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FROM ONE-SIZE-FITS-ALL TO CUSTOMIZED CARE: HOW 3D PRINTING IS TRANSFORMING THE FUTURE OF PHARMACEUTICALS AND PERSONALIZED MEDICINE

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Abstract: Three-dimensional (3D) printing is poised to be a transformative improvement withinside the pharmaceutical industry. The usage of 3D printing technology for drug delivery structures has grown exponentially, because of its ability adva ntages in customizing medicinal drugs and reaching balanced dosages. Over the beyond 15 years, 3D-revealed drug delivery structures have developed rapidly. This progressive technique leverages mechanical data to manufacture strong objects through layering substances consecutively. Also called additive manufacturing, 3D printing includes using a virtual record to create a three-dimensional solid object. This generation is applied to put together customized medicinal drugs thru computer-aided layout. Unlike the traditional "one-size-fits-all" technique, customized or precision medicinal drugs remember character differences, together with pharmacokinetics and genetic traits, that have proven advanced effects over traditional treatments. The finesse of 3D printing generation lies in its ability to fulfill character-unique desires through utilizing particular purposeful layout along advanced biocompatibility. This paper explores the improvements and ability of 3D printing within side the pharmaceutical field, highlighting its capability to revolutionize drug delivery and customized medicine.

***Index Terms* - Three-dimensional (3D) printing, personalized medications, Precision medications, Customizing, Biocompatibility.**

I. INTRODUCTION

Three-dimensional printing (3DP), also known as additive manufacturing, rapid prototyping or solid freeform manufacturing, is a revolutionary technology that creates three-dimensional objects from digital models by layering materials one after the other. Since its inception in the late 1980s, 3DP has found applications in a variety of engineering and non-medical manufacturing sectors, including automotive, aerospace, and consumer goods. Recently, the development of 3DP methods and the development of versatile biocompatible materials have promoted its adoption in the pharmaceutical industry [1]. 3DP technologies offer several advantages, such as customizable models and the ability to produce complex solid dosage forms with exceptional accuracy and precision. These methods make it possible to prepare solid dosage forms containing different drugs and excipients with adjustable dispersion and density profiles. In particular, 3DP can effectively solve the delivery challenges of poorly water-soluble drugs, peptides, potent drugs and multi-drug delivery systems. Despite these promising benefits, several challenges hinder the widespread commercial adoption of 3DP in pharmaceuticals. These include the need for pharmaceutical excipients and binders with optimal co-technological properties and desired product outcomes. In addition, 3DP adds complexity to product development, enabling the creation of advanced drugs such as multilayer tablets, tablet-in-tablet systems, osmotic dosage forms and multiparticulate systems. In addition, 3DP has several applications in the pharmaceutical industry, including the production of modified drug-release formulations, high-dose orodispersible tablets (ODTs), amorphous dispersions by hot melt extrusion and ultra-low dose (up to 3) . medicinal preparations. ng). These advances position 3DP as a transformative technology for pharmaceutical manufacturing, offering new solutions to drug delivery and formulation challenges [2].

II. 3D PRINTING TECHNOLOGY

The introduction of 3D printing generation withinside the pharmaceutical enterprise has opened new avenues for the manufacturing of personalized medication. Traditional production techniques frequently lack the power to cater to individual patient needs, main to a "one-size-fits-all" approach. In contrast, 3D printing gives the capability to tailor dosage forms to precise patient requirements, improving healing consequences and stopping undesirable toxicity. This study aims to discover the feasibility, benefits, and challenges related to the implementation of 3D printing generation for growing personalized dosage forms.

Three-dimensional technology, also known as 3D printing, is a major advancement in tissue engineering, dentistry, aerospace engineering, and construction. It has the potential to completely transform the healthcare system. Three-dimensional printing, or 3D printing, is a technique used in conjunction with computer-aided design (CAD) to create drug forms that minimize patient compliance, time savings, and flexibility[3,4]. The primary foundation of 3D printing technology is virtual design, which is kept in computer design files. A 3D scanner can create these files, and 3D software can create 3D digital copies of them [5]. (Figure 1)

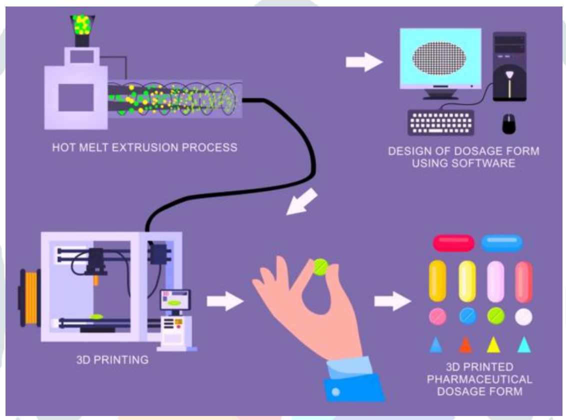

Figure 1: Process and CAD of 3D Printing [6].

III. VARIOUS 3D PRINTING TECHNIQUES

3.1 Stereo Lithography (SLA)

SLA is a polymerization method that uses a basin. The fundamental stages of the SLA process are as follows: the liquid layers of the tank are exposed to ultraviolet light (UV light), which causes the liquid to solidify selectively. In the final resin, the photoinitiator molecule (PI) is reacted with UV light and higher radiation. Only in the open state, the chemical polymerization reaction has a locally stimulating effect. A fresh superfine layer of the prepared resin is carefully applied after using this method to repair the first prepared layer [7]. As a result, the object is grown layer by layer. The direction of the incoming light beam or the irradiation method can be used to categorize this technique. In order to solidify the resin, UV light was applied in two different ways: from above as one approaches a free surface, or below through a transparent paint pool on a regulated treated surface. In digital light beam processing (DLP) - SLA, the radiation technique can be applied by highlighting a full-pixel drawing as a thin layer; in laser SLA, it can be applied by scanning each tiny point of a chosen cross-section with a laser beam. A light-sensitive polymer solution is used in this technique. When compounds are exposed to UV or DLP radiation, a chemical reaction known as gelation takes place [8, 9].

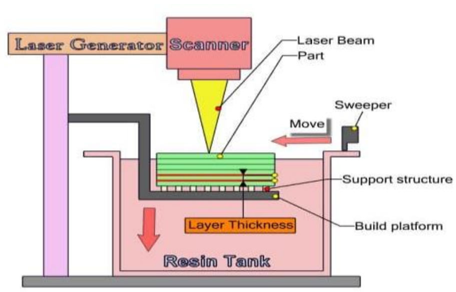

Figure 2: Diagram of Stereo Lithography modeling.

3.2 Fused Deposition Modeling (FDM)

The physical characteristics of the material used in the FDM process are the primary distinction between FDM and PAM. Because plastic fibers melt at specific temperatures, they are required. The process of hot melt extrusion (HME), which comes before fused deposition modeling (FDM), produces filaments by combining thermoplastic polymers into a powder or pellet using a hot melt extruder. To create filaments containing the active ingredient, the drug is combined with plasticizers and an appropriate polymer in the pharmaceutical industry [10].

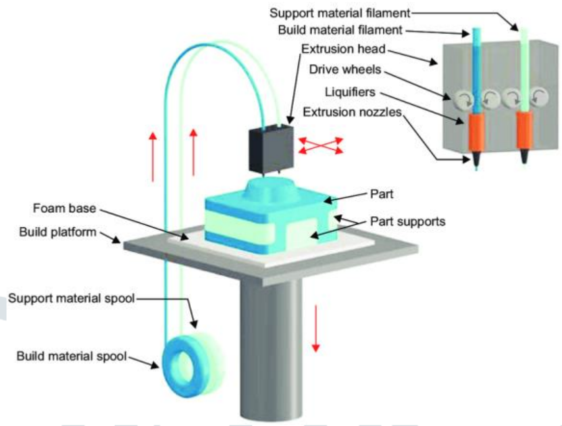

Figure 3: Fussed Deposition modeling [11].

3.3 Selective laser sintering

A continuous laser beam is used as a heat source to scan and align particles of predetermined size and shape in layers; the geometry of the scanned layers corresponds to the various parts of the models created from files produced by computer-aided design or stereo lithography; after the first layer is scanned, a second layer is scanned and placed over the first, repeating the process from bottom to top until the product is completed. Selective laser sintering is a rapid production process based on the use of powder-coated metal additives. The process is generally used for rapid prototyping. The laser selectively melted the powder material, reducing the thickness of the powder layer by one layer by scanning a cross-section or layer on the surface of the powder layer produced using a 3D modeling program [12].

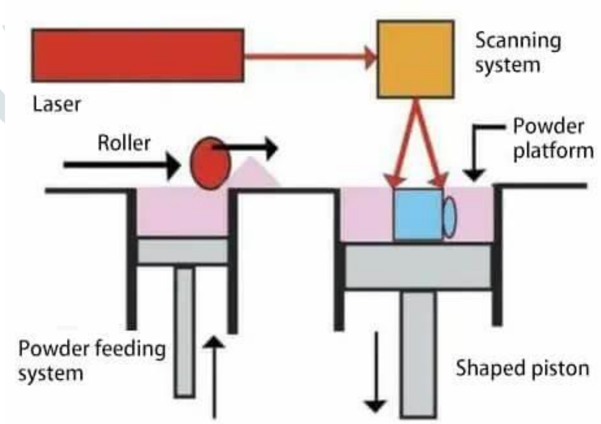

Figure 4: Selective laser sintering[12].

Table 1: Various technological innovation of 3D printing.

S. No	Technology innovation	Advancement	Working	Uses
1)	Vat photpolymerisation [20,21,22]	1.1 Stereolithograohy (SLA) It used a vat of liquid ultraviolet curable photopolymer resin and an ultraviolet laser	A 3D Printing is primarily based totally is primarily based totally at the vat photopolymerisation approach wherein a field is filledd with potopolymer resin and it is then hardend via	Part which can be published with virtual mild synthesis produces regular and perdictable mechanical

		individualy to create layer of object. 1.2 Digital light processing (DLP) DLP is a method of printing that uses light and photosensitive polymers. Continuos liquid interface production (CLP). Newest and fastest process that uses vat photopolymerisation is CLP.	way of means of a UV light source	houses growing components that solidify from the inside .
2)	Material extrusion[23,24]	2.1 Fused deposition modeling (FDM) This FDM technology works using a plastic filament or metal wire that is unwound with a coil. 2.2 Fuesd filament fabrication (FFF) It did not face any problem in using it . there are many different types of FFF 3D printer configurations	The nozzle is heated to soften the fabric and may be moved in each horizontal and vertical instructions with the aid of using a numerically managed mechanism. Which is without delay managed with the aid of using a computer. Aided manufacturing(CAM) software program package.	This generation is maximum typically utilized in 2 plastic 3-D printer filgment types 1)ABC (acrylonitrite butandiene styrene) & PLA (polylactic acid)
3)	Power bed fusion[25]	3.1 selective laser sintering (SLS) In this the laser selectively fuses the powder material for which it scans cross- section which are generated by the 3D modeling program in the surface of the surface of the powder bed. 3.2 Diect metal laser sintering (DMLS) Same as sls. All untouched powder remains in the same way and become a support structure for the object.	Used a completely excessive energy laser fuse small particle of plastic cermic and glass powder collectively in a mass that has favored 3-dimensional shape.	The maximum normally used techonolgy in that is selective laser sintering(SLS)
4)	Directed energy deposition[26]	Most of this process is used in the high-tech metal industry and in rapid manufacturing applications. It is after attached to a 3D printing apparatus with a multi-axis robotic arm and a nozzle that deposits metal powder or wire above a surface and an energy	It is oftene connected to a 3D priting equipment with a more than one axis robot arm and a nozzle that deposite metallic powder or cord above a floor and an power soure (laser ,electron beam or plasma arc) that melts it, in addition to a stable item on the end.	These soften all of the stable item on the end. 3-D printing considers the fast advent of part, the velocity of manufacturing may be eased

		source that melts it , as well as a solid object at the end.		again through post-processing.
5)	Binder jetting [27]	This technology was first developed in the massachuetts institute of technology in 1993 and 1995. Z corporation acquires its exclusive license.	Binder jetting makes use of materials :b a powder base material and a liquid binder .withinside the construct chamber, the powder is first unfold in identical layers after which the binder is carried out through jet nozzles which “glue” the powder partical into the form of a programmed 3D object.	The powder remaining in the 3d printing are used in the next object in 3D printing .

IV. DISADVANTAGES 3D PRINTING

The base of the thing is then created during printing when the printer head rotates and the composition's ink gradually separates into layers on the embedded substrate. Until the desired 3D product is finished, the process is repeated. Lastly, during the post-printing phase, the 3D product could need to have excess powder, solvent residues, polishing, and sintering removed [13, 14]. Microneedles can be used to deliver medications and vaccinations subcutaneously without causing pain, however the pharmaceutical sector still finds it challenging to use the production technology [15].

V. ADVANTAGES OF 3D PRINTING

Pharmaceutical 3D printing is gaining a lot of interest these days as a possible solution to lower waste costs and increase productivity, accuracy, and originality. Additionally, the new technology makes it possible to develop novel oral dosage forms and medical devices, which would be challenging to manufacture with conventional production methods [16, 17]. Tablets and capsules are examples of solid oral dosage forms that are frequently used for drug administration. They are often mass-produced by a sequence of steps that include blending, grinding, mixing, and lastly pressing into tablets. Additionally, one dose fits all in large-scale mass production, which may not take specific patient needs into account, is the goal of conventional manufacturing procedures. The traditional production process's primary drawbacks are that it takes a long time, costs a lot of money, and needs highly skilled workers [18, 19].

VI. FUTURE PROSPECTS FOR 3D PRINTING TECHNOLOGY

To enhance human health, a great deal of research and innovation is being prepared. In this field, 3D printing technology has also recently been introduced. 3D printers can be used to produce prostheses, limbs, jaws, crowns, bones and hearing aids for the human body exactly according to the size and fit of the person in question [28]. The traditional jewelry design process demands high technical knowledge of casting, mold, grinding, cutting, engraving, etc. These days, a 3D printer can create any intricate jewelry design and cut down on several steps in the conventional procedure. 3D printers are currently used by jewelry manufacturers [29]. A recent use of 3D printing technology is food printing. Food materials that are semi-solid, powdered, or viscous liquid can be created with a 3D printer. It's a very good approach to feed astronauts fresh food because specially built food printing cartridges are longer and include a controlled amount of nutrients. In our market, this idea is significantly superior [30]. Prototyping is the main application of FDM technology, which has shown to be economical. Researchers, innovators, and die-hard aficionados are the main target audience for this technology. Traditional object-making methods like injection molding and molding require costly and time-consuming prototype procedures. 3D printing technology helps businesses reduce costs and enhances the finished product. It is typically not necessary to tweak and increase the precision of the 3D object at the prototype stage. Stakeholders can afford the FDM 3D printers that are currently on the market. Individuals who possess a basic understanding of 3D modeling can use an FDM 3D printer to create personalized 3D models on 3D objects [31].

VII. BENEFITS TO PATIENTS

The capacity to fully tailor treatment based on the therapeutic or individual needs of the patient is a major advantage of 3D printing medicine. Patients may be required to choose a dose form type from a list in the future. This would enable them to choose formulation characteristics including taste, texture, color, shape, and size, which would boost patient autonomy and commitment to treatment modalities and enhance drug adherence [32]. makes it possible to produce medications with exact or even adjustable dosages. Combining many medications into a 3D-printed polyprintlet can also increase therapeutic effectiveness by lowering the possibility of adverse effects from mishandled dosage [33,34]. In the pharmaceutical sector, 3D printing may be utilized as a substitute production technique for producing customized or large-scale medications. Economically speaking, it's likely that centralized facilities will continue to offer high-volume, low-additive drug manufacturing processes like tablet or encapsulation at a reasonable price [35]. For children for whom traditional mass-produced dose forms may not be acceptable (because to poor taste or incorrect amounts, for example), the capacity to make medications in individual dosage, taste, shape, and size can have numerous benefits [36,37]. The elderly or those on complicated dosage schedules where repeated processing leads to a high tablet load may find 3D printing helpful. Multiple therapies might cause patient neglect and confusion, which increases the chance of dose errors, according to studies [38]. It is advantageous to combine different medications, dosages, and/or drug-release profiles into a single formulation as this has the potential to increase medication adherence and decrease administration errors. Nevertheless, conventional manufacturing processes produce fixed dose combinations only and do not support the individualization of "polypills" at this time. "Multiprints" can be created using 3D printing because of its adaptability and capacity to deliver accurate medicine distribution in space [39].

VIII. CONCLUSION

In conclusion, 3D printing technology presents significant potential for the manufacture of personalized dosage medicines, offering tailored solutions that better meet individual patient needs and enabling on-demand production. This innovative drug delivery system provides a compelling alternative to traditional methods by precisely controlling the location, rate, and timing of drug release, thereby enhancing therapeutic efficacy and safety. The future of 3DP in pharmaceuticals hinges on its ability to reliably produce personalized doses, paving the way for more effective and patient-specific treatments. As the technology advances and regulatory frameworks adapt, 3DP is poised to become a cornerstone in modern pharmaceutical manufacturing.

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