RESEARCH PAPER

Navigating the Legal Landscape of Advanced Drug Delivery Technologies: A Comparative Analytical Study

Dr. Deependra Nath Pathak[1], Dr. Radha Ranjan[2], Ms. Anupam Sinha[3], Pushpendra Kumar Anuragi[4], Dr. Govind Prasad Goyal[5], Vyas Kumar Yadav[6]

[1] Associate Professor, Amity Law School, Amity University Patna. Email: dnpathak@ptn.amity.edu

[2] Assistant Professor, Amity Law School, Amity University Patna. Email: radharanjan@alumni.nls.ac.in

[3] Assistant Professor, Amity Law School, Amity University Patna. Email: asinha@ptn.amity.edu

[4] Research Scholar (Law), University of Delhi. Email: adv.pushpendraanuragi@gmail.com

[5] Dean Students Welfare, IMS Law College, Noida. Email: deansw@imsnoida.com

[6] Assistant Professor, IMS Law College, Noida. Email: vyas.yadav@imsnoida.com

Received: 2nd Mar, 2026 | **Revised:** 14th Mar, 2026 | **Accepted:** 4th Apr, 2026 | **Available Online:** 20th Apr, 2026

ABSTRACT

The rapid evolution of advanced drug delivery technologies — encompassing nanotechnology-based carriers, artificial intelligence (AI)-guided therapeutics, combination products, and personalised medicine platforms — has fundamentally outpaced the regulatory and legal architectures designed to govern pharmaceutical innovation. This paper undertakes a comparative analytical examination of the legal frameworks applicable to advanced drug delivery technologies across three principal jurisdictions: the United States of America (USA), the European Union (EU), and the United Kingdom (UK). Drawing on doctrinal legal methodology, the study interrogates how existing pharmaceutical law, product liability doctrine, intellectual property regimes, and emerging AI governance instruments intersect — and often conflict — when applied to novel drug delivery systems. Key findings reveal structural fragmentation in regulatory classification, unresolved liability attribution in AI-integrated drug delivery, substantial intellectual property challenges unique to nanomedicine, and the legal inadequacy of emergency authorisation frameworks originally designed for conventional pharmaceuticals. The paper concludes with a call for adaptive, technology-neutral legislative reform and stronger international regulatory harmonisation, particularly under the International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use (ICH).

Keywords: drug delivery technology, pharmaceutical law, nanotechnology regulation, AI in drug development, combination products, product liability, intellectual property, ICH harmonisation, FDA, EMA, MHRA.

How to cite this article: Pathak DN, Ranjan R, Sinha A, Anuragi PK, Goyal GP, Yadav VK. Navigating the Legal Landscape of Advanced Drug Delivery Technologies: A Comparative Analytical Study. Int J Drug Deliv Technol. 2026;16(32s):694-703. DOI: 10.25258/ijddt.16.32s.77

Source of support: Nil.

Conflict of interest: The authors declare no conflict of interest.

1. INTRODUCTION

The intersection of pharmaceutical science and law has never been more dynamic — nor more contested. Drug delivery technology, broadly defined as the science and methodology of transporting therapeutic agents to their intended biological targets with precision and efficacy, has undergone a paradigm shift in the twenty-first century. Traditional oral tablets and injectable solutions have given way to liposomal nanoparticles, antibody-drug conjugates, implantable biosensors, AI-driven dose-optimisation algorithms, and 3D-printed personalised medicines. These innovations hold transformative promise for patient outcomes. Yet they simultaneously generate profound legal and regulatory uncertainty.

The challenge is not merely technical but deeply juridical. Legal systems are, by design, backward-looking: they codify rules in response to problems already encountered. Advanced drug delivery technologies, however, operate at the frontier of scientific possibility, generating novel legal questions for which existing statutory and common law frameworks were not designed. When a nanotechnology-enhanced drug induces an unanticipated adverse reaction, who bears legal liability — the device manufacturer, the pharmaceutical company, or the clinician who

administered it? When an AI model recommends a personalised drug dosage that subsequently harms a patient, does this constitute a product defect or medical negligence? Can a genetically tailored therapeutic be patented, and if so, on what legal basis?

This paper addresses these questions through a comparative analytical lens, examining the regulatory regimes of the USA, EU, and UK — three jurisdictions at the global forefront of pharmaceutical governance. The doctrinal method is employed to analyse primary legal texts (statutes, regulations, directives, and agency guidance documents), supplemented by reference to secondary academic and policy literature. The paper proceeds as follows: Section 2 establishes the conceptual and legal taxonomy of advanced drug delivery technologies. Section 3 examines the comparative regulatory approval frameworks. Section 4 analyses product liability and tort dimensions. Section 5 addresses intellectual property law challenges. Section 6 investigates the emerging governance of AI-integrated drug delivery. Section 7 discusses international harmonisation through ICH and related bodies. Section 8 offers conclusions and reform recommendations.

2. CONCEPTUAL AND LEGAL TAXONOMY OF ADVANCED DRUG DELIVERY TECHNOLOGIES

For legal purposes, a precise taxonomy of drug delivery technologies is indispensable. The law cannot regulate what it cannot classify, and misclassification — or failure to classify — is itself a significant source of legal risk. Advanced drug delivery systems may be broadly organised into four overlapping categories, each with distinct regulatory implications.

2.1 Nanotechnology-Based Drug Delivery Systems

Nanomedicine refers to the application of nanoscale materials — typically between 1 and 1000 nanometres — for therapeutic or diagnostic purposes. Liposomal formulations, polymeric nanoparticles, dendrimers, and quantum dots have been investigated as drug carriers capable of targeted, controlled release. The fundamental legal difficulty with nanomedicines is definitional: neither the US Federal Food, Drug, and Cosmetic Act (FDCA) nor the EU's Regulation (EC) No 726/2004 contains a statutory definition of "nanomaterial" in the pharmaceutical context. The FDA issued non-binding guidance in 2014 acknowledging that nanotechnology-based products may raise questions of safety, effectiveness, and manufacturing quality, but did not establish a binding definitional or classificatory regime (Food and Drug Administration, 2014). This definitional lacuna has direct legal consequences: it impedes predictable classification of nanomedicines as drugs, medical devices, or combination products — each pathway attracting different regulatory obligations and liability exposure.

2.2 Combination Products

Combination products integrate a drug with a biological product, medical device, or other component as a single entity or co-packaged unit. Drug-device combinations — such as drug-eluting stents, prefilled injection systems, or inhaler-drug systems — present acute classification difficulties. In the USA, the FDA's Office of Combination Products (OCP) determines the "primary mode of action" (PMOA) to assign regulatory jurisdiction to either the Center for Drug Evaluation and Research (CDER) or the Center for Devices and Radiological Health (CDRH). The classification process is governed by 21 CFR Part 3 and further elaborated in numerous guidance documents. The EU presents parallel complexity: Regulation (EU) 2017/745 on Medical Devices (MDR) and Directive 2001/83/EC on medicinal products establish separate regulatory tracks, and combination products may fall under either or require dual compliance, depending on the primary purpose of the constituent components (Albuquerque de Almeida et al., 2023). As Albuquerque de Almeida et al. observed, the regulatory frameworks for medical devices and drugs in the EU have not yet achieved full harmonisation, creating friction for combination product developers navigating dual compliance obligations.

2.3 Personalised and Gene Therapy Products

Advanced therapy medicinal products (ATMPs) — including gene therapies, somatic cell therapies, and tissue-engineered products — are regulated as a discrete category in the EU under Regulation (EC) No 1394/2007. In the USA, the FDA's Center for Biologics Evaluation and Research (CBER) exercises jurisdiction. Personalised medicine, particularly products derived from or tailored to an individual patient's genetic profile, poses acute legal challenges regarding manufacturing standards, batch release requirements, and informed consent — legal frameworks developed for mass-produced pharmaceuticals apply awkwardly to N-of-1 therapies.

2.4 AI-Integrated Drug Delivery Platforms

The integration of artificial intelligence — machine learning models, algorithmic dosing systems, and AI-driven clinical decision support tools — into drug delivery represents perhaps the most legally novel

development in contemporary pharmaceutical technology. AI may be embedded within a drug delivery device (e.g., a smart inhaler that adjusts dosing based on patient data) or may operate as an upstream design tool (e.g., AI-designed novel excipients or delivery mechanisms). In either configuration, the AI component raises questions of regulatory classification, liability allocation, and transparency that existing legal frameworks address, at best, imperfectly.

3. COMPARATIVE REGULATORY APPROVAL FRAMEWORKS

3.1 United States: The FDA Regime

The US regulatory framework, administered by the Food and Drug Administration (FDA), is widely regarded as one of the most rigorous pharmaceutical approval systems globally. Statutory authority derives primarily from the FDCA and the Public Health Service Act. Drug approval proceeds through the Investigational New Drug (IND) application, followed by a New Drug Application (NDA) or Biologics License Application (BLA), each requiring comprehensive clinical trial data demonstrating safety and efficacy across three phases of investigation.

For advanced drug delivery products, the FDA employs a risk-stratified approach. Medical devices are classified into three classes, with Class III (highest risk) requiring Premarket Approval (PMA). The FDA's Breakthrough Devices Program (BDP), established under the 21st Century Cures Act 2016, provides an expedited review pathway for innovative technologies. Data from the FDA indicate that from 2015 to 2024, the BDP designated 1,041 devices, though only 12.3% ultimately received marketing authorisation — a figure reflecting the stringent evidentiary demands of the approval process (Frontiers in Medical Technology, 2025). For combination products, the OCP functions as a coordination mechanism, but the bifurcation of regulatory centres retains the potential for inconsistent standards.

The FDA's interaction model with industry is particularly noteworthy from a legal standpoint. Companies may engage the FDA at no cost through pre-IND meetings, End-of-Phase meetings, and pre-submission meetings, providing regulatory clarity before full applications are filed. However, such meetings may be refused, and the guidance provided is non-binding — a limitation that increases legal uncertainty for novel delivery platforms (Celegence, 2024).

3.2 European Union: The EMA and MDR Regime

The EU regulatory framework for pharmaceuticals is administered primarily by the European Medicines Agency (EMA) in collaboration with the competent authorities of 27 Member States. The centralised procedure under Regulation (EC) No 726/2004 enables EMA to grant a single marketing authorisation valid across the EU. The revised Medical Device Regulation (Regulation (EU) 2017/745), which became fully applicable in May 2021, and the In-Vitro Diagnostic Regulation (Regulation (EU) 2017/746) significantly raised standards for device approval, introducing more stringent requirements for clinical evidence, post-market surveillance, and the designation of Notified Bodies (NBs).

A notable legal development is the Health Technology Assessment Regulation (HTAR, Regulation (EU) 2021/2282), which entered its implementation phase in January 2025. The HTAR mandates coordinated clinical assessments of certain high-risk medical devices and pharmaceutical products across EU Member States, with joint scientific evaluations intended to reduce duplication and increase methodological consistency (Frontiers in Medical Technology, 2025). This represents a significant step toward a more unified EU legal framework for advanced therapies, though national reimbursement decisions remain outside its scope.

The EU's approach to regulatory science advice differs from the FDA model in that the EMA charges fees for Scientific Advice, but imposes no firm limit on the frequency of interactions — a feature that, in practice, facilitates iterative guidance for complex innovative products (Celegence, 2024). The number of Notified Bodies certified under the MDR increased from approximately 20 in 2021 to 50 by 2024, partially alleviating access bottlenecks that had significantly delayed market entry for medical devices in the post-MDR transition period (Frontiers in Medical Technology, 2025).

3.3 United Kingdom: Post-Brexit MHRA Regime

Following the UK's withdrawal from the European Union, the Medicines and Healthcare products Regulatory Agency (MHRA) has operated as an independent regulatory authority. The UK has established its own pharmaceutical marketing authorisation procedure, creating what is, in effect, a third distinct legal regime for drug delivery technology products. The Innovative Licensing and Access Pathway (ILAP), enhanced in 2024, offers expedited market access for products targeting rare or life-threatening conditions through rolling data reviews and early scientific advice (ProPharma Group, 2024).

The Windsor Framework, operative from January 2025, introduced specific arrangements for the supply of medicines in Northern Ireland — a legally complex configuration arising from the post-Brexit political settlement that has created distinct supply chain and regulatory compliance obligations for companies serving both Great Britain and Northern Ireland markets. Post-Brexit, pharmaceutical companies face the need to navigate both the UK and EU regulatory landscapes for products intended for both markets, with duplicative submissions and potentially divergent requirements representing a material increase in regulatory burden and legal risk.

3.4 Emergency Authorisation: COVID-19 as a Legal Laboratory

The COVID-19 pandemic provided an unprecedented empirical test of the legal and regulatory frameworks governing emergency pharmaceutical authorisation. A comparative study examining Emergency Use Authorisations (EUAs) issued in the USA for 23 pharmaceutical products between December 2019 and July 2023 revealed significant inter-jurisdictional variation in approval rates, timelines, and subsequent drug development outcomes. As of July 2023, Japan had granted approval or permission for 14 drugs (60.9%), the EU for 14 (60.9%), the UK for 12 (52.2%), and China for three (13.0%) of the 23 US-EUA-designated products. Notably, the UK had the shortest period for approval, while the EU had the shortest period from EUA issuance to formal approval (Ozaki et al., 2024).

These findings illuminate important structural differences in the legal frameworks governing emergency authorisation. They also reveal the legal tensions inherent in rapidly approving novel drug delivery platforms — including lipid nanoparticle mRNA delivery systems — whose long-term safety profiles were, by definition, incompletely understood at the time of authorisation. The legal adequacy of informed consent standards under emergency authorisation conditions, and the post-market pharmacovigilance obligations arising therefrom, remain subjects of ongoing scholarly and regulatory debate.

4. PRODUCT LIABILITY AND TORT LAW DIMENSIONS

4.1 The Liability Architecture for Drug Delivery Failures

Product liability law provides the principal private law mechanism for redress when defective drug delivery technologies cause harm. However, the application of classical product liability doctrine to advanced drug delivery systems reveals significant doctrinal strain. The two dominant liability regimes — the US strict products liability framework (as articulated in the Restatement (Third) of Torts: Products Liability) and the EU's Product Liability Directive (Council Directive 85/374/EEC, now under revision) — both distinguish between manufacturing defects, design defects, and failures to warn. For advanced drug delivery systems, each of these categories poses distinct analytical difficulties.

A manufacturing defect occurs when a specific product unit deviates from its intended design. For nanomedicines produced using complex synthesis processes, demonstrating deviation from intended specifications is technically demanding — particularly where nanoscale variability is an inherent feature of the manufacturing process rather than an aberration. A design defect, by contrast, exists when the product's intended design is itself unreasonably dangerous. For novel drug delivery systems employing emerging technologies, the benchmark for "reasonable" safety is contested, and courts have historically struggled to evaluate design defectiveness in the context of cutting-edge medical technologies. The "state of the art" defence — available under both EU and UK law and functionally equivalent doctrines in US law — may shield manufacturers of genuinely novel technologies from liability, but this defence requires careful legal analysis of the state of scientific knowledge at the time of placing the product on the market.

4.2 Multi-Party Liability in Combination Products

The combination product architecture creates acute multi-party liability complexity. A drug-device combination product may involve a pharmaceutical manufacturer responsible for the active ingredient, a device manufacturer responsible for the delivery mechanism, a contract manufacturer, a distributor, and a dispensing healthcare professional — each potentially bearing partial liability in the event of product failure. In the USA, the learned intermediary doctrine has been applied to shield pharmaceutical manufacturers from direct liability to patients where adequate warnings were given to prescribing physicians. However, the doctrine's application to automated drug delivery systems — where the "intermediary" may be an algorithm rather than a human clinician — has not yet been authoritatively adjudicated.

In the EU, the revised Product Liability Directive (Directive 2024/2853/EU), which must be transposed into national law by December 2026, explicitly

extends product liability to digital products and AI-enabled systems. This is a legally significant development for AI-integrated drug delivery platforms: under the revised Directive, software embedded in a drug delivery device may constitute a "product" for liability purposes, and defects in the AI component may give rise to strict manufacturer liability. This represents a substantial departure from the prior legal position under the 1985 Directive, which did not expressly address software as a standalone product category.

4.3 Regulatory Compliance as a Defence

A recurring question in pharmaceutical product liability litigation is whether regulatory compliance — obtaining marketing authorisation from the FDA, EMA, or MHRA — operates as a complete or partial defence to tort liability. Under US federal law, the preemption doctrine (as developed in cases such as Wyeth v. Levine, 555 U.S. 555 (2009) and PLIVA, Inc. v. Mensing, 564 U.S. 604 (2011)) has produced a complex jurisprudence in which state law failure-to-warn claims against branded drug manufacturers may not be preempted, while generic manufacturers face a more constrained legal position. For advanced drug delivery technologies, where product specifications may evolve continuously post-approval (particularly for AI-enabled systems), the preemption analysis becomes more complex and unsettled.

5. INTELLECTUAL PROPERTY LAW AND DRUG DELIVERY INNOVATION

5.1 Patentability of Advanced Drug Delivery Systems

Intellectual property law — particularly patent law — performs a dual function in pharmaceutical innovation: it incentivises investment in research and development by granting temporary market exclusivity, while simultaneously creating legal mechanisms (such as compulsory licensing) intended to balance access to essential medicines. For advanced drug delivery technologies, the patent system presents both opportunity and constraint.

Nanomedicine represents one of the most active and contested areas of pharmaceutical patent prosecution. As established in legal literature, companies developing nanotechnology-based drug delivery vehicles routinely file patents on both the nanoscale materials and the therapeutic delivery processes in which they are employed (Springer Nature, 2007). A distinctive legal challenge arises from the fact that nanomaterials may behave fundamentally differently at the nanoscale than their bulk counterparts — a property that complicates the application of prior art doctrines, since existing patents on macroscale materials may not anticipate the nanoscale variant, yet the nanoscale version may also fail the non-obviousness requirement if the nanoscale properties were predictable from bulk properties (ScienceDirect, 2019).

The US Patent and Trademark Office (USPTO) and the European Patent Office (EPO) continue to develop examination practices specific to nanotechnology. A critical legal issue identified in the literature is patent claim breadth: nanotechnology inventors face a tension between drafting claims broadly enough to provide meaningful protection against design-around strategies and drafting claims narrowly enough to satisfy enablement and written description requirements. The US Supreme Court's decision in Amgen Inc. v. Sanofi, 598 U.S. 594 (2023), which invalidated broad antibody patent claims for lack of enablement, has significantly tightened the enablement standard in the biopharmaceutical space, with direct implications for broadly-drafted nanomedicine patents (Wolf Greenfield, 2024).

5.2 Evergreening and Drug Delivery Patent Strategies

The practice of pharmaceutical "evergreening" — extending effective patent monopoly through serial patenting of incremental innovations, including drug delivery reformulations — has attracted sustained legal scrutiny internationally. Pharmaceutical companies routinely seek patent protection for new salt forms, polymorphs, enantiomers, and controlled-release formulations of previously approved drug substances. While some such patents protect genuine innovations offering meaningful clinical benefit, critics argue that many represent attempts to extend market exclusivity beyond what is warranted by the incremental nature of the innovation. Several jurisdictions have enacted legislative or administrative measures to restrict low-value pharmaceutical patents: India's Section 3(d) of the Patents Act 1970, as interpreted by the Supreme Court in Novartis AG v. Union of India, (2013) 6 SCC 1, provides the most prominent example of a legal provision explicitly designed to prevent evergreening of drug delivery modifications that fail to demonstrate enhanced efficacy.

The Inflation Reduction Act 2022 in the USA introduced a novel legal tension between drug delivery innovation incentives and cost containment. By subjecting small molecule drugs to Medicare price negotiations after nine years of market exclusivity

(compared to 13 years for biologics), the Act created a legal structure that some commentators argue may distort innovation investment decisions, potentially redirecting pharmaceutical R&D toward biological delivery modalities at the expense of small molecule drug delivery innovations (Wolf Greenfield, 2024).

5.3 Data Exclusivity and Regulatory Data Protection

Distinct from patent protection, regulatory data exclusivity — the statutory period during which a reference product's clinical trial data cannot be relied upon by generic or biosimilar applicants — provides a parallel intellectual property mechanism of particular relevance to advanced drug delivery technologies. In the EU, Directive 2001/83/EC provides eight years of data exclusivity plus two years of market exclusivity (the "8+2" regime), with a one-year extension for new indications. In the USA, the Hatch-Waxman Act and the Biologics Price Competition and Innovation Act provide analogous protections for conventional drugs and biologics respectively. For advanced drug delivery technologies that straddle the drug-device boundary, the application of data exclusivity regimes is legally ambiguous: it is not always clear whether the clinical data generated in support of a combination product application attracts drug-type or device-type data protection, with significant downstream competitive implications.

6. ARTIFICIAL INTELLIGENCE AND THE LEGAL GOVERNANCE OF DRUG DELIVERY

6.1 The Regulatory Landscape for AI-Integrated Drug Delivery

The integration of artificial intelligence into drug delivery technology represents the most jurisprudentially complex frontier in contemporary pharmaceutical law. AI permeates multiple dimensions of the drug delivery value chain: computational drug design, AI-driven clinical trial optimisation, machine learning-based pharmacokinetic modelling, adaptive dosing algorithms, and AI-enabled post-market pharmacovigilance. Each application raises distinct regulatory and legal questions.

In January 2025, the FDA published draft guidance titled "Considerations for the Use of Artificial Intelligence to Support Regulatory Decision-Making for Drug and Biological Products," providing recommendations for AI use in regulatory submissions regarding safety, effectiveness, and quality (FDA, 2025). This guidance establishes a risk-based credibility assessment framework emphasising validation of context-specific AI models. The FDA's Center for Drug Evaluation and Research (CDER) AI Council, established in 2024, provides intra-agency oversight and coordinates CDER activities around AI use (FDA, 2024). By fall 2024, the FDA had received over 500 submissions incorporating AI components across various stages of drug development, yet stakeholders continued to report insufficient regulatory guidance, particularly for AI applications in clinical phases (El Saadany, 2024).

The EMA adopted a more cautious and structured approach. Its "Reflection Paper on the Use of Artificial Intelligence in the Medicinal Product Lifecycle," published in October 2024, emphasises a risk-based approach for AI development, deployment, and performance monitoring. A landmark development occurred in March 2025, when the EMA issued its first qualification opinion on AI methodology, accepting clinical trial evidence generated by an AI tool for diagnosing inflammatory liver disease — a decision with potentially far-reaching precedential significance for future AI-based regulatory submissions (FDLI, 2025). The MHRA in the UK has pursued an explicitly principles-based regulatory approach through its "AI Airlock" regulatory sandbox (2024–2025), designed to permit controlled experimentation with AI-enabled medical devices while identifying regulatory challenges in real-world conditions (IntuitionLabs, 2025).

6.2 Liability Attribution in AI-Driven Drug Delivery

The liability implications of AI integration in drug delivery remain one of the most legally unresolved questions in contemporary pharmaceutical law. The fundamental doctrinal difficulty is the attribution problem: when an AI-driven drug delivery system causes patient harm — whether through algorithmic error, biased training data, or unexpected emergent behaviour — existing legal frameworks do not clearly identify the responsible party. Potential defendants include the AI algorithm developer, the hardware manufacturer, the pharmaceutical company that deployed the AI system, the healthcare institution, and the treating clinician.

The EU's AI Act (Regulation (EU) 2024/1689), which entered into full legal effect in 2024 with Member State penalty frameworks required by August 2025, classifies AI systems used in pharmaceutical and medical device contexts as "high risk" under Annex III (EU AI Act, 2024). High-risk AI systems are subject to mandatory conformity assessments, transparency obligations, human oversight requirements, and

accuracy and robustness standards. Notably, the EU AI Act operates alongside — not in place of — the MDR and GDPR, creating a layered compliance architecture. For AI-integrated drug delivery products that also constitute medical devices, manufacturers must simultaneously satisfy MDR conformity assessment requirements, AI Act conformity requirements, and GDPR data protection obligations — a tripartite compliance burden that legal scholars have criticised as disproportionately complex and potentially innovation-inhibiting (IntuitionLabs, 2025).

A particularly acute liability question arises in the context of adaptive or continuously learning AI systems embedded in drug delivery platforms. Where a drug delivery device incorporates a machine learning model that modifies dosing recommendations based on real-world patient data acquired post-approval, questions arise as to whether post-approval adaptive changes require new regulatory approval, and whether harms caused by post-approval algorithmic modifications are attributable to the original manufacturer or to the modifying algorithm. The FDA's December 2024 guidance on "Marketing Submission Recommendations for a Predetermined Change Control Plan for Artificial Intelligence-Enabled Device Software Functions" attempts to address this through a prospective change control mechanism, but the legal sufficiency of this approach for liability purposes remains untested (FDA, 2024).

6.3 Data Protection and Privacy in AI Drug Delivery

AI-integrated drug delivery systems are, by their nature, data-intensive. The legal frameworks governing health data — the Health Insurance Portability and Accountability Act (HIPAA) in the USA, the General Data Protection Regulation (GDPR) in the EU, and the UK GDPR post-Brexit — impose significant obligations on entities that collect, process, or share patient health data through AI-enabled delivery platforms. The Court of Justice of the EU's 2024 ruling on health data in the digital economy has further emphasised the sensitivity of health data processed through AI and digital health systems, adding legal complexity to the deployment of AI drug delivery technologies reliant on large-scale patient data (Hogan Lovells, 2024). In the USA, state-level health privacy laws — including Washington State's My Health My Data Act (effective March 2024) — grant consumers the right to access, delete, and withdraw consent for personal health data, with potential application to AI drug delivery systems that process health-related information (IntuitionLabs, 2025).

7. INTERNATIONAL REGULATORY HARMONISATION AND THE ICH FRAMEWORK

7.1 The Role and Evolution of ICH

International regulatory fragmentation — the state in which materially different legal requirements govern the same drug delivery technology in different jurisdictions — represents both a legal and a public health problem. It increases the cost of drug development (as parallel regulatory processes must be managed across jurisdictions), delays patient access, and creates arbitrage opportunities that may be exploited to the detriment of patients in regulatory systems with lower standards. The International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use (ICH) has been the principal international mechanism for addressing pharmaceutical regulatory fragmentation since its founding in 1990.

The ICH was established at a meeting in Brussels in April 1990, representing regulatory agencies and industry associations from Europe, Japan, and the United States, with the primary goal of harmonising diverse regulatory requirements to enable efficient development and registration of safe, effective, and high-quality medicines (Pharmaceutical Technology, 2024). Following a fundamental reformation completed in 2015, the ICH reconstituted itself as an independent, non-profit legal entity with an Assembly as its governing body, and expanded its membership to include regulatory authorities beyond the founding three regions. By 2024, the ICH comprised 14 national medicine or health authority members and 22 Observer organisations (Pharmaceutical Technology, 2024).

7.2 ICH Guidelines and Advanced Drug Delivery Technologies

ICH guidelines — organised into Quality (Q), Safety (S), Efficacy (E), and Multidisciplinary (M) categories — provide internationally recognised technical standards that, while formally non-binding, are widely adopted by regulatory authorities in ICH member jurisdictions. For advanced drug delivery technologies, several ICH guidelines are of particular legal relevance. ICH Q8 (Pharmaceutical Development), Q9 (Quality Risk Management), and Q10 (Pharmaceutical Quality System) collectively establish a framework for quality-by-design principles applicable to complex drug delivery systems, including nanomedicines. ICH E6 (Good Clinical Practice) governs the ethical and

scientific standards for clinical trials, with implications for the conduct of trials involving novel delivery platforms. ICH M7 (Assessment and Control of DNA Reactive Impurities) and M9 (Biopharmaceutics Classification System-based Biowaivers) address specific aspects of pharmaceutical quality relevant to advanced formulations.

Critically, no ICH guideline currently provides comprehensive, binding standards specifically tailored to nanotechnology-based drug delivery, AI-integrated pharmaceutical systems, or combination products. The ICH's M12 guideline on Drug Interaction Studies and the ongoing reflection on real-world evidence (RWE) in regulatory decision-making represent incremental steps toward harmonisation in adjacent areas, but the specific legal and technical challenges posed by the most advanced drug delivery technologies remain inadequately addressed at the international level.

7.3 The Limits of Harmonisation and Prospects for Reform

While ICH represents the most developed mechanism for international pharmaceutical regulatory harmonisation, it faces structural limitations as a legal instrument. ICH guidelines are not treaties; they create no binding international legal obligations on member jurisdictions. Adoption is voluntary, and the pace of guideline development — dependent on consensus among regulators, industry, and other stakeholders — has historically lagged the rate of technological innovation. For emerging drug delivery technologies, the practical consequence is that regulatory divergence persists across even the core ICH jurisdictions, requiring manufacturers to manage multiple regulatory pathways simultaneously and creating legal uncertainty regarding the applicable standards.

Bilateral regulatory cooperation agreements — such as the Mutual Recognition Agreements (MRAs) between the EU and USA on Good Manufacturing Practice (GMP) inspections — provide a supplementary mechanism for reducing regulatory duplication. Project Orbis, coordinated by the FDA and providing a framework for concurrent submission and review of oncology products among international partners including the MHRA, exemplifies how structured bilateral and multilateral cooperation can accelerate patient access to innovative products while maintaining regulatory rigour (ProPharma Group, 2024). The legal architecture supporting expanded international regulatory cooperation for advanced drug delivery technologies — particularly in the AI and nanomedicine domains — merits substantial further development.

8. CONCLUSIONS AND REFORM RECOMMENDATIONS

This paper has demonstrated that the legal frameworks governing advanced drug delivery technologies — across the USA, EU, and UK — are characterised by structural fragmentation, doctrinal strain, and a significant lag behind the pace of technological innovation. Four principal legal deficits emerge from the comparative analysis.

First, definitional and classificatory inadequacy: existing pharmaceutical and medical device laws lack the definitional infrastructure to accommodate novel drug delivery modalities, particularly nanomedicines and AI-integrated platforms. Regulatory misclassification or classificatory indeterminacy imposes legal uncertainty and compliance costs disproportionate to the risks involved.

Second, unresolved liability attribution: classical product liability doctrine — whether the strict liability regime applicable in the USA or the Directive-based framework operative in the EU — does not provide clear or predictable answers to the liability questions generated by multi-component, AI-integrated drug delivery systems. The revised EU Product Liability Directive (2024/2853/EU) represents a significant step toward addressing the digital and AI liability gap, but its interaction with pharmaceutical-specific liability regimes requires careful legal analysis as it is transposed into national law.

Third, intellectual property law misalignment: the incentive structures embedded in current patent and data exclusivity regimes are not optimally calibrated for advanced drug delivery innovation. Overly broad claim practices in nanomedicine patenting risk creating patent thickets that may impede subsequent innovation, while the Amgen v. Sanofi enablement decision signals a tightening of standards that may make it more difficult to obtain robust patent protection for genuinely innovative nanomedicine delivery systems.

Fourth, AI governance fragmentation: the absence of comprehensive, internationally harmonised legal standards for AI in drug development creates a patchwork of national regulatory requirements that may simultaneously impede innovation and leave regulatory gaps. The FDA, EMA, and MHRA are pursuing broadly convergent but institutionally distinct approaches, creating compliance complexity for globally operating pharmaceutical developers.

Against this analysis, this paper proposes the following reform directions. Legislatures and regulatory agencies should develop explicit, technology-specific

legal definitions for nanomedicines, AI-integrated drug delivery systems, and advanced combination products — definitions that are technology-neutral in their operative standards while providing sufficient legal clarity for regulatory classification. The ICH should be empowered — through the development of new multidisciplinary guidelines — to address the specific legal and technical challenges of AI-integrated drug delivery and nanomedicine, moving beyond the current guideline framework which was designed for conventional pharmaceutical modalities. International regulatory bodies should deepen bilateral and multilateral regulatory cooperation frameworks, building on Project Orbis and existing MRAs, to create streamlined legal pathways for advanced drug delivery technologies that meet internationally harmonised safety and efficacy standards. Finally, the legal frameworks governing AI liability in pharmaceutical contexts should be developed with explicit attention to the specific characteristics of drug delivery AI — including adaptive learning, data dependency, and the multi-party supply chain — rather than relying on the application of general AI liability rules that may not adequately reflect the pharmaceutical context.

The governance of advanced drug delivery technology is ultimately a question not only of regulatory science but of legal design. The law must be adaptive enough to accommodate innovation without abandoning its fundamental commitment to patient safety, equitable access, and accountability. Meeting this challenge will require sustained engagement between legal scholars, regulatory scientists, industry stakeholders, and patient advocates — across jurisdictions and across disciplines.

REFERENCES

Albuquerque de Almeida, M., Goettsch, W., & Costa, J. (2023). Different regulatory framework for medical devices and drugs in the European Union: Impact on clinical research and health technology assessments. *The International Journal of Health Planning and Management*, *38*(4), 870–887. https://doi.org/10.1002/hpm.3671

Celegence. (2024). *Regional differences of regulatory frameworks for pharma approvals*. https://www.celegence.com/regional-differences-regulatory-frameworks-pharma-approvals/

El Saadany, H. (2024). The future of AI regulation in drug development: A comparative analysis. *Journal of Law and the Biosciences*, *12*(2), lsaf028. https://doi.org/10.1093/jlb/lsaf028

Food and Drug Administration. (2014). *Guidance for industry: Considering whether an FDA-regulated product involves the application of nanotechnology*. U.S. Department of Health and Human Services.

Food and Drug Administration. (2024, December). *Marketing submission recommendations for a predetermined change control plan for artificial intelligence-enabled device software functions*. U.S. Department of Health and Human Services. https://www.fda.gov

Food and Drug Administration. (2025, January). *Considerations for the use of artificial intelligence to support regulatory decision-making for drug and biological products* [Draft Guidance]. U.S. Department of Health and Human Services. https://www.fda.gov

Food and Drug Law Institute. (2025). Regulating the use of AI in drug development: Legal challenges and compliance strategies. *FDLI Update*. https://www.fdli.org/2025/07/regulating-the-use-of-ai-in-drug-development-legal-challenges-and-compliance-strategies/

Frontiers in Medical Technology. (2025). Regulatory landscape of accelerated approval pathways for medical devices in the United States and the European Union. *Frontiers in Medical Technology*, *7*. https://doi.org/10.3389/fmedt.2025.1586070

Hogan Lovells. (2024). *Q2/2024 life science law update: Key developments for pharma and device companies in the EU*. https://www.hoganlovells.com/en/publications/life-science-law-update-key-developments-for-pharma-device-companies-in-eu_2

IntuitionLabs. (2025). *AI regulatory and legal frameworks for biopharma in 2025*. https://intuitionlabs.ai/articles/ai-biopharma-regulation-2025

Jayasheel, B. G. (2010). Regulatory requirements for marketing fixed dose combinations. *Perspectives in Clinical Research*, *1*(4), 120–122.

Kondal, A., Murali Krishna, G. V., & Bansal, D. (2024). Ensuring safety and efficacy in combination products: Regulatory challenges and best practices. *Frontiers in Medical*

Technology, *6*, 1377443. https://doi.org/10.3389/fmedt.2024.1377443

Ozaki, A., Saito, H., & Tanimoto, T. (2024). Comparison of regulatory approval system for medicines in emergency among Japan, the United States, the United Kingdom, Europe, and China. *PLOS ONE*. https://doi.org/10.1371/journal.pone.0309756

Pharmaceutical Technology. (2024, November). *How global drug regulations are evolving*. https://www.pharmaceutical-technology.com/sponsored/how-global-drug-regulations-are-evolving/

ProPharma Group. (2024, October). *European pharmaceutical regulations: 2024 review and 2025 trends to watch*. https://www.propharmagroup.com/thought-leadership/european-pharmaceutical-regulations-2024-review-trends-to-watch/

Singh, P., Paxton, E., & Auclair, D. (2025). Regulating the AI-enabled ecosystem for human therapeutics. *Communications Medicine*, *5*, 181. https://doi.org/10.1038/s43856-025-00910-x

Wasti, S., Lee, J., Kim, Y., Lee, D., & Kim, J. (2023). Ethical and legal challenges in nanomedical innovations: A scoping review. *Frontiers in Genetics*, *14*, 1163392. https://doi.org/10.3389/fgene.2023.1163392

Wolf Greenfield. (2024, January). *A look ahead: Key intellectual property legal topics in 2024*. https://wolfgreenfield.com/articles/a-look-ahead-key-intellectual-property-legal-topics-in-2024

Wolf Greenfield. (2025, January). *A look ahead: Key intellectual property legal developments in 2024 — and what to expect in 2025*. https://wolfgreenfield.com/articles/key-ip-developments-2024-and-what-to-expect-2025

Legal Instruments Cited

Amgen Inc. v. Sanofi, 598 U.S. 594 (2023).

PLIVA, Inc. v. Mensing, 564 U.S. 604 (2011).

Wyeth v. Levine, 555 U.S. 555 (2009).

Novartis AG v. Union of India, (2013) 6 SCC 1 (Supreme Court of India).

Biologics Price Competition and Innovation Act 2009 (USA), Pub. L. No. 111-148.

Council Directive 85/374/EEC of 25 July 1985 on the approximation of the laws, regulations and administrative provisions of the Member States concerning liability for defective products (Product Liability Directive), 1985 OJ (L 210) 29.

Directive 2001/83/EC of the European Parliament and of the Council of 6 November 2001 on the Community code relating to medicinal products for human use, 2001 OJ (L 311) 67.

Directive 2024/2853/EU of the European Parliament and of the Council on liability for defective products (Revised Product Liability Directive), 2024 OJ (L 2024/2853).

Hatch-Waxman Act (Drug Price Competition and Patent Term Restoration Act), Pub. L. No. 98-417 (1984) (USA).

Health Insurance Portability and Accountability Act 1996 (HIPAA), Pub. L. No. 104-191 (USA).

Inflation Reduction Act 2022, Pub. L. No. 117-169 (USA).

Patents Act 1970 (India), s 3(d).

Regulation (EC) No 726/2004 of the European Parliament and of the Council of 31 March 2004 laying down Community procedures for the authorisation and supervision of medicinal products, 2004 OJ (L 136) 1.

Regulation (EC) No 1394/2007 of the European Parliament and of the Council of 13 November 2007 on advanced therapy medicinal products, 2007 OJ (L 324) 121.

Regulation (EU) 2016/679 (General Data Protection Regulation), 2016 OJ (L 119) 1.

Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices (MDR), 2017 OJ (L 117) 1.

Regulation (EU) 2021/2282 of the European Parliament and of the Council of 15 December 2021 on health technology assessment (HTAR), 2021 OJ (L 458) 1.

Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence (AI Act), 2024 OJ (L 1689) 1.

21 CFR Part 3 (Product Jurisdiction) (USA).

21st Century Cures Act, Pub. L. No. 114-255 (2016) (USA).

Washington My Health My Data Act, SB 1155 (2023) (USA).