thin strips or implants to people. These are designed to make treatments work better, be easier to use, and fit different needs. For instance, there are very thin films that dissolve in the mouth, small implants that release medicine slowly over time, and inhalers that send the medicine directly to the lungs. In addition, in the case of the patches that only contain micro-sized needles, they are pasted on the skin and thus painlessly dispense the medicine. Moreover, nanoparticles deliver the drug to the parts of the body which are affected. So, these are the new and creative dosage forms and the technology of the drug delivery devices that is the progress realization of the pharmaceutical industry, which provides new opportunities for the patients to be instructed well and receive better treatment. The ones that are being researched aim to focus on certain patient needs, lower side effects, and increase treatment efficacy. Some of them are already existing in the market, whereas others are still in the stage of research and development, which will lead to further trials that will solidify them eventually in clinical use[50].

V. 3D Printed Polypill

3D prints the polypill, and it is the medication that has several drugs in one pill. It is done using 3D printing technology, in which one gets accurate control of the composition and dosage of each drug. The aim of the bullet will be to make medicine consumption straightforward for them assuming that they are on multiple medications, thus the pressure of managing their treatment will be lightened. Though the polypill can be given for various diseases such as heart disease, diabetes, or high blood pressure, one dose for all these can be used. It is a very promising approach to healthcare, which is aimed at enhancing the medication compliance and patient outcomes[51].

Regulation Concerning 3D Printing for Pharmaceutical Manufacturing

3D printing for pharmaceutical manufacturing and its regulation is a dynamic development that is made within the whole complex set of rules within the pharmaceutical field. The main problem of the regulatory agencies is that, as more advanced technologies are developed and applications of printing are used in the treatments of diseases, the regulations will have to be more far-reaching than ever before.

Directives set the standards for the 3D printing of the processes and the safety of the envelopes, plus the checks are done to the parts in the manufacture of them. The labelling and traceability of products are also regulated, under which market (monitoring of medicine production) and surveillance happen through drug-safety period. The new directions of sync in regulatory requirements across jurisdictions ('standardize' the process) will be the result, and that will render it easier for the manufacturers to obtain a global market while the patient safety standards will stay sturdy. The struggle is seen mainly with the drug 3D printing field and it calls for the evolution of the regulatory frameworks in the drug and pharma sectors to find the best solutions in this direction[52].

Practical Considerations for pharmaceutical industry

Along the pharmaceutical sector, many things play a role in developing, manufacturing, and eventually distributing drugs. Their all safety, effectiveness, and availability are the desired aims in these processes. In pharmaceutical industry theroportion regulation plays the cornerstone of the process by very fine compliance with the standards of the scrutiny, as per the FDA and EMA report which is essentially critical to ensure these drugs come to existence in the first palaces. Fixing up the mechanisms for quality assurance and control that are very strong is an ample deal in the manufacturing process. They ensure that the products have consistency and are in agreement with the Good Manufacturing Practices (GMP). Further back it tells us that; a huge venture into the two categories of research drives innovation through drug discovery, preclinical, and clinical trials and the final stage of the formulation. Getting the flows in the supply chain right is as important as ensuring that no obstacles stand between the patient and the cure (need). Adoption of advanced production methods such as processes like continuous manufacturing and 3D printing strengthens speediness and pliability through cost-effective, high-quality products. Therefore, strategies of pricing and market access are the main determiners of the success of medicine affordability in the market Miplablefeation Company is building, acquiring, renewing the patents, and initiating competitiveness. That call for the implementation of the pharmacovigilance program which is responsible for safety in the market, having been developed as an AI social robot. If you look after the Good Distribution Practices (GDP), you are going to be overseeing it correctly and distributing these medications without causing them toacidate. On the other hand, new technologies like artificial intelligence and digital health allow the pharmaceutical companies to remain the frontrunners in innovation and also provide the most effective healthcare services. The factors mentioned above interact to influence the pharmaceutical industry tool aim at are the better of the drug patients and the health of the general population by how they alter the framework of the pharmaceutical industry[53].

CURRENT CHALLENGES AND FUTURE PERSPECTIVES OF 3D PRINTING TECHNOLOGY

The modernization of the pharmaceutical manufacturing has been bringing about small changes over the past decade through their implementation of process analytical technology (PAT) and continuous manufacturing, yet the actual method used in the production of tablets and capsules has not even changed. However, the use of 3D printing in drug delivery, pharmaceutical product development, and manufacturing has brought a completely new perspective to pharmaceutical preparation and manufacturing. 3D Printing has been a fast-emerging industry in the pharmaceuticals field. Research is carried out in 3D printing to create a personal prescription, improve delivery systems, and help patients with treatment. Using a very new technology 3D printing allowed for the creation of a new field called personal dosing technology that way patient could have the medication at home the medication is more effective and therefore, the patient can better manage the treatment[54].At present, personalized dosing using 3D printing technologies is being pilot tested in Europe, China as well as Singapore. U.S. Pharmacopeia (USP) and the U.S. FDA have been organizing dialogue sessions and workshops to develop and adopt standards to prevent such disturbing occurrences. Quantity-scale commercialization and 3D printing pharmaceutical products are required to undertake the standard regulatory pathways. Besides, besides the approved one product, Spritam, a few other investigational new drug (IND) applications have been granted clearance in both the United States and China for the initial clinical trials of 3D-printed drug products. The 3D printing technology does not lag in the process of its correlation with other technologies used and those that are newly developed[55].

Surely, AI-driven 3D printing in pharmaceuticals is enhancing drug delivery and medical devices personalizing treatments and optimizing designs. At present, AI participates in the production of individualized drug delivery systems, increases manufacturing accuracy and provides the equipment for rapid prototyping. It also ensures that the quality of the 3D printing is being monitored in real time by its own self-regulatory quality control regulation.It is hypothesized that AI will be even more connected to genetic coding to create treatments that are more personalized and also is expected to develop new 3D printing materials. Progressive steps might attribute to hi-tech implants with intrapartum monitoring and global distribution of enzyme replacement therapies. To tackle the new technologies, the rules and ethical questions will more evolve[56].

In a similar vein, the adaptability of the technology will result in reduced costs through both smarter more efficient manufacturing and the preparation of more affordable drugs, particularly targeted for rare disorders and individualized medications. That is because with the advent of 3D printed drugs the parts they are made of will be separate from the final whole of the drugs intended to be use in the body helping to avoid potential challenges[57].

CONCLUSION

3D printing technology is gearing up to transform Pharma world with the help of its new ideas which are production and delivery of personalized medicine, and general patient care. The emergence of 3D printing technology in pharmaceuticals has provided a plethora of benefits in different sectors of medicine such as the manufacturing of personalized doses, medical implants, transdermal delivery systems, and the creation of new drug delivery devices[58]. The pharmaceutical industry is rapidly changing due to the switching of the traditional drug development and manufacturing to the use of advanced technologies such as Artificial Intelligence (AI) and 3D printing. Thus, AI uses sophisticated calculations to process data and make forecasts, while 3D printing is the creation technique of exact, personalized items where each layer is printed separately. Both of these new technologies are switching the complete set of thinking in terms of how medicines are designed, produced and distributed.AI-driven 3D printing involves an exciting performance that could be the production of very personalized medicines which would be ideal for the needs of individual patients and developing elaborate drug delivery system[59] The future of Three-Dimensional Printing in the pharmaceuticals sector is reality that holds the big hope of transformation of the diagnosis process, the manufacturing methods, and the general healthcare to the benefit of all patients who would use the affordable, efficient, and personalized medicines.[60].

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