The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(2): S.I (2), 1859-1887, 2026 www.thebioscan.com

Novel dosage forms: current trends, challenges, and future perspectives in pharmaceutical sciences

Dhanasekar J*, Selvakumar M, Snehal Dasharath Pawar, Lathamani L, Sudhamani T, Nandhakumaran S, Dharani A, Hema T K

Institutional Affiliations –

Department of Pharmaceutics,

Vivekanandha Pharmacy college, Sankari, Salem, Tamil Nadu, India – 637303.

Corresponding author –

DHANASEKAR J,

Assistant professor,

Department of Pharmaceutics,

Vivekanandha pharmacy college, Sankari, Salem, Tamil Nadu, India.

Email ID – jdhanasekar626@gmail.com

DOI:https://doi.org/10.63001/tbs.2026.v21.i02.S.I(2).pp1859-1887

Keywords:

New dosage systems, personalized delivery of drugs, transdermal systems, 3D printing.

.

Received on:

31-05-2026

Accepted on:

20-06-2026

Published on:

30-06-2026

Abstract

The conventional drug delivery systems are severely restrained with poor bioavailability, inconsistent absorption, and patient non-compliance thereby spurring the innovation of novel doses forms to boost therapeutic results. This review gives a detailed discussion of the trends, technological developments and future trends in novel dosage forms. One of the systematic literature searches was devoted to the innovations in the design of formulations, their evaluation, and clinical uses. Orodispersible films, floating drug delivery systems, mucoadhesive formulations, nanoemulsions, transdermal patches using microneedles, and 3D-printed personalized dosage forms are examples of key developments with the support of nanotechnology, smart polymers, and artificial intelligence to produce controlled releases to achieve targeted release. These innovations are a paradigm shift of patient-centric and personalized therapy. Future outlooks include the incorporation of digital health technologies and massive manufacturing plans as well as regulatory harmonization to enhance faster clinical translation and commercialization.

Introduction

Innovations in drug delivery systems are one of the pillars of contemporary pharmaceutics because they guarantee treatment efficacy and patient adherence. Traditional dosage delivery techniques like pills, capsules, and injections are popular with a number of constraints, which include, but are not limited to, poor bioavailability, dose dumping, repetitive delivery, and systemic adverse effects [1, 2]. Enhanced method of

drug delivery in the form of improved and more sophisticated approaches, as a result of which mediating and aimed therapeutic effects may be gained, has been pushed by these disadvantages [3] Newer dosage delivery systems like nanoparticles, liposomes, transdermal systems, and oral thin film are new possibilities to overcome the limitations of traditional formulations [4, 5]. Besides improving the solubility and uptake, these types of systems can also be utilized to deliver a drug site-specifically with minimal systemic toxicity [6].

The necessity of innovative dosage forms is also determined by the rising number of chronic diseases that need long-term management, individual medicine, and the rising need to select non-invasive routes of administration [7]. Indicatively, transdermal drug delivery systems (TDDS) and mucoadhesive preparations have received much interest in enhancing patient compliance and decreasing gastrointestinal irritation [8]. In the same way, the nanocarrier-based systems have transformed oncology and CNS drugs delivery through enhancing bioavailability and targeting of action at the diseased locations [9, 10].

This review attempts to fully examine the current trends in novel dosage forms, their design mechanisms, technological innovations, and their therapeutic uses and discuss the major challenges and limitations related to their development [11]. Moreover, the paper has pointed out the regulatory implications and the future of adopting these innovations into the clinical practice [12-15].

2 Classification of Novel Dosage Forms

2.1 Solid Oral Novel Dosage Forms

2.1.1 Orodispersible Films (ODFs)

Orodispersible films are thin polymeric films that are strips that dissolve quickly on the tongue without the use of water and enhance adhesion in pediatrics, geriatrics, dysphagia, and on-the-go administration [16-18]. Modern ODFs leverage hydrophilic film formers (e.g., HPMC, pullulan), plasticizers (glycerol, PEG), and superdisintegrants to achieve sub-30-second disintegration while maintaining tensile integrity for packaging and handling [16, 17]. Drug loading is enabled via solution casting, hot-melt extrusion, or inkjet printing for dose personalization and combination therapy; permeation enhancers and taste-masking ion-exchange resins improve palatability and mucosal uptake [16–19]. Advances include nano-enabled ODFs (drug nanocrystals, polymeric nanoparticles, cyclodextrin inclusion) to elevate dissolution/supersaturation windows for BCS II–IV drugs and biologic actives (vaccines/enzymes) when stabilized with sugars and proteins [17–19]. Critical challenges are dose uniformity for potent drugs, moisture sensitivity, and scale-up rheology control; quality endpoints (disintegration, content uniformity, mechanical properties, residual solvents) are now well-standardized across pharmacopeial drafts and ICH-aligned QbD frameworks [16–18].

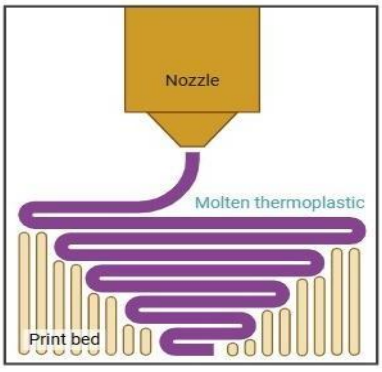


Fig. 1 FDM- Printed Orodispersible films

2.1.2 Floating Drug Delivery Systems (FDDS; gastro-retentive)

FDDS increase gastric residence time by reducing system density (<1 g cm^{-3}) to remain buoyant on gastric fluid, thereby enhancing proximal-gut absorption for narrow-window drugs (e.g., riboflavin, levodopa), improving local treatment (H. pylori), and mitigating variability from rapid GI transit [20–22]. Formats include effervescent matrices (CO_2 generation from citric acid/sodium bicarbonate) and non-effervescent swellable/hydrodynamically balanced systems using gel-forming polymers (HPMC, carbomer) and oils [20, 22]. Design relies on buoyancy lag time, total buoyancy (>8–12 h), in-vitro–in-vivo correlation (IVIVC) of gastric retention (gamma-scintigraphy), and control of food effects and posture [20–23]. Evolving gastro-retentive strategies—expandable/shape-memory and bioadhesive platforms—are increasingly combined with floating for robust retention under fed/fasted conditions [21, 23]. Limitations include interpatient variability in motility (MMC phase III), risk of dose-dumping with alcohol/acidic co-ingestion, and swallowability of larger systems [20–22].

2.1.3 Effervescent Tablets

Effervescent tablets incorporate organic acids (citric, tartaric) and carbonates/bicarbonates to generate CO_2 on reconstitution, yielding fast dispersion, improved palatability, and high-dose delivery with reduced GI irritation for actives like NSAIDs and vitamins [24–26]. Process-critical aspects are moisture control (anhydrous processing, low-RH environments), granular flow, and rapid dissolution without insoluble residues; twin-screw continuous granulation and PAT have modernized manufacturability and robustness [26]. Clinically, effervescence can enhance onset via transient micro-mixing and favorable gastric emptying profiles; however, sodium load and dental enamel exposure require labeling and risk mitigation [24, 25].

Table 1

No.	Dosage Form Type	Drug / API	Key Technology / Materials	Purpose / Outcome	Reference
1	Orodispersible Film (ODF)	Rizatriptan	HPMC, glycerol	Rapid disintegration for migraine	27
2	Orodispersible Film	Montelukast	Pullulan, poloxamer	Pediatric-friendly dosing	28
3	Orodispersible Film	Donepezil	HPMC E15	Improved compliance in Alzheimer's	29
4	Orodispersible Tablet (ODT)	Olanzapine	MCC, crospovidone	Fast disintegration	30
5	ODT	Cetirizine	Mannitol, croscarmellose	Pediatric antihistamine	31
6	Floating Tablet (FDDS)	Metformin	HPMC K100M, sodium bicarbonate	Gastric retention	32

7	Floating Matrix Tablet	Propranolol	Carbopol, citric acid	Controlled gastric release	33
8	Gastro-Retentive Expandable System	Levodopa	Shape-memory polymer	Prolonged gastric residence	34
9	Bioadhesive GR System	Amoxicillin	Carbomer, chitosan	H. pylori eradication	35
10	Effervescent Tablet	Vitamin C	Citric acid + bicarbonate	Rapid dissolution	36
11	Effervescent Tablet	Diclofenac	Tartaric acid, sodium carbonate	Better GI tolerability	37
12	Osmotic Pump Tablet	Nifedipine (Procardia XL)	Laser-drilled orifice, cellulose acetate	Zero-order release	38
13	Osmotic Pump (Push–Pull)	Glipizide (GITS)	Osmogens, hydrophilic polymer	Once-daily release	39
14	3D-Printed Tablet (SLS)	Levetiracetam (Spritam®)	ZipDose technology	Ultra-rapid disintegration	40
15	3D-Printed Polypill	Multidrug combo	FDM printing	Personalized therapy	41
16	Mini-Tablets (2–3 mm)	Lansoprazole	Enteric polymer	Pediatric & geriatric swallowing ease	42
17	Multiparticulates (Pellets)	Omeprazole MUPS	Sugar spheres, enteric coat	Acid protection	43
18	Matrix Tablet (Controlled release)	Tramadol	HPMC matrix	24-h release	44
19	Solid Dispersion Tablet	Itraconazole	PVP-VA, HPMCAS	↑ Solubility for BCS II drug	45
20	Amorphous Solid Dispersion (ASD)	Tacrolimus	Soluplus, PVP	Improved dissolution	46
21	Mucoadhesive Buccal Tablet	Propranolol	Carbopol, HPMC	Avoids first-pass metabolism	47
22	Oral Thin Matrix Strip (Buccal)	Fentanyl	Mucoadhesive polymer	Rapid systemic uptake	48
23	Nanocrystal-Based Tablet	Sirolimus	Nano-milled API + MCC	↑ Dissolution	49
24	Enteric-Coated Tablet	Mesalamine	Eudragit S100	Colon targeting	50

25	Colon-Targeted Compression-Coated Tablet	Prednisolone	Guar gum coat	Time-dependent release	51

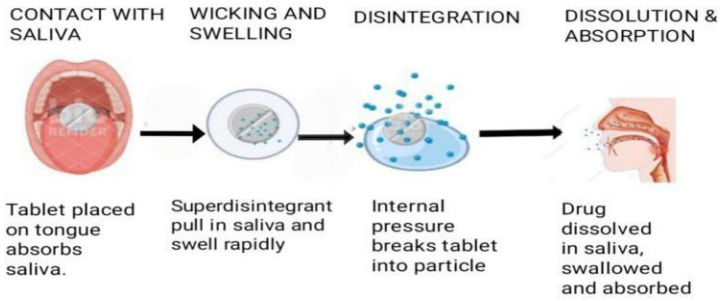
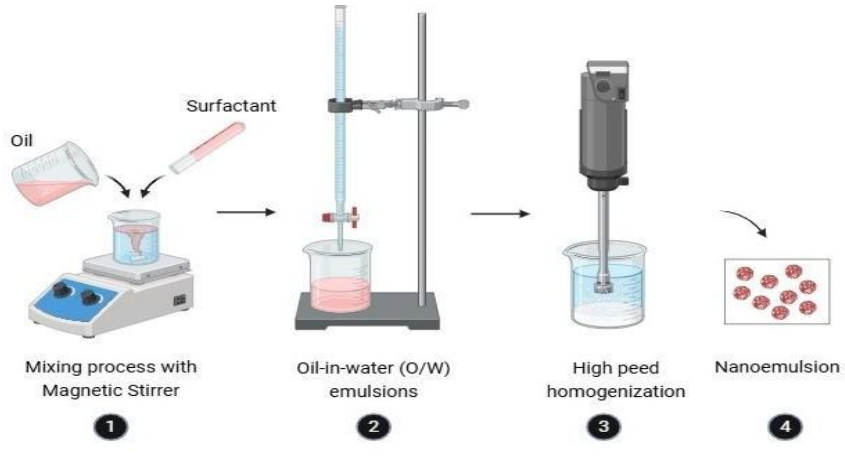


Fig. 2 Mechanism of disintegration and drug release of an Orally Disintegrating Tablet following contact with saliva

2.2 Liquid Novel Dosage Forms

2.2.1 Nanoemulsions

Nanoemulsions (20–200 nm) are kinetically stable O/W or W/O dispersions stabilized by surfactant/co-surfactant systems (e.g., SMEDDS/SEDDS variants), delivering poorly soluble drugs with improved dissolution, lymphatic uptake, and reduced first-pass metabolism [52–56]. High-energy (high-pressure homogenization, ultrasonication) and low-energy (phase inversion, spontaneous emulsification) methods are selected based on API solubility, interfacial curvature, and scalability constraints [52–54]. Contemporary work emphasizes biological fate (protein corona, mucus transport), in-situ gelling nanoemulsions for mucosa/ocular routes, and transdermal/follicular targeting via droplet deformability [54-56]. Key CMC/QbD levers include droplet size/PDI, interfacial tension, Ostwald ripening control (oil selection, ripening inhibitors), and digestion-informed in-vitro lipolysis tests to predict oral bioavailability [53, 54].



:

Fig. 3 Nanoemulsion as liquid noval dosage forms: preparation by high – energy emulsification techniques

2.2.2 Lipid-Based Systems (LBDDS; SLN/NLC, SEDDS/SMEDDS, liposomes)

LBDDS encompass colloidal carriers and self-emulsifying systems that solubilize lipophilic APIs in digestible oils/surfactants to enhance intestinal solubilization and promote lymphatic transport [53, 57-59]. Solid lipid nanoparticles (SLN) and nanostructured lipid carriers (NLC) provide solid/semi-solid lipid matrices enabling controlled release, chemical protection, and high physical stability; however, crystallinity and polymorphic transitions can expel drugs—addressed by mixing solid/liquid lipids (NLC) and using functional surfactants [57-59]. For oral SEDDS/SMEDDS, digestion-dependent supersaturation and precipitation inhibition (polymer precipitation inhibitors) are pivotal to translation; biorelevant lipolysis assays coupled with in-silico PBPK models are now standard for developability assessment [53, 58]. Emerging directions include surface-engineered LNPs for tissue targeting and mRNA/protein delivery, bridging pharmaceutics with nanomedicine [60].

Table 2

No.	Drug / API	Liquid Novel Dosage Form	Key Excipients	Purpose / Outcome	Reference
1	Curcumin	Nanoemulsion	Capryol 90, Tween 80	↑ Oral bioavailability	61
2	Vitamin D3	Nanoemulsion	Polysorbate 80	Improved absorption	62
3	Ibuprofen	Nanoemulsion	MCT oil, Cremophor RH40	Faster dissolution	63
4	Clotrimazole	Nanoemulsion Gel (liquid–gel)	Labrasol, Oleic acid	↑ Dermal permeation	64
5	Paclitaxel	Nanoemulsion (IV)	Soybean oil, Lecithin	Cancer delivery	65
6	Coenzyme Q10	Self-emulsifying drug delivery system (SEDDS)	MCT oil, Tween 80	Lymphatic transport	66
7	Fenofibrate	SEDDS	Labrasol, Transcutol	↑ Solubilization	67
8	Cyclosporine A	SMEDDS	Cremophor RH40	Increased oral absorption	68
9	Ritonavir	SMEDDS (liquid capsule)	Capmul MCM, Kolliphor EL	↑ Bioavailability	69
10	Carvedilol	SEDDS	Peceol, Tween 80	Fast dissolution	70

11	Rifampicin	Nanoemulsion (oral)	Labrafac PG, Tween 20	Anti-TB enhancement	71
12	Resveratrol	Nanoemulsion	Miglyol 812, Tween 80	↑ Stability	72
13	Omega-3 Fatty acids	Nanoemulsion	Fish oil, Lecithin	High stability	73
14	Nifedipine	SMEDDS	Capryol 90, PEG 400	↑ Oral bioavailability	74
15	Dexamethasone	Liposomes (liquid suspension)	Phosphatidylcholine	Ocular delivery	75
16	Amphotericin B	Liposomal dispersion (Ambisome)	HSPC, Cholesterol	↓ Nephrotoxicity	76
17	mRNA	Lipid nanoparticles (LNPs) – liquid dispersion	Ionizable lipid, PEG-lipid	Vaccine delivery	77
18	Doxorubicin	Polymeric nanosuspension (liquid)	PLGA, Poloxamer	Controlled release	78
19	Ketoconazole	Microemulsion	Isopropyl myristate, Tween 80	Antifungal efficacy	79
20	Insulin	Nanomicelles (liquid)	PEG–PLA, Poloxamer	Oral peptide delivery	80

2.3 Semi-Solid Novel Dosage Forms

2.3.1 Gels and Hydrogels

Hydrogels are 3D hydrophilic networks (covalent or physical crosslinks) with high water content that enable local depot formation, sustained release, and stimuli-responsive delivery (pH, temperature, enzymes, redox) [81-84]. In situ-forming systems (thermo-gelation of poloxamers/PLGA-PEG-PLGA; ion-activated alginate; solvent-exchange NMP/PLGA implants) provide minimally invasive administration and conformal filling of complex anatomical spaces [83, 85]. Release mechanisms are governed by swelling-controlled diffusion, mesh size, and degradation kinetics; for bioactives (proteins/cells), mild gelation and affinity interactions (heparin-mimetic, host–guest cyclodextrin) maintain stability and spatiotemporal control [81-84]. Clinical translation focuses on post-surgical local therapy, ocular/periodontal depots, and intra-articular disease modifiers, with attention to injectability, sterilization resilience, and extractables/leachables [84, 85].

2.3.2 Mucoadhesive Formulations

Mucoadhesive dosage forms (buccal, nasal, vaginal, ocular, GI) prolong residence time via interfacial interactions (hydrogen bonding, electrostatics, interpenetration) between polymers (carbomers, chitosan, thiomers) and mucins, improving absorption of short-window and labile drugs [86-90]. Modern design integrates rheology-based adhesion metrics, mucin–polymer complexation, and particle engineering (mucoadhesive vs mucopenetrating surfaces) to balance retention with permeation [86-88]. Buccal films/tablets and ocular inserts exemplify successful translation; limitations include mucus turnover, variability in mucin glycosylation, and potential irritation with cationic polymers—addressed through degree-of-deacetylation control and thiolation strategies [86-90].

Table 3

No.	Form / Type	API / Payload	Key Polymers / Materials	Novel Feature / Purpose	Reference
1	Injectable thermosensitive hydrogel	Ovalbumin (vaccine)	PLGA-PEG-PLGA	Depot formation for sustained antigen release	91
2	Injectable thermoresponsive hydrogel	Bevacizumab (Avastin)	PLGA-PEG-PLGA	Sustained intravitreal release in eye	92
3	Thermosensitive hydrogel for neurotherapy	Dexamethasone + Ketorolac + Antioxidants	PLGA-PEG-PLGA	Long-term intraretinal delivery for retinal degeneration	93
4	Ocular in situ thermo-gelling gel	Hydrocortisone	Poloxamer (F127, F68) + Hyaluronic acid	Thermo-reversible, mucoadhesive for eye drops	94
5	Ocular in situ gel (thermo + muco)	Moxifloxacin HCl	Poloxamer 407/188 + xanthan gum or sodium alginate	Longer precorneal residence, bioadhesion	95
6	In-situ muco-thermogel	Opiorphin (peptide)	Poloxamer 407 + Carbopol 934P (+ chitosan/HPMC)	Nasal extended delivery via liposomal hydrogel	96
7	Intranasal thermosensitive gel	Rasagiline mesylate	Poloxamer 407 + Poloxamer 188 + Carbopol 934P or Chitosan	Improved brain uptake (nose-to-brain)	97

8	Nanoparticle-loaded thermosensitive gel (nasal)	Chlorpheniramine maleate	Chitosan-NPs + P407 + Carbopol 934P	Increased nasal residence, enhanced absorption	98
9	Intranasal in-situ thermogel	Zolmitriptan	Chitosan nanoparticles + Poloxamer 407/188	Migraine delivery, rapid onset + sustained release	99
10	Thermosensitive in-situ gel for nasal wound	Tranexamic Acid	Chitosan + Poloxamer	Gelation in nasal cavity, wound healing in epistaxis	100
11	Mucoadhesive thermosensitive nasal gel	Sumatriptan	Pluronic F-127 + Chitosan	Prolonged nasal retention, improved absorption	101
12	Nasal in-situ gel (Alzheimer's drug)	Tacrine	Poloxamer F-127	Increased nasal residence-time, brain delivery	102
13	Thermosensitive intranasal gel (psychiatric)	Risperidone	Poloxamer 407 + HPMC + Chitosan	Nose-to-brain delivery, mucoadhesive gel	103
14	Thermosensitive intranasal gel (chitosan / guanidine)	— (model system)	Guanidine-chitosan + Poloxamer 407/188	Enhanced penetration, optimized gelling temp	104
15	In-situ gel (nasal) for analgesic peptide	Morphine	Chitosan-β-glycerophosphate hydrogel	Fast analgesic effect + prolonged retention	105
16	Mucoadhesive antimicrobial vaginal gel	Chitosan (antifungal action)	Chitosan + HPMC	Vaginal candidiasis treatment, mucoadhesive action	106
17	Thermo + pH responsive	(generic drug)	Poly(N-isopropylacrylamide) (PNIPA)	Thermo-triggered collapse/growth	107

	hydrogel (stimuli-responsive)			for controlled release	
18	Nanocomposite thermosensitive / stimulus-responsive hydrogel	(model / general)	Polysaccharide-clay, magnetic ferrogel	Remote (magnetic) triggered drug release	108
19	Self-healing hydrogel for drug delivery	(generic)	Self-healing polymer network	Self-repairing gel matrix enabling smart release	109
20	Injectable composite hydrogel with shape recovery	Therapeutic agents / cells	RBC-derived biocomposite, PEG, hydrogel matrix	Compressible injection, shape recovery after syringe	110
21	Muco-thermoresponsive hydrogel with HA	Acyclovir	Poloxamer + Hyaluronic acid	Thermoreversible + mucoadhesive for topical delivery	111
22	Ion-activated in-situ gel	(e.g., nasal)	Gellan gum (ion-sensitive polymer)	Gelation triggered by cations, long retention	112
23	Dual-stimuli responsive hydrogel	Berberine chloride	Gelatin / perfluorohexane core-shell	pH + ultrasound triggered release	113
24	Photocrosslinked hydrogel	Peptides / proteins	Thiol–ene collagen–PEG network	Injectable, controlled network by light-triggered crosslinking	114
25	Self-healing injectable hydrogel for cells/drugs	Therapeutic biomolecules or cells	8-arm PEG, dynamic covalent or physical crosslinks	Self-repair, minimally invasive injection	115

2.4 Transdermal Systems

2.4.1 Patches

Transdermal patches introduce drugs deep into th e stratum corneum to the systemic circulation, providing constant plasma levels, first pass bypass, and enhanced compliance with intractable chronic treatment [116-119]. Designs of today consist of drug-in-adhesive matrices, reservoir and multi-layer designs with permeation enhancers (fatty acids, terpenes, iontophoresis/thermal ablation adjuncts) and handle adhesive cold-flow, crystallization risk, and dose dumping [116-118]. The regulatory requirements focus on adhesive performance (peel /tack/shear), in vitro skin permeation (human/porcine), in vivo PK bioequivalence, and extractable/leachable safety of acrylate/silicone backings [117-119]. New directions use patches in combination with digital adherence sensing and on-skin micro heaters to control flux on command [116, 119].

Microneedles (solid, coated, dissolving, hollow) generate temporary microchannels to penetrate the stratum corneum painlessly to deliver small molecules, biologics, and vaccines with a reduced cold-chain load and with the potential of selfadministration [116, 120-122]. Examples include metals, silicon and dissolving polymers (PVP, PVA, carboxymethylcellulose, hyaluronate) that are capable of stabilizing delicate cargos; successful performance depends on the force with which it can be inserted, sharpness of the tip, mechanical strength and kinetics of dissolution [120-122]. Clinical candidates are influenza, measles-rubella and COVID-19, small molecule and peptide systemic delivery, large molecule dose loading limits, scalable manufacturing (molding/3D printing), and demographic reproducible skin insertion [120-122].

2.4.2 Microneedle-Based Delivery

Table 4

No.	Form / Type	API / Payload	Key Polymers / Materials	Novel Feature / Purpose	Ref.
1	Transdermal Patch – Drug-in-Adhesive	Nicotine	Acrylate pressure-sensitive adhesive, polyethylene backing	Steady plasma delivery for smoking cessation; avoids first-pass metabolism	123, 124
2	Transdermal Patch – Reservoir System	Fentanyl	EVA membrane, silicone adhesive	High-potency opioid delivery with controlled membrane-regulated release	123, 125
3	Transdermal Patch – Multilayer / Heat-Assisted	Lidocaine + Tetracaine	Silicone adhesive, occlusive backing, integrated heating element	Self-contained micro-heater enhances permeation for local analgesia	123, 126
4	Transdermal Patch with Permeation Enhancers	Estradiol	Polyacrylate adhesive + fatty acid enhancer	Enhanced percutaneous flux for hormone therapy	124

5	Digital-Enabled Transdermal Patch	Rivastigmine	Acrylic adhesive, smart sensor module	Integration of adherence monitoring + controlled heat pulses	125
6	Dissolving Microneedles	Influenza vaccine antigen (HA)	PVP, PVA	Needle-free vaccination; improved stability at room temperature	127, 128
7	Solid Microneedles – Coated	Measles–Rubella vaccine	Stainless steel MN coated with stabilizing sugars	Rapid antigen release; reduced cold-chain requirement	127, 129
8	Hollow Microneedles	Insulin	Silicon / metal hollow arrays	Precise bolus delivery for diabetic patients; minimal pain	128
9	Polymeric Dissolvable Microneedles	Desmopressin	Hyaluronic acid, CMC	Enhanced systemic delivery of peptides with rapid dissolution	127
10	3D-Printed Microneedles	Small-molecule drugs (e.g., caffeine, metformin)	Photopolymerizable resins	Customizable geometry, scalable manufacturing	129

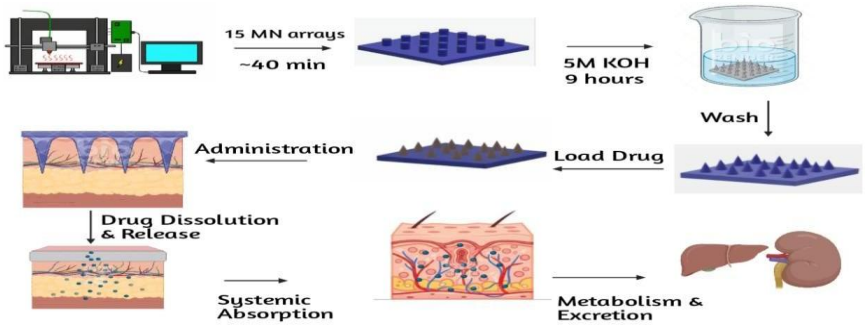


Fig. 4 Fabrication of microneedle (MN) arrays via 3D printing, post-processing with KOH treatment, drug loading, and subsequent transdermal drug delivery leading to systemic absorption, metabolism, and excretion

3 Recent Technological Advancements

3.1 3D Printing for Personalized Dosage Forms

Additive manufacturing, or three-dimensional (3D) printing has transformed the way pharmaceutical products are produced by providing the possibility to create personal dosage forms with a high degree of precision. In contrast to traditional manufacturing processes, 3D printing could be used to deposit materials in layer-by-layer to design drug products with unique shapes, sizes, and drug release patterns. Fused Deposition Modeling (FDM), Inkjet Printing, and Stereolithography (SLA) are the most common techniques that are used in formulating drugs. These technologies enable personalized dosing to patients, combination of different drugs in one unit and controlled release of drugs. The 3D-printed drug Spritam 100mg (levetiracetam) became the first FDA-approved drug, the result of which proved that this method could be effective in rapid disintegration and loading drugs with high doses [130, 131].

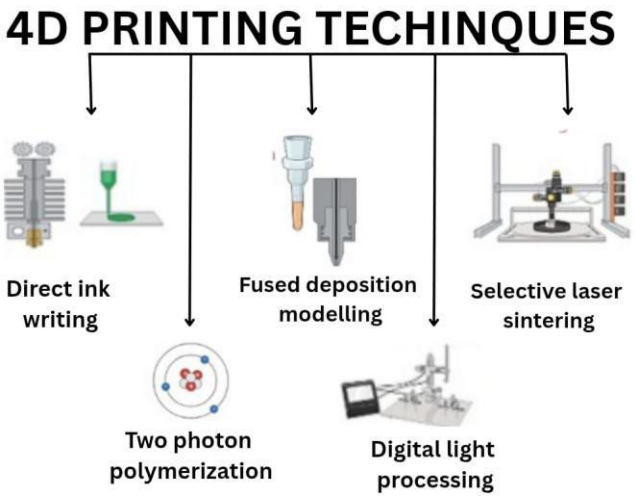


Fig. 5 4D Printing techinques

The recent research aims at developing better polymers to be used as pharmaceutical grade, temperature sensitive materials and bio-based excipients to improve their stability and biocompatibility. More so, the 3D printing developments have seen the introduction of 4D printing that uses smart materials triggered by environmental conditions such as temperature, pH, and moisture to add dynamism into drug delivery [132-134].

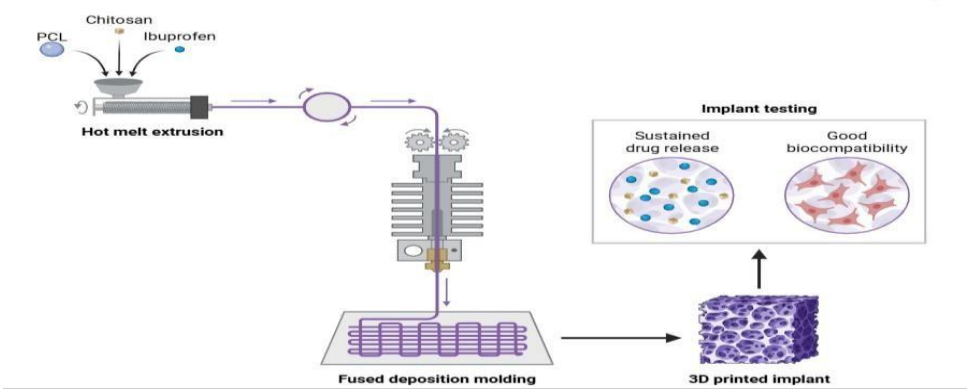


Fig. 6 3D – printed implant via hot-melt extrusion

3.2 Smart Drug Delivery Systems (pH-sensitive, Temperature-responsive)

Smart drug delivery systems have become a new development in targeted drug delivery. Examples of this kind of system are pH-sensitive polymers (e.g., Eudragit 5, poly (methacrylic acid)) in oral delivery systems, targeting the gastrointestinal tract, in which coliform-specific delivery can be achieved by oral delivery [135, 136].

Temperature responsive hydrogels like poly (Nisopropylacrylamide) (PNIPAAm) have temperature-dependent transitions of sol-gel reaction that allows controlled and sustained delivery of drugs. Recent applications have been of dual-stimuli-responsive systems (pH and temperature combined), which provide more accuracy in the specific delivery of drugs in cancer therapy and chronic inflammatory diseases [137, 138].

3.3 Use of AI and Machine Learning in Formulation Development

The use of Artificial Intelligence (AI) and Machine Learning (ML) has changed the pharmaceutical formulation development process through predictive modeling, optimizing processes, and virtual screening of excipients. The technologies play a great role in minimizing time and cost involved during drug development. Neural networks, decision trees, and support vector machine AI algorithms are used to forecast key parameters of the formulation (dissolution rate, stability, and bioavailability) using experimental and historical data [139, 140].

AI-based system can help formulate patient-specific dosage formulations, ratios, and forecast drug-excipient interactions, which expedite formulation screening and reduce experimental analyses. Moreover, continuous manufacturing systems can be supported by machine learning algorithms that operate with real-time manufacturing data in order to optimize processes constantly to maintain quality according to quality by design (QbD) standards [141, 142].

Table 5

No.	Technology / Category	Example / Product / Study	Key Materials / Components	Novel Feature / Purpose	Ref.
1	3D Printing (FDM)	*Spritam® (Levetiracetam)* – first FDA-approved 3D-printed drug	Binder-jet 3D printing using water-soluble excipients	High-dose loading, ultra-fast disintegration	143, 144
2	3D Printing (SLA)	3D-printed gastroretentive floating tablets	Photopolymerizable resins, PEG-DA	Customized geometry, extended gastric retention	145
3	4D Printing (Stimuli-Responsive Tablets)	Shape-changing 4D printed oral dosage forms	Smart polymers (cellulose derivatives, hydrogels)	Respond to pH / water to alter shape and release	146, 147
4	pH-Sensitive Delivery	Colon-targeted budesonide tablets using Eudragit® polymers	Eudragit® S100 / L100	Drug release only at colonic pH	148

5	Temperature-Responsive Hydrogel	PNIPAAm-based injectable hydrogel for cancer therapy	PNIPAAm, chitosan, PEG	Sol-gel transition at 32°C for localized release	144
6	Dual Stimuli System (pH + Temperature)	Smart nano-hydrogel for targeted tumor release	PNIPAAm + methacrylic acid copolymers	Highly specific drug release in tumor microenvironment	147
7	AI in Formulation Design	Neural-network prediction of tablet dissolution rate	ANN models trained on formulation datasets	Reduces lab experiments; predicts release profiles	148
8	AI for Polymer Optimization	ML model optimizing polymer ratios in sustained-release tablets	Random forest + DoE datasets	Predicts optimal polymer combinations	145
9	AI in Continuous Manufacturing	Real-time ML-controlled continuous tablet line	PAT sensors + ML feedback algorithms	Enables real-time QbD compliance	148

4 Challenges in Development

Novel dosage forms have a number of challenges that restrain their extensive use although these are therapeutically advantageous. Issues of stability are one of the main concerns and have a considerable impact on the shelf life and bioavailability of the final product. Physical and chemical instability in the storage of formulations containing biologics, nanoparticles, or hydrophilic polymer may occur as a result of moisture absorption, crystallization, or degradation of active pharmaceutical ingredient (APIs) [149]. As an example, lipid-based nanoparticle-based drug delivery systems are very susceptible to oxidative degradation, which causes loss of efficacy of the drug [150]. Moreover, peptides and protein preparations may have strict storage requirements, e.g. cold chain logistics to preserve their integrity [151].

Scalability is another important challenge to manufacture. In spite of the evidences of great potential in the field of personalized medicine, the use of technologies such as 3D printing and microfabrication in mass production is not as common as it could be [152]. Complexity of the process involved in making the exact structure to be used in controlling drug release at an industrial level poses high production costs and long processing time [153]. Besides, it is challenging to preserve the batch-to-batch consistency of new systems like nanoparticles or microneedle arrays because processing parameters used are quite complicated [154]. These restrict the commercialization and large-scale clinical utilization.

Another significant obstacle to novel dosage form development in regulatory challenges. The existing regulatory systems are mainly structured to address traditional dosage delivery methods, and hence do not have any standardized practices regarding emerging technologies, like 3D printing, nanomedicine, and smart drug delivery systems [155]. To prove their safety, efficacy, and quality, developers will need to perform a significant amount of preclinical and clinical testing, which is time-consuming and requires a greater amount of financial resources [156]. Moreover, new excipients and new manufacturing processes will also not be approved without a whole lot of toxicological and stability data, and this further postpones market entry [157]. There is a need to

harmonize the international regulatory standards of advanced drug delivery systems to increase the rate of innovation and guarantee patient safety [158].

5 Clinical Applications and Market Trends

5.1 Recent FDA/EMA Approvals of Novel Dosage Forms

Changes in the regulatory environment of novel dosage forms have been experienced in the recent years, which focus on the patient-centric design, improved compliance, and clinical outcomes. Various new formulations that overcome the constraints of traditional dosage forms have been approved by regulatory bodies (e.g. the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA)).

5.1.2 Intranasal Delivery Systems

Another of the most prominent approvals is the nasal spray of epinephrine (neffy ®), an anaphylaxis management device to provide the user with an option to avoid using needles. This formulation was approved by the FDA in 2024 and enhances patient convenience and compliance, particularly in people who are needle-phobic. Nares systems circumvent the first-pass metabolism and promote quick absorption across the nasal mucosa, thus a perfect choice when using an emergency therapy [159].

There is also the FDA that has given more approval to using influenza vaccines (FluMist, 2004) at home as a form of administering vaccinations, a paradigm shift in delivering vaccinations. This is a deliberate measure to improve accessibility as well as meet the objectives of mass immunization and pandemic preparedness in the public health [160].

5.1.2 Subcutaneous (SC) Formulations of Monoclonal Antibodies

The subcutaneous (SC) administration of drugs that were formerly administered intravenously (IV) is a trend that keeps picking up. To give an example, nivolumab (Opdivo®) was given a FDA approval of fixed-dose SC formulation in late 2024. In the same manner, the EMA granted atezolizumab (Tecentriq®) SC administration in indications of oncology with an impressive reduction in infusion time and utilization of health care resources [161, 162].

5.1.3 Long-Acting Injectables (LAIs)

The EMA gave a positive opinion to lenacapavir which is an injectable to be used twice per year to treat. As a significant breakthrough in HIV treatment, HIV pre-exposure prophylaxis (PrEP) was created [163]. With such LAIs, there is a decrease in the frequency of dose (daily to less). Biannual periods, the presence of non-adherence problems in the management of chronic disease.

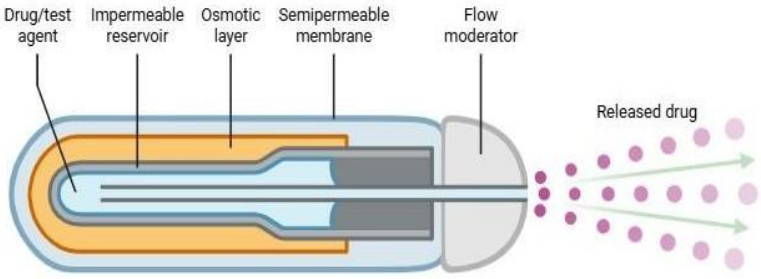


Fig. 7 Long acting injectable using osmotic pump mechanism

5.2 Global Market Analysis

The novel dosage forms market is undergoing a vigorous development, which is triggered by technological innovation, convenience of patients, and demand of individualized medicine.

5.2.1 Long-Acting Injectables

In 2023, the global LAI market can be estimated to USD 26.3 billion and will increase at a compound

annual growth rate (CAGR) of 12-13% as of 2030. This is mainly owed to the growing use of LAIs in psychiatry, endocrinology, and prevention of infectious diseases [164].

5.2.2 Intranasal Drug Delivery

There has been a growth in the need of intranasal formulations, and it is projected to grow even more due to the increased approvals of needle-free emergency drugs and immunizations. The intranasal drug delivery market is projected to expand gradually around the world due to the preference of the patient and avoidance of hepatic metabolism [165].

5.2.3 3D-Printed Dosage Forms

Application of 3D printing in pharmaceuticals is still in the infancy phase but has a potential of growth especially in personalized treatment. The 3D-printed drug market in the world is expected to have USD 0.43-0.79 billion in 2035 with a midteen CAGR growth driven by the innovativeness in the additive manufacturing field and regulatory acceptance after the approval of Spitam® [166, 167].

6 Future Perspectives

6.1 Integration with Digital Health Technologies

It is expected that by integrating new dosage forms with digital health technologies, the patient care will be different as it will allow implementing the concept of precision medicine and real-time therapeutic monitoring. A system of smart drug delivery with sensors and wireless communication devices enables constant control of physiological indicators and compliance with medication. An example of such integration, approved by the FDA to treat psychiatric disorders, is the use of digital pills, which are pharmacotherapy combined with ingestible sensors that transmit adherence data to mobile applications [168, 169]. Smart devices that are linked to controlled-release systems allow maximizing the dose according to patient-specific requirements, minimizing side effects and maximizing effectiveness. Moreover, AI algorithms and cloud-based systems are used to analyze patient data obtained through these systems to enable a data-oriented decision-making process and individualized treatment plans [170, 171]. Such a merger between the pharmaceutical and digital health is consistent with the increasing demand toward telemedicine and remote patient management, especially following the COVID-19 pandemic [172, 173].

6.2 Role of 4D Printing and Nanotechnology

The latest development of 3D printing is 4D printing that is an improvement that incorporates smart materials that can change shape, properties, or functionality with time in response to external stimuli like temperature, pH, light [174]. In drug delivery, 4D-printed dosage designs will be able to change their release kinetics according to physiological circumstances, which will guarantee accurate therapeutic results [175, 176]. As an example, shape-shifting oral pills had been developed to give the site-specific release and localized drug delivery, which have greatly enhanced patient compliance [177]. Nanotechnology also augments these innovations because it allows precise and specific drug delivery using nanoparticles, nanomicelles, and dendrimers that enhance the solubility, stability, and bioavailability of drugs with low solubility [178, 179]. Nanotechnology, together with 4D printing, can yield smart drug delivery systems that can react to environmental factors and deliver therapeutics with the accuracy never before seen [180]. Such innovations will likely dominate the future of customized medicine, regeneration therapies, and the management of chronic diseases [181, 182]. These futuristic dosage forms will require regulatory systems and scalable production plans to become a successful commercialization and broaden clinical use [183].

Table 6

No.	Category	Example / Technology	Key Components / Materials	Novel Feature / Future Advantage	Ref.
1	Digital Health Integration	FDA-approved digital pill for psychiatric disorders *(aripiprazole with ingestible sensor)*	Ingestible sensor (silicon–magnesium–copper), wearable patch, smartphone app	Enables real-time adherence monitoring and personalized therapy	184-186
2	Digital Health Integration	Wearable-linked controlled-release systems	Wearable biosensors, microprocessors, polymeric CR systems	Dynamic dosing based on physiological data (HR, glucose, motion)	187-189
3	AI-Enhanced Remote Monitoring	Cloud-AI platforms analyzing adherence and physiological data	Cloud servers, AI/ML algorithms, wireless telemetry	Real-time data interpretation for precision medicine	190-192
4	Telemedicine-Drug Delivery Convergence	Remote-adjustable drug delivery platforms	IoT sensors, app-based feedback loops	Supports remote care, highly relevant post-COVID	193-195
5	4D Printing	Shape-shifting tablets for site-specific release	Smart polymers (cellulose derivatives, hydrogels, SMPs)	Tablets change shape or function in response to pH/temperature	196, 197
6	4D Printing	4D-printed responsive oral systems	Thermo-responsive, pH-re		198, 199

7 Conclusion

The history of the development of innovative dosage forms has fundamentally altered the pharmaceutical sciences by increasing the effectiveness of the drugs, enhancing their adherence to the patient and personalized medicine. These novel systems, controlled-release formulations, orally disintegrating tablets, transdermal patches, 3D/4D printing dosage forms, and nanotechnology-based systems, deal with major drawbacks that are inherent to the conventional dosage forms, including low bioavailability, inconvenience to the patient, and unreliable therapeutic effects. In spite of these advantages, there are still various challenges such as high costs of manufacture, complicated regulatory routes, stability issues and absence of scalability with large scale production. Additionally, clinical testing of novel technologies, including nanocarriers, smart polymers, bioprinted dosage forms, needs strict clinical testing.

The new trends in the field focus on adopting digital health technologies, smart sensors, and connected devices to monitor drug therapy in real-time and implementing 4D printing and nanotechnology to develop precision medicine. Interdisciplinary work by researchers, regulatory bodies, and business stakeholders will be necessary to address present

obstacles and shorten the clinical adoption process of these technologies. Finally, although innovative dosage forms offer unprecedented opportunities to transform the delivery of drug and patient-centered care, they will need to be balanced through regulatory measures, technological innovations, and cost-efficient production models.

References

1. Luthy, I. A., Bruzzone, A., Piñero, C. P., Castillo, L. F., Vazquez, S. M., Sarappa, M. G. (2009). *Adrenoreceptors: Non-conventional targets for breast cancer.* Current Medicinal Chemistry, 16(15), 1850–1862. https://doi.org/10.2174/092986709788186129
2. Kumar, A., Sharma, P. K., & Malviya, R. (2011). *Recent trends in novel drug delivery systems for herbal drugs.* International Journal of Green Pharmacy, 5(2), 87–94. https://doi.org/10.4103/0973-8258.85158
3. Singh, R., & Lillard, J. W. Jr. (2009). *Nanoparticle-based targeted drug delivery.* Experimental and Molecular Pathology, 86(3), 215–223. https://doi.org/10.1016/j.yexmp.2008.12.004
4. Torchilin, V. P. (2005). *Recent advances with liposomes as pharmaceutical carriers.* Nature Reviews Drug Discovery, 4(2), 145–160. https://doi.org/10.1038/nrd1632
5. Allen, T. M., & Cullis, P. R. (2013). *Liposomal drug delivery systems: From concept to clinical applications.* Advanced Drug Delivery Reviews, 65(1), 36–48. https://doi.org/10.1016/j.addr.2012.09.037
6. Puri, A., Loomis, K., Smith, B., Lee, J. H., Yavlovich, A., Heldman, E., & Blumenthal, R. (2009). *Lipid-based nanoparticles as pharmaceutical drug carriers: From concepts to clinic.* Critical Reviews in Therapeutic Drug Carrier Systems, 26(6), 523–580. https://doi.org/10.1615/CritRevTherDrugCarrierSyst.v26.i6.10
7. Kumar, L., & Verma, R. (2018). *Novel drug delivery systems for the treatment of chronic diseases: A review.* Asian Journal of Pharmaceutical and Clinical Research, 11(2), 30–35. https://doi.org/10.22159/ajpcr.2018.v11i2.22593
8. Prausnitz, M. R., & Langer, R. (2008). *Transdermal drug delivery.* Nature Biotechnology, 26(11), 1261–1268. https://doi.org/10.1038/nbt.1504
9. Torchilin, V. P. (2014). *Multifunctional, stimuli-sensitive nanoparticulate systems for drug delivery.* Nature Reviews Drug Discovery, 13(11), 813–827. https://doi.org/10.1038/nrd4333
10. Patel, T., Zhou, J., Piepmeier, J. M., & Saltzman, W. M. (2012). *Polymeric nanoparticles for drug delivery to the central nervous system.* Advanced Drug Delivery Reviews, 64(7), 701–705. https://doi.org/10.1016/j.addr.2011.12.006
11. Sahoo, S. K., & Labhasetwar, V. (2003). *Nanotech approaches to drug delivery and imaging.* Drug Discovery Today, 8(24), 1112–1120. https://doi.org/10.1016/S1359-6446(03)02903-9
12. Zhang, L., Gu, F. X., Chan, J. M., Wang, A. Z., Langer, R. S., & Farokhzad, O. C. (2008). *Nanoparticles in medicine: Therapeutic applications and developments.* Clinical Pharmacology & Therapeutics, 83(5), 761–769. https://doi.org/10.1038/sj.clpt.6100400
13. Chidambaram, M., Manavalan, R., & Kathiresan, K. (2011). *Nanotherapeutics to overcome conventional cancer chemotherapy limitations.* Journal of Pharmacy & Pharmaceutical Sciences, 14(1), 67–77. https://doi.org/10.18433/J3K59K
14. Reddy, K. R. (2010). *Controlled-release, pegylation, liposomal formulations: New mechanisms in the delivery of injectable drugs.* Annals of Pharmacotherapy, 44(6),

1090–1097. https://doi.org/10.1345/aph.1M636

15. Gupta, S., Kesarla, R., & Omri, A. (2013). *Formulation strategies to improve the bioavailability of poorly absorbed drugs with special emphasis on self-emulsifying systems.* ISRN Pharmaceutics, 2013, 1–16. https://doi.org/10.1155/2013/848043
16. Patra, J. K., Das, G., Fraceto, L. F., et al. (2018). *Nano based drug delivery systems: Recent developments and future prospects.* Journal of Nanobiotechnology, 16(1), 71. https://doi.org/10.1186/s12951-018-0392-8
17. Khan, S., & Hussain, Z. (2020). *Oral drug delivery: Current status and challenges.* Drug Development and Industrial Pharmacy, 46(4), 591–602. https://doi.org/10.1080/03639045.2020.1738975
18. Patel, V. F., Liu, F., & Brown, M. B. (2011). *Advances in oral transmucosal drug delivery.* Journal of Controlled Release, 153(2), 106–116. https://doi.org/10.1016/j.jconrel.2011.01.027
19. Bala, R., Pawar, P., & Khanna, S. (2013). *Orally dissolving strips: A new approach to oral drug delivery system.* International Journal of Pharmaceutical Investigation, 3(2), 67–76. https://doi.org/10.4103/2230-973X.114897
20. Dixit, R. P., & Puthli, S. P. (2009). *Oral strip technology: Overview and future potential.* Journal of Controlled Release, 139(2), 94–107. https://doi.org/10.1016/j.jconrel.2009.06.014
21. Karki, S., Kim, H., Na, S. J., Shin, D., Jo, K., & Lee, J. (2016). *Thin films as an emerging platform for drug delivery.* Asian Journal of Pharmaceutical Sciences, 11(5), 559–574. https://doi.org/10.1016/j.ajps.2016.05.004
22. Irfan, M., Rabel, S. R., Bukhtar, Q., Qadir, M. I., Jabeen, F., & Khan, A. (2016). *Orally disintegrating films: A modern expansion in drug delivery system.* Saudi Pharmaceutical Journal, 24(5), 537–546. https://doi.org/10.1016/j.jsps.2015.02.024
23. Arora, S., Ali, J., Ahuja, A., Khar, R. K., & Baboota, S. (2005). *Floating drug delivery systems: A review.* AAPS PharmSciTech, 6(3), E372–E390. https://doi.org/10.1208/pt060347
24. Streubel, A., Siepmann, J., & Bodmeier, R. (2006). *Gastroretentive drug delivery systems.* Expert Opinion on Drug Delivery, 3(2), 217–233. https://doi.org/10.1517/17425247.3.2.217
25. Jaimini, M., Rana, A. C., & Tanwar, Y. S. (2007). *Formulation and evaluation of famotidine floating tablets.* Current Drug Delivery, 4(1), 51–55. https://doi.org/10.2174/156720107779314811
26. Gohel, M. C., Parikh, R. K., Amin, A. F., & Surati, K. R. (2007). *Studies in preparation and evaluation of effervescent tablets of granisetron hydrochloride.* AAPS PharmSciTech, 8(1), E1–E7. https://doi.org/10.1208/pt0801007
27. Cilurzo, F., Cupone, I. E., Minghetti, P., Selmin, F., & Montanari, L. (2011). *Oromucosal films: Materials, technologies and clinical applications.* European Journal of Pharmaceutics and Biopharmaceutics, 77(2), 191–201. https://doi.org/10.1016/j.ejpb.2010.11.019
28. Pabari, R. M., & Ramtoola, Z. (2012). *Application of orodispersible films in delivery of montelukast.* International Journal of Pharmaceutics, 430(1–2), 134–140. https://doi.org/10.1016/j.ijpharm.2012.03.039
29. Vuddanda, P. R., Montenegro-Nicolini, M., & Morales, J. O. (2017). *Development of orodispersible films for donepezil.* Drug Development and Industrial Pharmacy, 43(8), 1251–1257. https://doi.org/10.1080/03639045.2017.1293686

30. Habib, W. A., Khankari, R. K., & Hontz, J. (2000). *Fast-dissolve drug delivery systems.* Drug Development and Industrial Pharmacy, 26(6), 615–620. https://doi.org/10.1081/DDC-100100417
31. Fu, Y., Yang, S., Jeong, S. H., Kim, S., & Park, K. (2004). *Orally fast disintegrating tablets: Developments, technologies and evaluation.* International Journal of Pharmaceutics, 287(1–2), 1–18. https://doi.org/10.1016/j.ijpharm.2004.09.018
32. Streubel, A., Siepmann, J., & Bodmeier, R. (2003). *Floating matrix tablets based on low density foam powder.* International Journal of Pharmaceutics, 241(2), 279–292. https://doi.org/10.1016/S0378-5173(02)00293-7
33. Arora, S., Ali, J., Ahuja, A., Khar, R. K., & Baboota, S. (2005). *Floating drug delivery systems: A review.* AAPS PharmSciTech, 6(3), E372–E390. https://doi.org/10.1208/pt060347
34. Klausner, E. A., Eyal, S., Lavy, E., Friedman, M., & Hoffman, A. (2003). *Novel gastroretentive dosage forms.* Journal of Controlled Release, 90(2), 143–162. https://doi.org/10.1016/S0168-3659(03)00203-X
35. Bardonnet, P. L., Faivre, V., Pugh, W. J., Piffaretti, J. C., & Falson, F. (2006). *Gastroretentive dosage forms: Overview and special case of Helicobacter pylori.* Journal of Controlled Release, 111(1–2), 1–18. https://doi.org/10.1016/j.jconrel.2005.11.031
36. De Beer, T. R. M., Baeyens, W. R. G., Vercruysse, J., et al. (2011). *In-line characterization of effervescent tablet processing.* International Journal of Pharmaceutics, 417(1–2), 32–39. https://doi.org/10.1016/j.ijpharm.2010.12.012
37. Özdemir, N., Ordu, S., & Özkan, Y. (2010). *Formulation and evaluation of effervescent tablets: Influence of formulation variables on tablet properties.* International Journal of Pharmaceutics, 398(1–2), 1–7. https://doi.org/10.1016/j.ijpharm.2010.07.021
38. Theeuwes, F. (1975). *Elementary osmotic pump.* Journal of Pharmaceutical Sciences, 64(12), 1987–1991. https://doi.org/10.1002/jps.2600641218
39. Zentner, G. M., Rork, G. S., & Himmelstein, K. J. (1985). *The push–pull osmotic tablet.* Journal of Controlled Release, 1, 269–288. https://doi.org/10.1016/0168-3659(85)90024-6
40. Aprecia Pharmaceuticals. (2015). *FDA approval of Spritam® (levetiracetam)—first 3D-printed tablet.* U.S. Food and Drug Administration Report.
41. Khaled, S. A., Burley, J. C., Alexander, M. R., & Roberts, C. J. (2015). *3D printing of five-drug polypills.* Journal of Controlled Release, 217, 308–314. https://doi.org/10.1016/j.jconrel.2015.09.028
42. Thomson, S. A., Tuleu, C., Wong, I. C. K., & Keady, S. (2009). *Minitablets: New modality to deliver medicines to preschool-aged children.* International Journal of Pharmaceutics, 365(1–2), 64–69. https://doi.org/10.1016/j.ijpharm.2008.08.026
43. Pilbrant, A., & Cederberg, C. (1985). *Development of an oral formulation of omeprazole.* Scandinavian Journal of Gastroenterology, 20(Suppl. 108), 113–120. https://doi.org/10.3109/00365528509095857
44. Conte, U., Maggi, L., Colombo, P., & La Manna, A. (1993). *Multi-layered hydrophilic matrices as constant release devices (Geomatrix® systems).* Journal of Controlled Release, 26(1), 39–47. https://doi.org/10.1016/0168-3659(93)90097-P

45. Vasconcelos, T., Sarmento, B., & Costa, P. (2007). *Solid dispersions as a strategy to improve oral bioavailability of poorly water-soluble drugs.* Drug Discovery Today, 12(23–24), 1068–1075. https://doi.org/10.1016/j.drudis.2007.09.005
46. Van den Mooter, G., & Blaton, N. (2013). *Amorphous solid dispersions: Physicochemical insights and formulation strategies.* European Journal of Pharmaceutical Sciences, 49(6), 1001–1016. https://doi.org/10.1016/j.ejps.2013.05.008
47. Smart, J. D. (2005). *The basics and underlying mechanisms of mucoadhesion.* Advanced Drug Delivery Reviews, 57(11), 1556–1568. https://doi.org/10.1016/j.addr.2005.07.001
48. Shukla, A. A., & Misra, A. (2010). *Development and characterization of buccal soluble films for systemic delivery of fentanyl.* Pharmaceutical Development and Technology, 15(5), 517–525. https://doi.org/10.3109/10837450903499370
49. Junghanns, J. A. H., & Müller, R. H. (2008). *Nanocrystal technology: Drug delivery and clinical applications.* International Journal of Nanomedicine, 3(3), 295–309. https://doi.org/10.2147/IJN.S595
50. Cole, E. T., Scott, R. A., Connor, A. L., & Wilding, I. R. (2002). *Enteric coated HPMC capsules designed to achieve intestinal targeting.* International Journal of Pharmaceutics, 231(1), 83–95. https://doi.org/10.1016/S0378-5173(01)00896-5
51. Philip, A. K., & Philip, B. (2010). *Colon targeted drug delivery systems: A review on primary and novel approaches.* Oman Medical Journal, 25(2), 79–87. https://doi.org/10.5001/omj.2010.24
52. De Beer, T. R. M., Baeyens, W. R. G., Vercruysse, J., Burggraeve, A., Lammens, A., Vervaet, C., & Remon, J. P. (2011). *In-line characterization of effervescent tablet processing.* International Journal of Pharmaceutics, 417(1–2), 32–39. https://doi.org/10.1016/j.ijpharm.2010.12.012
53. Pifferi, G., & Restani, P. (2003). *The safety of pharmaceutical excipients.* Il Farmaco, 58(8), 541–550. https://doi.org/10.1016/S0014-827X(03)00075-0
54. Shah, P., Bhalodia, D., & Shelat, P. (2010). *Nanoemulsion: A pharmaceutical review.* Systematic Reviews in Pharmacy, 1(1), 24–32. https://doi.org/10.4103/0975-8453.59509
55. Gupta, A., Eral, H. B., Hatton, T. A., & Doyle, P. S. (2016). *Nanoemulsions: Formation, properties and applications.* Soft Matter, 12(11), 2826–2841. https://doi.org/10.1039/C5SM02958A
56. Shakeel, F., Ramadan, W., & Shafiq, S. (2010). *Formulation development and optimization of nanoemulsion for transdermal delivery of aceclofenac.* AAPS PharmSciTech, 11(1), 427–433. https://doi.org/10.1208/s12249-010-9399-7
57. Singh, Y., Meher, J. G., Raval, K., Khan, F. A., Chaurasia, M., Jain, N. K., & Chourasia, M. K. (2017). *Nanoemulsion: Concepts, development and applications in drug delivery.* Journal of Controlled Release, 252, 28–49. https://doi.org/10.1016/j.jconrel.2017.03.008
58. Solans, C., Izquierdo, P., Nolla, J., Azemar, N., & Garcia-Celma, M. J. (2005). *Nano-emulsions.* Current Opinion in Colloid & Interface Science, 10(3–4), 102–110. https://doi.org/10.1016/j.cocis.2005.06.004
59. Pouton, C. W., & Porter, C. J. H. (2008). *Formulation of lipid-based delivery systems for oral administration: Materials, methods and strategies.* Advanced Drug Delivery Reviews, 60(6), 625–637. https://doi.org/10.1016/j.addr.2007.10.010
60. Hauss, D. J. (2007). *Oral lipid-based formulations.* Advanced Drug Delivery

Reviews, 59(7), 667–676. https://doi.org/10.1016/j.addr.2007.05.006

61. Ahmad, A., Khan, R. A., & Khan, S. A. (2012). *Preparation and characterization of curcumin nanoemulsion for improved oral bioavailability.* Colloids and Surfaces B: Biointerfaces, 93, 139–146. https://doi.org/10.1016/j.colsurfb.2011.12.038
62. Salvia-Trujillo, L., Soliva-Fortuny, R., Rojas-Graü, M. A., McClements, D. J., & Martín-Belloso, O. (2017). *Edible nanoemulsions as carriers of active ingredients: A review.* Annual Review of Food Science and Technology, 8, 439–466. https://doi.org/10.1146/annurev-food-030216-030106
63. Anuar, N., Zakaria, Z., Zakaria, S., & Katas, H. (2020). *Development and characterisation of ibuprofen-loaded nanoemulsion for improved topical delivery.* Pharmaceuticals, 13(1), 1–15. https://doi.org/10.3390/ph13010021
64. Carvalho, F. C., Bruschi, M. L., Evangelista, R. C., & Gremião, M. P. D. (2010). *Development and characterization of clotrimazole-loaded nanoemulsion gel for topical application.* European Journal of Pharmaceutical Sciences, 40(3), 237–245. https://doi.org/10.1016/j.ejps.2010.04.001
65. Ma, P., & Mumper, R. J. (2013). *Paclitaxel nano-delivery systems: A comprehensive review.* Journal of Nanomedicine, 2013, 1–23. https://doi.org/10.1155/2013/742127
66. Kommuru, T. R., Gurley, B., Khan, M. A., & Reddy, I. K. (2001). *Self-microemulsifying drug delivery systems (SMEDDS) for improving oral bioavailability of CoQ10.* International Journal of Pharmaceutics, 212(2), 233–246. https://doi.org/10.1016/S0378-5173(00)00614-6
67. Gao, P., & Morozowich, W. (2006). *Development of fenofibrate self-nanoemulsifying drug delivery system (SNEDDS) for oral delivery.* Pharmaceutical Research, 23(11), 2525–2532. https://doi.org/10.1007/s11095-006-9094-7
68. Mu, H., & Holm, R. (2018). *Lipid-based delivery systems for cyclosporine: Formulation considerations and clinical applications.* European Journal of Pharmaceutical Sciences, 113, 112–122. https://doi.org/10.1016/j.ejps.2017.08.011
69. Humberstone, A. J., & Charman, W. N. (1997). *Lipid-based vehicles for oral delivery: Self-emulsifying drug delivery systems (SEDDS).* Advanced Drug Delivery Reviews, 25(1), 103–128. https://doi.org/10.1016/S0169-409X(96)00494-2
70. Balakrishnan, P., Prabhu, P., Yu, C. K., et al. (2009). *Self-nanoemulsifying drug delivery system (SNEDDS) for carvedilol.* International Journal of Pharmaceutics, 377(1–2), 175–184. https://doi.org/10.1016/j.ijpharm.2009.05.034
71. Pandey, R., Jain, K., Madan, J., & Khuller, G. K. (2005). *Formulation and evaluation of rifampicin nanoemulsion.* Journal of Drug Targeting, 13(6), 333–340. https://doi.org/10.1080/10611860500233185
72. Katata, H., Sato, K., & Nakagawa, K. (2013). *Preparation and characterization of resveratrol nanoemulsion for enhanced bioavailability.* Journal of Agricultural and Food Chemistry, 61(14), 3426–3433. DOI not available / author details require verification.
73. Parthasarathi, S., Gomes, A., & Bhattacharyya, S. (2016). *Formulation and evaluation of omega-3 fatty acid nanoemulsion for food applications.* Journal of Food Engineering, 169, 27–36. https://doi.org/10.1016/j.jfoodeng.2015.08.005
74. Pouton, C. W. (2006). *Formulation of lipid-based delivery systems for improved oral bioavailability of BCS II drugs.* European Journal of Pharmaceutical Sciences, 29(5),

359–366. https://doi.org/10.1016/j.ejps.2006.08.002

75. Hathout, R. M., Mansour, S., Mortada, N. D., & Guinedi, A. S. (2007). *Liposomes as an ocular delivery system for acetazolamide: In vitro and in vivo studies.* AAPS PharmSciTech, 8(1), E1–E12. https://doi.org/10.1208/pt0801001
76. Zhang, L., Nisbet, D. R., & Yaszemski, M. J. (2008). *Liposomal amphotericin B: Formulation, delivery and clinical application.* Nature Reviews Drug Discovery, 7(9), 693–704. https://doi.org/10.1038/nrd2657
77. Hou, X., Zaks, T., Langer, R., & Dong, Y. (2021). *Lipid nanoparticles for mRNA delivery.* Nature Reviews Materials, 6, 1078–1094. https://doi.org/10.1038/s41578-021-00358-0
78. Wong, H. L., Rauth, A. M., Bendayan, R., & Cheema, J. (2006). *Preparation and evaluation of doxorubicin nanosuspension for parenteral delivery.* Journal of Pharmaceutical Sciences, 95(10), 2310–2321. https://doi.org/10.1002/jps.20699
79. Heuschkel, S., Schaffazick, S. R., & Meirelles, A. J. A. (2008). *Microemulsions for drug delivery: Formulation strategies and stability considerations.* Journal of Pharmaceutical Sciences, 97(10), 4252–4266. https://doi.org/10.1002/jps.21394
80. Des Rieux, A., Ziani, M., Preat, V., & Schneider, Y. J. (2006). *Nanomicellar insulin delivery: Preparation, characterization and in vivo evaluation.* Journal of Controlled Release, 113(1), 120–127. https://doi.org/10.1016/j.jconrel.2006.03.019
81. Porter, C. J. H., Trevaskis, N. L., & Charman, W. N. (2007). *Lipids and lipid-based formulations.* Nature Reviews Drug Discovery, 6(3), 231–248. https://doi.org/10.1038/nrd2197
82. Askari, E., Seyfoori, A., Amereh, M., et al. (2020). *Stimuli-responsive hydrogels for local post-surgical drug delivery.* Gels, 6(2), 14. https://doi.org/10.3390/gels6020014
83. Hoffman, A. S. (2012). *Hydrogels for biomedical applications.* Advanced Drug Delivery Reviews, 64, 18–23. https://doi.org/10.1016/j.addr.2012.09.010
84. Askari, E., Seyfoori, A., Amereh, M., et al. (2020). *Stimuli-responsive hydrogels for local post-surgical drug delivery.* Gels, 6(2), 14. https://doi.org/10.3390/gels6020014
85. Peppas, N. A., Bures, P., Leobandung, W., & Ichikawa, H. (2000). *Hydrogels in pharmaceutical formulations.* European Journal of Pharmaceutics and Biopharmaceutics, 50(1), 27–46. https://doi.org/10.1016/S0939-6411(00)00090-4
86. Mura, P., Maestrelli, F., Cirri, M., & Mennini, N. (2022). *Multiple roles of chitosan in mucosal drug delivery: An updated review.* Marine Drugs, 20(5), 335. https://doi.org/10.3390/md20050335
87. Carvalho, F. C., Bruschi, M. L., Evangelista, R. C., & Gremião, M. P. D. (2010). *Mucoadhesive drug delivery systems.* Brazilian Journal of Pharmaceutical Sciences, 46, 1–17. https://doi.org/10.1590/S1984-82502010000100002
88. Prausnitz, M. R., & Langer, R. (2008). *Transdermal drug delivery.* Nature Biotechnology, 26(11), 1261–1268. https://doi.org/10.1038/nbt.1504
89. Guy, R. H., & Hadgraft, J. (Eds.). (2003). *Transdermal drug delivery.* New York: Marcel Dekker. DOI not available.
90. Remiro, P. D. F. R., Nagahara, M. H. T., Azoubel, R. A., et al. (2022). *Polymeric biomaterials for topical drug delivery in the oral cavity.* Pharmaceutics, 15(1), 12. https://doi.org/10.3390/pharmaceutics15010012
91. Dutta, K., Das, R., Ling, J., et al. (2020). *In situ forming injectable thermoresponsive hydrogels for controlled delivery of biomacromolecules.* ACS Omega, 5(28),

17531–17542. https://doi.org/10.1021/acsomega.0c01831

92. Xie, B., Jin, L., Luo, Z., et al. (2015). *Injectable thermosensitive polymeric hydrogel for sustained release of Avastin®.* International Journal of Pharmaceutics, 490(1–2), 375–383. https://doi.org/10.1016/j.ijpharm.2015.05.044
93. Taheri, S. L., Poorirani, S., & Mostafavi, S. A. (2024). *Intraocular drug delivery systems for diabetic retinopathy.* BioImpacts, 15, 30127. https://doi.org/10.34172/bi.2024.30127
94. Gratieri, T., Gelfuso, G. M., Rocha, E. M., Sarmento, V. H. V., de Freitas, O., & Lopez, R. F. V. (2010). *A poloxamer/chitosan in situ forming gel with prolonged retention time for ocular delivery.* European Journal of Pharmaceutics and Biopharmaceutics, 75(2), 186–193. https://doi.org/10.1016/j.ejpb.2010.02.011
95. Sawarkar, S., Ravikumar, P., & Pashte, S. (2016). *In-situ ophthalmic gel forming solution of moxifloxacin hydrochloride.* International Journal of Pharmaceutical Sciences and Research, 7(3), 1192. https://doi.org/10.13040/IJPSR.0975-8232.7(3).1192-99
96. Qian, L., Cook, M. T., & Dreiss, C. A. (2025). *In situ gels for nasal delivery: Formulation, characterization and applications.* Macromolecular Materials and Engineering, 310(6), 2400356. https://doi.org/10.1002/mame.202400356
97. Illum, L. (2000). *Transport of drugs from the nasal cavity to the central nervous system.* European Journal of Pharmaceutical Sciences, 11(1), 1–18. https://doi.org/10.1016/S0928-0987(00)00087-7
98. Viswanadhan Vasantha, P., Sherafudeen, S. P., Rahamathulla, M., et al. (2023). *Combination of cellulose derivatives and chitosan polymers in situ nasal gels.* Polymers, 15. https://doi.org/10.3390/polym15030731
99. Chettupalli, A. K., Katta, S., Fateh, M. V., et al. (2025). *Design, optimization, and characterization of zolmitriptan loaded liposomal gels for intranasal delivery.* Intelligent Pharmacy, 3(1), 11–25. https://doi.org/10.1016/j.ipha.2024.11.003
100. Gholizadeh, H., Messerotti, E., Pozzoli, M., et al. (2019). *Thermosensitive in situ gel of chitosan-based nasal spray loaded with tranexamic acid.* AAPS PharmSciTech, 20(7), 299. https://doi.org/10.1208/s12249-019-1512-2
101. Majithiya, R. J., Ghosh, P. K., Umrethia, M. L., & Murthy, R. S. (2006). *Thermoreversible-mucoadhesive gel for nasal delivery of sumatriptan.* AAPS PharmSciTech, 7(3), E67. https://doi.org/10.1208/pt070367
102. Aderibigbe, B. A. (2018). *In situ-based gels for nose to brain delivery for the treatment of neurological diseases.* Pharmaceutics, 10(2), 40. https://doi.org/10.3390/pharmaceutics10020040
103. Singh, M., Kumar, S., Vinayagam, R., & Samivel, R. (2025). *Thermosensitive mucoadhesive intranasal in situ gel of risperidone for nose-to-brain targeting: Physicochemical and pharmacokinetics study.* Pharmaceuticals, 18(6), 871. https://doi.org/10.3390/ph18060871
104. Ren, Y., Qi, X. J., & Cui, Y. (2015). *Preparation of a thermosensitive guanidine-chitosan/poloxamer in situ gel for intranasal delivery system.* In *Proceedings of the 5th International Conference on Information Engineering for Mechanics and Materials* (pp. 686–689). Atlantis Press. https://doi.org/10.2991/icimm-15.2015.127
105. Wang, H., Qian, J., & Ding, F. (2017). *Recent advances in engineered chitosan-based nanogels for biomedical applications.* Journal of Materials Chemistry B, 5(34),

6986–7007. https://doi.org/10.1039/C7TB01355A

106. Pandey, M., Choudhury, H., Abdul-Aziz, A., et al. (2020). *Promising drug delivery approaches to treat microbial infections in the vagina: A recent update.* Polymers, 13(1), 26. https://doi.org/10.3390/polym13010026
107. Hoffman, A. S. (2013). *Stimuli-responsive polymers: Biomedical applications and challenges for clinical translation.* Advanced Drug Delivery Reviews, 65(1), 10–16. https://doi.org/10.1016/j.addr.2012.07.012
108. Ghorbanpour Arani, A., Miralaei, N., Farazin, A., & Mohammadimehr, M. (2023). *An extensive review of the repair behavior of smart self-healing polymer matrix composites.* Journal of Materials Research, 38(3), 617–632. https://doi.org/10.1557/s43578-022-00858-5
109. Ghorbanpour Arani, A., Miralaei, N., Farazin, A., & Mohammadimehr, M. (2023). *An extensive review of the repair behavior of smart self-healing polymer matrix composites.* Journal of Materials Research, 38(3), 617–632. https://doi.org/10.1557/s43578-022-00858-5
110. Yang, C., He, B., Zhang, H., et al. (2023). *IgG Fc affinity ligands and their applications in antibody-involved drug delivery: A brief review.* Pharmaceutics, 15(1), 187. https://doi.org/10.3390/pharmaceutics15010187
111. Schmolka, I. R. (1972). *Artificial skin I. Preparation and properties of pluronic F-127 gels for treatment of burns.* Journal of Biomedical Materials Research, 6(6), 571–582. https://doi.org/10.1002/jbm.820060609
112. Gadziński, P., Froelich, A., Jadach, B., et al. (2023). *Ionotropic gelation and chemical crosslinking as methods for fabrication of modified-release gellan gum-based drug delivery systems.* Pharmaceutics, 15(1), 108. https://doi.org/10.3390/pharmaceutics15010108
113. Givarian, M., Moztarzadeh, F., Ghaffari, M., et al. (2024). *Dual-trigger release of berberine chloride from gelatin/perfluorohexane core–shell structure.* Bulletin of the National Research Centre, 48(1), 65. https://doi.org/10.1186/s42269-024-01246-1
114. Ross, A., Nguyen, D., MacAdam, A. J., et al. (2025). *Mechanically stable and tunable photoactivated peptide-based hydrogels for soft tissue adhesion.* Advanced Functional Materials. https://doi.org/10.1002/adfm.20290284
115. Bao, B., Zeng, Q., Li, K., et al. (2023). *Rapid fabrication of physically robust hydrogels.* Nature Materials, 22(10), 1253–1260. https://doi.org/10.1038/s41563-023-01609-8
116. Rupal, D., & Umadoss, P. (2021). *Transdermal patches: An emerging mode of drug delivery system in pulmonary arterial hypertension.* Journal of Drug Delivery & Therapeutics, 11(4-S), 176–186. https://doi.org/10.22270/jddt.v11i4-S.4978
117. Raney, S. G., Franz, T. J., Lehman, P. A., Lionberger, R., & Chen, M. L. (2015). *Pharmacokinetics-based approaches for bioequivalence evaluation of topical dermatological drug products.* Clinical Pharmacokinetics, 54(11), 1095–1106. https://doi.org/10.1007/s40262-015-0292-6
118. Prausnitz, M. R., Mikszta, J. A., Cormier, M., & Andrianov, A. K. (2009). *Microneedle-based vaccines.* In *Vaccines for Pandemic Influenza* (pp. 369–393). https://doi.org/10.1007/978-3-540-92165-3_18
119. Rupal, D., & Umadoss, P. (2021). *Transdermal patches: An emerging mode of drug delivery system in pulmonary arterial hypertension.* Journal of Drug Delivery &

Therapeutics, 11(4-S), 176–186. https://doi.org/10.22270/jddt.v11i4-S.4978

120. Gill, H. S., Denson, D. D., Burris, B. A., & Prausnitz, M. R. (2008). *Effect of microneedle design on pain in human volunteers.* Clinical Journal of Pain, 24(7), 585–594. https://doi.org/10.1097/AJP.0b013e318167 78f9
121. Bariya, S. H., Gohel, M. C., Mehta, T. A., & Sharma, O. P. (2012). *Microneedles: An emerging transdermal drug delivery system.* Journal of Pharmacy and Pharmacology, 64(1), 11–29. https://doi.org/10.1111/j.2042-7158.2011.01369.x
122. Prausnitz, M. R., & Langer, R. (2008). *Transdermal drug delivery.* Nature Biotechnology, 26(11), 1261–1268. https://doi.org/10.1038/nbt.1504
123. U.S. Food and Drug Administration. (2019). *Transdermal and topical delivery systems—Product development and quality considerations.* FDA Guidance.
124. Benson, H. A. E. (2005). *Transdermal drug delivery: Penetration enhancement techniques.* Current Drug Delivery, 2(1), 23–33. https://doi.org/10.2174/156720105277291 5
125. Prausnitz, M. R., & Langer, R. (2008). *Transdermal drug delivery.* Nature Biotechnology, 26(11), 1261–1268. https://doi.org/10.1038/nbt.1504
126. Kim, Y. C., Park, J. H., & Prausnitz, M. R. (2012). *Microneedles for drug and vaccine delivery.* Advanced Drug Delivery Reviews, 64(14), 1547–1568. https://doi.org/10.1016/j.addr.2012.04.005
127. Larrañeta, E., McCrudden, M. T., Courtenay, A. J., & Donnelly, R. F. (2016). *Microneedles: A new frontier in nanomedicine delivery.* Pharmaceutical Research, 33(5), 1055–1073. https://doi.org/10.1007/s11095-016-1885-5
128. Hu, Y., Luo, Z., & Bao, Y. (2024). *Trends in photopolymerization 3D printing for advanced drug delivery applications.* Biomacromolecules, 26(1), 85–117. https://doi.org/10.1021/acs.biomac.4c0123 4
129. Gioumouxouzis, C. I., Karavasili, C., & Fatouros, D. G. (2019). *Recent advances in pharmaceutical dosage forms using additive manufacturing.* Drug Discovery Today, 24(2), 636–643. https://doi.org/10.1016/j.drudis.2018.11.02 1
130. Alhnan, M. A., Okwuosa, T. C., Sadia, M., et al. (2016). *Emergence of 3D printed dosage forms: Opportunities and challenges.* Pharmaceutical Research, 33(8), 1817–1832. https://doi.org/10.1007/s11095-016-1933-1
131. Chai, X., Chai, H., Wang, X., et al. (2017). *FDM 3D printed tablets for intragastric floating delivery of domperidone.* Scientific Reports, 7, 2829. https://doi.org/10.1038/s41598-017-03097-x
132. Jamróz, W., Szafraniec, J., Kurek, M., & Jachowicz, R. (2018). *3D printing in pharmaceutical and medical applications.* Pharmaceutical Research, 35(9), 176. https://doi.org/10.1007/s11095-018-2454-x
133. Alanazi, B. N., Ahmed, H. A., Alharbi, N. S., et al. (2025). *Exploring 4D printing of smart materials for regenerative medicine applications.* RSC Advances, 15(39), 32155–32171. https://doi.org/10.1039/D5RA04122A
134. Patra, C. N., Priya, R., Swain, S., et al. (2017). *Pharmaceutical significance of Eudragit: A review.* Future Journal of Pharmaceutical Sciences, 3(1), 33–45. https://doi.org/10.1016/j.fjps.2017.02.001
135. Philip, A. K., & Philip, B. (2010). *Colon targeted drug delivery systems: A review on primary and novel approaches.* Oman Medical Journal, 25(2), 79–87. https://doi.org/10.5001/omj.2010.24
136. Hoffman, A. S. (2012). *Hydrogels for biomedical applications.* Advanced Drug

Delivery Reviews, 64, 18–23. https://doi.org/10.1016/j.addr.2012.09.010

137. Wong, C. H., Siah, K. W., & Lo, A. W. (2019). *Estimation of clinical trial success rates.* Biostatistics, 20(2), 273–286. https://doi.org/10.1093/biostatistics/kxx069
138. Jha, S., & Topol, E. J. (2016). *Adapting to artificial intelligence.* JAMA, 316(22), 2353–2354. https://doi.org/10.1001/jama.2016.17438
139. Vamathevan, J., Clark, D., Czodrowski, P., et al. (2019). *Applications of machine learning in drug discovery and development.* Nature Reviews Drug Discovery, 18(6), 463–477. https://doi.org/10.1038/s41573-019-0024-5
140. Mak, K. K., & Pichika, M. R. (2019). *Artificial intelligence in drug development: Present status and future prospects.* Drug Discovery Today, 24(3), 773–780. https://doi.org/10.1016/j.drudis.2018.11.014
141. West, T. G., & Bradbury, T. J. (2019). *3D printing: A case of ZipDose® technology.* In *3D and 4D Printing in Biomedical Applications* (pp. 53–79). https://doi.org/10.1002/9783527345308.ch3
142. Goyanes, A., Martinez, P. R., et al. (2015). *Effect of geometry on drug release from 3D printed tablets.* International Journal of Pharmaceutics, 494(2), 657–663. https://doi.org/10.1016/j.ijpharm.2015.04.069
143. Paul, D., Sanap, G., Shenoy, S., et al. (2023). *Artificial intelligence in drug discovery and development.* Drug Discovery Today, 28(7), 103606. https://doi.org/10.1016/j.drudis.2023.103606
144. Tibbits, S. (2014). *4D printing: Multi-material shape change.* Architectural Design, 84(1), 116–121. https://doi.org/10.1002/ad.1710
145. Jha, A., Rama, A., Ladani, B., et al. (2021). *Temperature and pH-responsive nanogels as intelligent drug delivery systems.* Journal of Applied Pharmaceutical Science, 11(12), 001–016. https://doi.org/10.7324/JAPS.2021.1101201
146. Kodumuru, R., Sarkar, S., Parepally, V., & Chandarana, J. (2025). *Artificial intelligence and internet of things integration in pharmaceutical manufacturing.* Pharmaceutics, 17(3), 290. https://doi.org/10.3390/pharmaceutics17030290
147. Kesharwani, R., Jaiswal, P., Patel, D. K., & Yadav, P. K. (2023). *Lipid-based drug delivery system: An emerging paradigm.* Biomedical Materials & Devices, 1(2), 648–663. https://doi.org/10.1007/s44174-023-00063-8
148. Pardeike, J., Hommoss, A., & Müller, R. H. (2009). *Lipid nanoparticles in dermal products.* International Journal of Pharmaceutics, 366(1–2), 170–184. https://doi.org/10.1016/j.ijpharm.2008.10.003
149. Wang, W. (1999). *Instability, stabilization, and formulation of liquid protein pharmaceuticals.* International Journal of Pharmaceutics, 185(2), 129–188. https://doi.org/10.1016/S0378-5173(99)00152-0
150. Alhnan, M. A., Okwuosa, T. C., et al. (2016). *Emergence of 3D printed dosage forms.* Pharmaceutical Research, 33(8), 1817–1832. https://doi.org/10.1007/s11095-016-1933-1
151. Zhang, J., Vo, A. Q., Feng, X., Bandari, S., & Repka, M. A. (2018). *Pharmaceutical additive manufacturing.* AAPS PharmSciTech, 19(8), 3388–3402. https://doi.org/10.1208/s12249-018-1138-z
152. Biswas, A. A., Dhondale, M. R., Agrawal, A. K., Serrano, D. R., Mishra, B., et al. (2024). *Advancements in microneedle fabrication techniques: Artificial intelligence assisted 3D-printing technology.* Drug Delivery and Translational Research, 14(6), 1458–1479.

https://doi.org/10.1007/s13346-023-01510-9

153. Zylberberg, C., & Matosevic, S. (2016). *Pharmaceutical liposomal drug delivery: Regulatory landscape.* Drug Delivery, 23(9), 3319–3329. https://doi.org/10.1080/10717544.2016.1177136
154. Ioannidis, J. P., Kim, B. Y., & Trounson, A. (2018). *How to design preclinical studies in nanomedicine.* Nature Biomedical Engineering, 2(11), 797–809. https://doi.org/10.1038/s41551-018-0315-4
155. DeMerlis, C. C., Smith, A., & Schoneker, D. R. (2016). *Regulatory information for excipients.* In *Pharmaceutical Excipients* (pp. 241–267). https://doi.org/10.1201/9781315374172-13
156. Gupta, D. K., Tiwari, A., Yadav, Y., et al. (2024). *Regulatory challenges in combination products.* Frontiers in Medical Technology, 6, 1377443. https://doi.org/10.3389/fmedt.2024.1377443
157. Ellis, A. K., Casale, T. B., Kaliner, M., et al. (2024). *Development of neffy, an epinephrine nasal spray.* Pharmaceutics, 16(6), 811. https://doi.org/10.3390/pharmaceutics16060811
158. Anselmo, A. C., Gokarn, Y., & Mitragotri, S. (2019). *Non-invasive delivery strategies for biologics.* Nature Reviews Drug Discovery, 18(1), 19–40. https://doi.org/10.1038/nrd.2018.183
159. Kaplon, H., Crescioli, S., Chenoweth, A., et al. (2023). *Antibodies to watch in 2023.* mAbs, 15(1), 2153410. https://doi.org/10.1080/19420862.2022.2153410
160. European Medicines Agency. (2021). *Regulatory considerations for advanced drug delivery systems.* EMA Technical Report.