

Artificial Intelligence Enabled Pharmaceutical Formulation and Drug Delivery: An Integrated Review of Formulation Technologies, Phytopharmaceuticals, and Oncology Applications

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ABSTRACT:

Recent advances in pharmaceutical sciences demonstrate a strong convergence of formulation technology, phytopharmaceutical development, nanomedicine, and artificial intelligence (AI). This review integrates published research spanning taste masking technologies, quality-by-design (QbD)-based formulations, 3D printing, nanostructured drug carriers, phytoconstituent extraction, and AI-driven drug delivery and oncology applications. Emphasis is placed on how AI and data-driven approaches are reshaping formulation development, personalized medicine, cancer therapeutics, and healthcare decision-making. The paper also highlights recent trends, patents, and future prospects in intelligent pharmaceutical product development.

Keywords: *Artificial intelligence, Drug delivery systems, Quality by Design, Phytopharmaceuticals, Nanomedicine, Oncology, Personalized medicine*

1. INTRODUCTION:

Pharmaceutical research has evolved from empirical formulation practices to systematic, data-driven strategies integrating Quality by Design (QbD), computational modeling, and artificial intelligence [1]. Modern challenges such as poor drug palatability, low bioavailability, multidrug resistance in cancer, and patient-specific therapeutic needs demand innovative solutions [6,7,12]. The body of work reviewed herein reflects these advancements across formulation science, phytochemistry, nanotechnology, and AI-enabled healthcare as shown in Figure 1[4].

2. Taste Masking and Patient-Centric Formulation Design:

Taste masking remains critical for pediatric and geriatric formulations. Conventional approaches such as coating, complexation, and microencapsulation have been supplemented by novel technologies including ion-exchange resins, solid lipid carriers, and polymeric matrices. Recent reviews highlight patent trends demonstrating increasing industrial interest in patient-centric dosage forms [2]. AI-assisted excipient selection and sensory prediction models are emerging as promising tools to accelerate taste-masked formulation development [16,18].

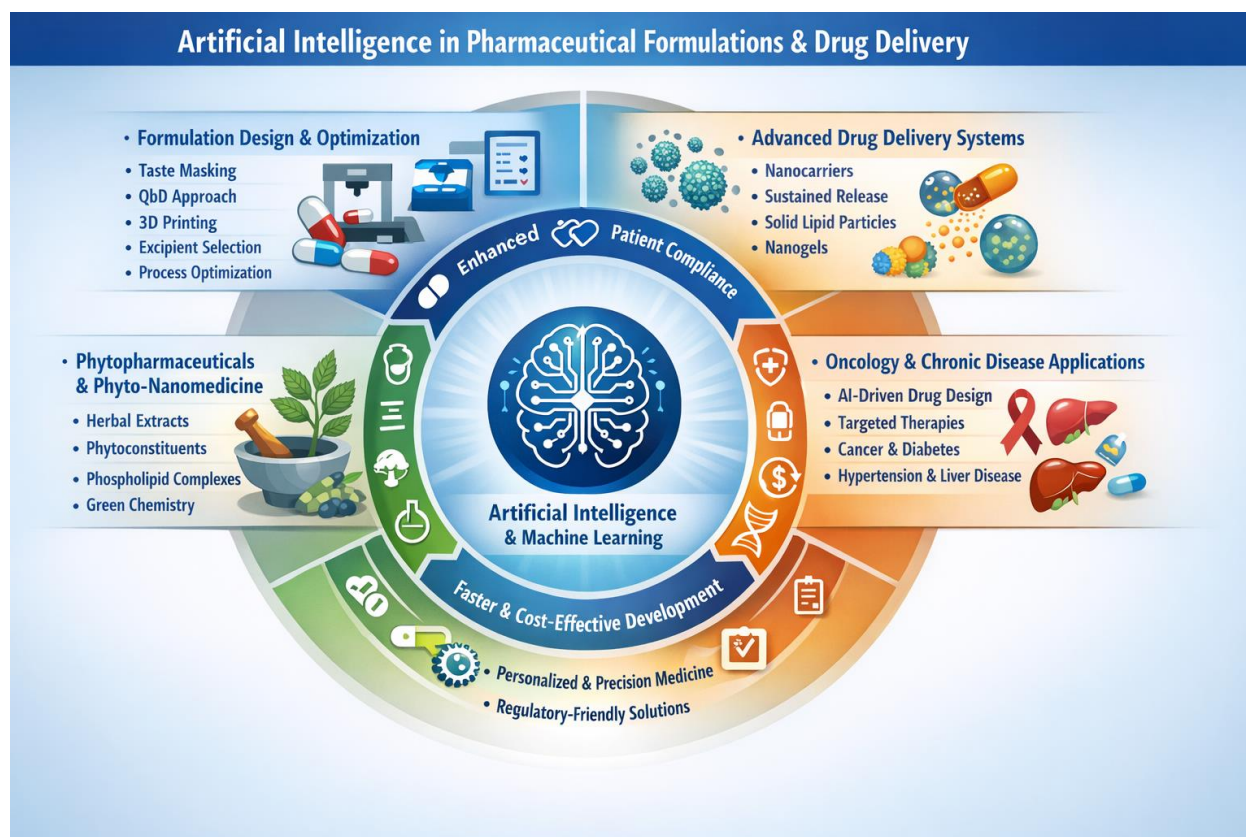


Figure 1: Artificial Intelligence–Enabled Pharmaceutical Formulation and Drug Delivery

3. Quality by Design (QbD) in Modern Dosage Forms:

QbD has become a regulatory-accepted framework for robust pharmaceutical development. Applications include:

- Sublingual and sustained-release tablets [5,9]
- Phospholipid complexes of herbal drugs (e.g., *Terminalia arjuna*) [3]
- Delayed-release and matrix-based oral formulations [17]
- 3D printed tablets for personalized medicine [8]

Design space optimization using statistical tools is increasingly complemented by machine learning algorithms that predict critical quality attributes and reduce experimental burden [16].

4. 3D Printing and Personalized Medicine:

3D printing technology enables on-demand fabrication of personalized dosage forms with controlled release profiles. Studies on pregabalin tablets demonstrate the feasibility of QbD-driven 3D printing to tailor drug release for neuropathic pain management. Integration of AI with 3D printing workflows offers real-time process control and customization based on patient-specific data.

5. Phytopharmaceuticals and Phyto-Nanomedicine:

Renewed interest in herbal medicines has driven innovation in extraction, identification, and formulation of phytoconstituents [11]. Advanced analytical and green chemistry approaches improve reproducibility and sustainability [29]. Phyto-nanomedicine, including nanogels and phospholipid complexes, enhances solubility, stability, and therapeutic efficacy in inflammation, wound healing, and dermatological conditions such as psoriasis [13,19,22].

6. Nanostructured Drug Delivery Systems:

Nanostructured carriers such as solid lipid microparticles, nanogels, and nanoemulsions offer targeted and sustained drug delivery [10]. Applications extend to antiviral therapy, antimicrobial delivery, and cancer management. In neuroendocrine cancer and other malignancies, nanocarriers improve therapeutic index and reduce systemic toxicity [20,21]

7. Artificial Intelligence in Drug Delivery and Pharmaceutical R&D:

AI and machine learning are transforming pharmaceutical research through:

- Predictive modeling of drug–excipient interactions [16]
- Optimization of formulation and process parameters [18]
- *In silico* drug design and target identification [28]

- Clinical decision support and outcome prediction [29]

AI-driven studies in oncology, including HER2-resistant breast cancer and immunotherapy response prediction, demonstrate the power of computational approaches in addressing complex biological systems [14,31].

8. AI in Oncology and Chronic Disease Management:

Beyond formulation science, AI plays a vital role in cancer prognosis, immunotherapy optimization, and management of chronic diseases such as diabetes, hypertension, and liver disorders [23-25]. Reviews on monoclonal antibodies, EGFR inhibitors, and dietary interventions highlight multidisciplinary strategies combining pharmacology, biotechnology, and digital health [27,30].

9. Healthcare Practice, Safety, and Human Factors:

Systematic reviews on medication errors and oncology nursing knowledge underscore the importance of education, clinical decision support, and AI-assisted risk reduction in healthcare systems [15,26]. Intelligent tools can enhance patient safety and optimize therapeutic outcomes.

10. Patents, Recent Trends, and Future Perspectives:

Patent analysis reveals growing innovation in taste masking, AI-based formulation design, and nanotechnology-enabled drug delivery. Future research is expected to focus on:[32-35]

- Explainable AI for regulatory acceptance
- Digital twins for pharmaceutical manufacturing
- Personalized, on-demand medicines
- Sustainable and green formulation technologies

11. CONCLUSION:

The integration of artificial intelligence with pharmaceutical formulation, phytomedicine, and nanotechnology represents a paradigm shift toward intelligent, patient-centric drug development. The collective research reviewed demonstrates significant progress while highlighting the need for interdisciplinary collaboration to translate these innovations into clinically and commercially successful products.

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