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REVIEW ARTICLE

ADVANCES IN FDM 3D PRINTING FOR ORAL DOSAGE FORMS: A REVIEW OF TUNABLE DRUG RELEASE STRATEGIES

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Abstract

Three-dimensional printing (3D printing) has recently gained significant attention as an innovative technology in pharmaceutical sciences, particularly for the development of oral dosage forms. Among additive manufacturing approaches, fused deposition modeling (FDM) is among the most promising techniques due to its flexibility, cost-effectiveness, and potential for personalized drug delivery. This review discusses the fundamental principles, commonly used materials, and recent technological advancements in FDM-based production of oral pharmaceutical dosage forms. Central to this discussion is FDM's ability to tailor drug release, enabling immediate, controlled, and delayed profiles by manipulating formulation composition and printing parameters. We critically evaluate polymer selection, formulation strategies, and process variables that govern release kinetics. Potential advantages, including patient-specific dosing, improved drug stability, and cost-effectiveness, are discussed alongside persistent challenges related to regulatory approval and manufacturing scalability. By synthesizing current evidence, this review aims to clarify the role of FDM-based 3D printing in advancing personalized oral dosage forms.

Keywords: 3D printing, fused deposition modeling, hot-melt extrusion, oral dosage forms, polymers, tunable drug release.

INTRODUCTION

Fused deposition modeling (FDM) was originally introduced by Scott Crump in 1989 and subsequently commercialized through Stratasys. Since then, a wide range of three-dimensional (3D) printing technologies has emerged and evolved. The application of 3D printing in pharmaceutical sciences began in 1996 with the fabrication of drug delivery systems, marking a major milestone in the field. This advancement facilitated the development of several pharmaceutical 3D-printing techniques, including inkjet printing and related additive manufacturing methods. Modern pharmaceutical product development utilizes a wide range of three-dimensional (3D) printing technologies, including powder bed fusion and binder jetting techniques, extrusion-based approaches such as fused deposition modeling (FDM) and pressure-assisted microsyringe systems, as well as stereolithography (SLA), selective laser sintering (SLS), digital light processing (DLP), and inkjet printing methods[1]. The FDA's approval of the 3D-printed orally disintegrating tablet Spritam (levetiracetam) in 2015 marked a significant advancement in pharmaceutical manu-facturing, demonstrating the potential of 3D printing technology to produce complex, patient-specific dosage forms[2]. Fused deposition modeling (FDM) is a widely applied 3D printing technology known for its favorable balance between cost and performance. In the pharmaceutical field, it has gained significant attention for the development of customized drug delivery systems. Numerous recent investigations have employed FDM to manufacture patient-specific tablets designed to meet individual therapeutic needs[3]. The FDM technique deposits successive layers of molten material onto a platform using a polymeric filament. One of the most critical parameters in the FDM technique is filament quality[4]. Combining hot-melt extrusion (HME) with FDM to manufacture printable filaments proved useful[5]. Printable filaments are typically fabricated by hot-melt extrusion (HME) from thermoplastic polymers with defined dimensions and mechanical characteristics[6]. The filament is heated to a softened state and then forced through a nozzle, where it is deposited onto the build platform to create a successive layer. This process is repeated sequentially, with each new layer being added until the complete three-dimensional tablet structure is formed. Fused deposition modeling (FDM) is widely used to fabricate personalized oral dosage forms[7]. FDM printers have

been used to prepare drug products with different release patterns, including immediate, sustained, controlled, and delayed-release tablets, using various polymers[8]. For example, different grades of hydroxypropyl methylcellulose (HPMC), specifically HPMC 2910 and HPMC 2208, were evaluated for the development of bilayer tablet formulations. In this system, one layer was designed to achieve sustained drug release, incorporating HPMC 2208 in combination with poly(acrylic acid) (PAA) to modulate release behavior. Conversely, the immediate-release layer employed HPMC 2910 as a binder, with microcrystalline cellulose (MCC) and sodium starch glycolate (SSG) as disintegrants to promote rapid tablet disintegration[9]. Polyvinyl alcohol (PVA) is also used as a polymer in FDM 3D-printed tablets to facilitate rapid drug release[10]. Using FDM, bilayer tablets exhibiting distinct drug release profiles were fabricated. The upper layer was formulated with Eudragit RL to provide sustained release, whereas the lower layer incorporated polyvinyl alcohol (PVA) to enable immediate drug release[11]. HME produced hydroxyl-propyl cellulose filaments at temperatures ranging from 50-165°C for the manufacture of pulsatile-release tablets[12]. Polycaprolactone (PCL) and Polyethylene oxide (PEO) at 100 K and 200 K were used to achieve extended release. Arabic gum was incorporated as a plasticizing agent to improve melt flow characteristics, while Gelucire® 44/14 was added as a release-modifying excipient to enhance drug dissolution and release behavior[13].

METHODS

This narrative review examined fused deposition modeling (FDM) for oral dosage forms, emphasizing how materials, filament preparation, and printing settings influence drug release (immediate, controlled/sustained, delayed, pulsatile). Literature searches were performed using databases such as PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar for English-language papers published between 2010 and 2026 using combinations of terms such as fused deposition modeling/FDM, 3D printing, oral dosage forms, tablets, capsules, drug release, immediate, controlled, sustained, delayed, pulsatile, and polymer names (e.g., PVA, HPMC, Eudragit, PCL, PLA), including “hot-melt extrusion. Additionally, the reference lists of relevant primary studies and review articles were manually examined to identify further pertinent publications. Studies were included if they reported FDM-based fabrication of oral solid dosage forms with details on materials, filament or process conditions, print parameters, and/or dissolution outcomes; non-oral applications, non-FDM methods without direct relevance, conceptual pieces without experimental data, and non-English reports were excluded. From each study, data were extracted on the API, polymer/excipient system, and filament method, print settings (nozzle/bed temperatures, layer height, infill, shell, speed), geometry, mechanical/porosity data were available, dissolution methods, and release kinetics, special architectures (bilayer, shell–core, gastro-floating, polypill), stability, and limitations. Evidence was synthesized thematically by release strategy, material system, and design/parameterization to compare how formulation and printing choices influence mechanics and dissolution. Ethics approval was not required for this literature-based work. Full search strings and the included study list are available upon request.

Fused deposition modeling (FDM) technology

Fused Deposition Modeling (FDM) was developed in 1989 by the American engineer Scott Crump. Several years later, he and his wife established the company Stratasys, which went on to introduce the first commercially available FDM 3D printer. The technique operates through a computer-controlled process in which a thermoplastic filament is heated to a molten state and then precisely deposited in successive layers onto a build platform to construct the final object. Thermoplastic filaments are commonly produced using hot-melt extrusion (HME), and three main strategies are employed for drug incorporation. In the first method, the drug is introduced after filament fabrication by immersing the preformed filament in a drug-containing solution, allowing passive diffusion of the active compound into the polymer matrix. The second, and more widely adopted, technique involves blending the drug directly with a physical mixture of the polymer and selected excipients before extrusion, yielding a drug-loaded filament upon processing. The third approach relies on producing an empty filament structure, which is then loaded with the drug either during or after manufacturing, using solid or liquid formulations. Among these methods, the pre-extrusion blending approach is generally preferred, as it typically enables higher drug-loading efficiency and a more uniform distribution within the filament[14]. The initial stage in FDM printing involves a drug-loaded polymer filament. The drug-loaded processes were performed by incubating commercial polyvinyl alcohol (PVA) filaments in a highly concentrated drug solution[15]. The raw materials are typically introduced into the printer as filaments with defined dimensions and mechanical properties. These filaments are commonly produced through hot-melt extrusion (HME) using thermoplastic polymers[6]. The drug is incorporated into a polymer matrix with various excipients via hot-melt extrusion (HME), a technique commonly used to manufacture filaments for fused deposition modeling (FDM). In this process, a screw-driven extruder within a heated barrel applies both thermal energy and mechanical pressure to melt and homogenize the formulation. The resulting molten blend is subsequently cooled, forming a uniform filament that serves as the feed material for FDM printing[15].

Pharmaceutical applications of FDM

Many FDM-printed tablets exhibit higher mechanical strength than conventionally compressed tablets, supporting exploration of abuse-deterrent and alcohol-resistant formulations[16]. FDM has been used to create personalized dosage forms with osmotic mechanisms supporting defined API loading and release patterns. More specifically, cellulose acetate was used to form the outer layer of a medication containing an

osmotically active core[17]. In recent years, fused deposition modeling (FDM) has attracted significant interest for fabricating gastroretentive drug delivery systems. Research in this area has demonstrated the adaptability of FDM by developing various dosage forms, including tablets, capsules, capsule-based devices, and pulsatile release formulations, under-scoring the broad potential of this technology in advanced pharmaceutical design[15]. Fused deposition modeling (FDM) has been used to fabricate floating drug delivery systems designed to provide sustained-release characteristics. In this approach, filaments were formulated using hypro-mellose acetate succinate (HPMCAS) as the primary polymer matrix, along with polyethylene glycol (PEG 400) serving as a plasticizer to enhance filament flexibility and processability[18]. Using fused deposition modeling (FDM) 3D printing, fast-dissolving oral films (FDFs) were fabricated, incorporating a drug-loaded core layer with an additional taste-masking coating printed on top. The films were further engineered with a mesh-like structural design to enhance surface area, thereby accelerating disintegration time[19]. PVA was found to be a suitable polymer for fabricating orodispersible films using the FDM technique[20]. Fused Deposition Modeling 3D printing was explored as an additive manufacturing technique for fabricating polyvinyl alcohol (PVA)-based mucoadhesive films designed to achieve unidirectional drug release. In this formulation strategy, chitosan was added to enhance mucosal adhesion and permeation. Additionally, ethylcellulose, along with commercially available wafer sheets, was used as a backing layer to support directional drug delivery and limit diffusion in undesired directions[21]. Biodegradable polymer microneedle (MN) arrays prepared via fused deposition modeling (FDM) using polylactic acid, an FDA-approved, renewable, bio-degradable, thermoplastic material[22].

Orthodontic retainers are patient-specific, wearable medical devices designed to support dental alignment and protection. These devices can be manufactured using 3D printing technologies such as hot-melt extrusion (HME) and fused deposition modeling (FDM), where poly(lactic acid) (PLA) and poly-caprolactone (PCL) serve as the primary polymeric matrix materials[23]. To reduce both the incidence and severity of adverse drug reactions, 3D printing technology can be used to fabricate dosage forms with tailored release profiles. This may be achieved through single-formulation blends or by designing multilayer structures and reservoir-based printed tablets. One of the most extensively investigated applications of pharmaceutical 3D printing is the development of dosage forms with sophisticated and programmable drug-release kinetics. In this context, modifying the geometry and structural design of printed systems enables precise control over drug-release behavior, allowing the creation of formulations with distinct, targeted release profiles[24]. The applicability of fused deposition modeling (FDM) for the fabrication of capsule-based drug delivery systems was first explored by Melocchi and colleagues (Melocchi *et al*.,). In their work, the conventional polymeric coating used in reservoir-type dosage forms was substituted with a release-regulating shell composed of two components, a cap and a body, which are subsequently assembled and filled after manufacturing[6]. Researchers have introduced a new design strategy, called Gaplet, for fabricating cellulosic tablets via FDM printing to enhance drug release rates. This approach exploits FDM technology's ability to construct intricate geometries, producing tablets with intentionally engineered collapsible structures. The formulation consists of interconnected modular units that generate internal void spaces within the tablet matrix, promoting rapid structural disintegration upon contact with a dissolution medium and enabling rapid fragmentation within a few minutes[25]. Fused deposition modeling (FDM) offers multiple benefits in pharmaceutical applications, particularly its cost-effectiveness and high design flexibility. These features make it a promising technique for producing solid oral dosage forms (SODFs) with diverse geometries, complexities, and internal architectures, as well as on-demand, cost-effective production. This technique enables straightforward control of drug-releasebehavior by modifying the dosage form's geometry, dimensions, and internal infill structure. It further accommodates relatively high drug loading and the incorporation of multiple active pharmaceutical ingredients within a single system. In addition, it can produce dosage forms with acceptable drug-content uniformity and strong mechanical integrity, often eliminating the need for additional post-processing steps. Fused deposition modeling also offers the advantage of a broad range of compatible, printable materials[26].

However, FDM has notable limitations. It typically requires high processing temperatures and prior filament preparation, which can be unsuitable for thermally labile APIs and may lead to API or excipient degradation. The platform still lacks an extensive range of truly biocompatible and biodegradable thermoplastic polymers optimized for oral use. Pre-processing steps for filament making add complexity, and, depending on the specific setup, material choices may be constrained (e.g., to those compatible with the printer's energy input). These thermal and material constraints can limit the applicability of FDM despite its design strengths[27,28].

Polymers used in FDM-based 3DP

In device printing, common engineering polymers include PLA, ABS, PP, PE, PEEK, and PMMA[29]. For pharmaceutical dosage forms, pharmaceutically acceptable excipients such as PVA, HPMC, PVP, Eudragit grades, and ethyl cellulose are typically used to prepare drug-loaded filaments[30]. Hydrophobic, poorly permeable matrices such as Eudragit RL and ethyl cellulose often produce very slow drug release[31].

Drug-release patterns with FDM

Drugs manufactured via FDM have different release patterns, including immediate, sustained, controlled, and delayed release tablets, depending on the type of polymer used[32]. Arafat *et al*., used FDM 3DP to manufacture capsule-shaped theophylline tablets composed of multiple interconnected compartments (Gaplets), which were fabricated using fused

deposition modeling (FDM). Hot-melt extrusion (HME) was employed to produce hydroxypropyl cellulose (HPC)-based filaments loaded with theophylline. Compared with conventional solid 3D-printed tablets lacking internal gaps and with formulations containing disintegrants, the Gaplet design demonstrated a more rapid drug-release profile. Furthermore, gastro-retentive floating dosage forms incorporating the same drug and HPC matrix were successfully printed using FDM, thereby enabling sustained, prolonged drug release[9]. Chai *et al*., used fused deposition modeling (FDM) to fabricate intragastric floating tablets for sustained-release domperidone[24]. Other groups developed immediate-release theophylline FDM-printed tablets. The formulation was developed by incorporating the drug into various pharmaceutical polymers, including HPC, Eudragit EPO, and Kollidon VA 64, along with the disintegrant SSG, thereby eliminating the need for a plasticizer. Notably, the incorporation of HPC markedly enhanced the mechanical strength and overall properties of the produced filaments[12]. Melocchi *et al*., applied the same 3D printing (3DP) approach to develop a capsule-based system intended for the oral pulsatile delivery of paracetamol. Hydroxypropyl cellulose (HPC) filaments were fabricated using hot-melt extrusion (HME) at processing temperatures ranging from 50°C to 165°C, depending on the HPC concentration in the formulation[33]. In fused deposition modeling (FDM), polyvinyl alcohol (PVA) is among the most commonly used polymers due to its suitable melting characteristics. Specifically, the molten polymer exhibits a sufficiently high viscosity to maintain structural integrity during layer formation, yet low enough to allow smooth extrusion through the printer nozzle[34]. Numerous published studies have demonstrated the applicability of polyvinyl alcohol (PVA) in 3D printing technologies. For instance, Tagami *et al*., incorporated curcumin into PVA filaments via soaking and subsequently used these filaments to fabricate fused deposition modeling (FDM)- printed tablets. The resulting tablets exhibited progressively delayed dissolution profiles as curcumin loading increased, likely due to the drug's poor aqueous solubility[11]. Gioumouxouzis *et al*., produced a bilayer oral solid dosage form via 3D printing containing glimepiride and metformin, two drugs used to treat diabetes. The two layers exhibited distinct release patterns. Indeed, the metformin layer was prepared with the polymer Eudragit RL to achieve sustained drug release, while the glimepiride layer was prepared with the polymer PVA to achieve immediate release[10]. Wei *et al*., formulated FDM-based 3D-printed tablets for the immediate release of carvedilol, using polyvinyl alcohol (PVA) as the primary filament material. Sorbitol was incorporated as a plasticizer to improve PVA's extrusion performance during filament preparation. However, filament fabrication and tablet printing required a relatively high processing temperature of 210°C. Consequently, the use of PVA in FDM 3D printing is generally limited to drug compounds that have sufficient thermal stability to withstand elevated temperatures. Cotabarren *et al*., designed a polyvinyl alcohol (PVA)-based capsular system for personalized drug delivery via fused deposition modeling (FDM) 3D printing, using a single-step fabrication process. Sodium cromoglicate, commonly used to manage chronic intestinal inflammatory diseases and mastocytosis, was used as the model drug in this investigation. The fabricated capsular device exhibited an immediate drug-release profile[35]. Eudragit RL, RS, E, and L100-55 are among the most commonly utilized Eudragit derivatives in fused deposition modeling (FDM)–based three-dimensional printing[36]. Korte and Quodbach developed tablets using fused deposition modeling (FDM) with Eudragit RL serving as the sustained-release polymer matrix. Stearic acid and PEG 4000 were incorporated as plasticizers to facilitate filament fabrication, while theophylline hasbeenselected as the model drug for its high thermal stability during printing.

Polyvinylpyrrolidone (PVP) has been employed in the formulation of fast-release tablets fabricated through fused deposition modeling (FDM) 3D printing. In this system, PVP and triethyl citrate (TEC) functioned as plasticizers, while talc was incorporated as a filler. Theophylline and dipyridamole were selected as model active pharmaceutical ingredients (APIs) and integrated into the filament matrix. The resulting 3D-printed tablets demonstrated efficient drug loading of both model compounds and exhibited rapid release profiles, enabling immediate liberation of the incorporated drugs[37]. The same research group subsequently designed gastric-resistant, shell-core, delayed-release tablets using dual fused deposition modeling (FDM) 3D printing. The formulation contained theophylline, budesonide, or diclofenac sodium as active pharmaceutical ingredients, with talc or tribasic sodium phosphate as fillers. Polyvinylpyrrolidone (PVP) and triethyl citrate (TEC) were used as plasticizers in the preparation of the tablet core. The drug-free outer shell consisted of a methacrylic acid copolymer (Eudragit L100-55), the same plasticizer used in the core formulation, and talc as an additional plasticizer[38]. Viidik *et al*., recently investigated the use of polycaprolactone (PCL) combined with Arabic gum to fabricate indomethacin tablets via fused deposition modeling (FDM) 3D printing. The drug-loaded feedstock filaments were first produced by hot-melt extrusion (HME) and subsequently printed into tablets. The final formu-lations exhibited a sustained drug-release profile[39].

Fanous *et al*., developed intermediate-release (IR) tablets using fused deposition modeling (FDM) 3D printing technology for the poorly water-soluble drug lumefantrine. The formulation employed a basic butylated methacrylate copolymer (Eudragit EPO) as the primary matrix polymer, along with xylitol as a hydrophilic plasticizer and maltodextrin as a pore-forming agent to modulate drug-release characteristics (38). Fina *et al*., employed fused deposition modeling (FDM) to fabricate tablets with an insoluble outer shell designed for zero-order drug release and a core formulated for extended release. In their study, paracetamol was utilized as the model drug to evaluate the system’s performance (40). Gastro-floating tablets

with extended gastric residence time have also been successfully developed using fused deposition modeling (FDM)-based 3D printing. Traditionally, floating solid oral dosage forms are designed using either effervescent systems that generate carbon dioxide to provide buoyancy or non-effervescent approaches that rely on lowering the formulation's apparent density. In this context, Chai *et al*., investigated the production of intragastric floating sustained-release tablets containing domperidone, a dopamine D2 receptor antagonist, via FDM technology. Their findings demonstrated that the floating behaviour of the printed formulations was strongly influenced by tablet density. Additionally, both *in vitro* and *in vivo* studies demonstrated that the 3D-printed gastro-floating tablets maintained consistent buoyancy while providing an extended, controlled drug-release profile[31]. Khaled *et al*., developed an extrusion-based 3D-printed polypill incorporating captopril, nifedipine, and glipizide for the combined management of hypertension and diabetes. The formulation was engineered as a multi-compartment system, consisting of three distinct sections: two compartments designed to provide sustained release of glipizide and nifedipine, and a third compartment functioning as an osmotic pump for captopril delivery. In this design, captopril release was driven by osmotic pressure, whereas nifedipine and glipizide were primarily released by diffusion. Overall, the polypill was intended to improve therapeutic outcomes in patients presenting with coexisting diabetes and hypertension[41]. The same research team later formulated a five-component polypill for cardiovascular disease management, combining immediate-release aspirin and hydrochlorothiazide with sustained-release formulations of pravastatin, atenolol, and ramipril[42]. More recently, Tabriz *et al*., analyzed the feasibility of manufacturing a bilayer tablet containing rifampicin and isoniazid via FDM for the treatment of tuberculosis. While the rifampicin layer was designed to provide delayed-release of the medicine, the isoniazid layer was modified to enable immediate drug absorption in both acidic and alkaline environments[43]. Scoutaris *et al*., prepared candy-shaped solid oral dosage forms (SODFs) containing indomethacin using fused deposition modeling (FDM). Various geometries, including heart, lion, and bottle shapes, were successfully fabricated. These formulations effectively masked the drug's inherent bitter taste while providing rapid drug release[44]. Recently, Lafeber *et al*., developed pediatric tablet formulations containing furosemide and sildenafil. The prepared tablets met the required pharmacopeial standards, demonstrating acceptable mass uniformity, content uniformity, and conventional drug release profiles[45]. Melocchi *et al*., were among the first to explore the application of 3D printing in capsule manufacturing. In their study, they employed fused deposition modeling (FDM) to produce a swellable, erodible capsular system based on hydroxypropyl cellulose (HPC) for oral pulsatile drug delivery. The developed device exhibited a distinct lag phase before rapid and complete drug release[46]. Charoenying *et al*., advanced the development of capsular drug delivery systems by employing 3D printing technology to fabricate a floating device designed for a commercially available amoxicillin capsule. When combined with the conventional capsule, the 3D-printed structure significantly enhanced gastric floating duration and resulted in a more sustained drug-release profile compared with the capsule alone[47]. Nober *et al*., investigated the application of fused deposition modeling (FDM) to fabricate enteric capsules composed of polylactic acid (PLA), Eudragit L100-55, and polyethylene glycol (PEG 400) as a thermo-plasticizer. Riboflavin-5′-phosphate, used as a colored model drug, was incorporated into the capsule system. The formulation exhibited good stability under acidic conditions, as no drug release was detected in simulated gastric fluid at pH 1.2 over 2 hours. However, rapid and complete dissolution was observed within 45 minutes at pH 6.8, which simulates intestinal conditions. These findings suggest successful enteric protection of the dosage form and confirm its pH-responsive drug release characteristics(5).

CONCLUSIONS

Fused deposition modeling (FDM) enables precise control over geometry, internal architecture, and composition, allowing for the customization of oral drug-release kinetics, including immediate, sustained, delayed, and pulsatile profiles. This adaptability facilitates personalized treatment regimens and improves clinical outcomes by minimizing side effects, increasing patient adherence, and enhancing therapeutic efficacy. The integration of FDM in 3D-printed pharmaceuticals offers unprecedented precision in drug release and delivery, marking a substantial advancement within the pharmaceutical industry. Continued development of heat-tolerant formulations, standardized filaments, in-line quality control, and regulatory frameworks is crucial for widespread adoption and for producing more individualized and effective medicines for a broad range of medical conditions.

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AUTHOR'SCONTRIBUTION

Abdullah A: conceptualization, methodology, investigation, formal analysis, data curation, writing original draft, review, and editing.

DATA AVAILABILITY

The associated author can provide the empirical data used to support the study's conclusions upon request.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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