Global Research Trends in Artificial Intelligence and Machine Learning for Drug Delivery Technology: A Bibliometric and Science Mapping Analysis (2015–2026)

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Abstract

Artificial Intelligence (AI) and Machine Learning (ML) have emerged as transformative technologies in pharmaceutical research, significantly influencing the design, optimization, and personalization of drug delivery systems. AI-assisted approaches are increasingly applied to predict drug release kinetics, optimize formulation parameters, identify novel drug carriers, enhance therapeutic efficacy, and accelerate pharmaceutical product development. Despite the rapid growth of this interdisciplinary research area, a comprehensive understanding of its global scientific evolution, collaborative networks, and emerging research themes remains limited.

The present study aims to systematically map the global research landscape of AI and ML applications in drug delivery technology through a bibliometric analysis of publications published between **2015 and 2026**. Bibliographic records will be retrieved from the **Scopus** database using a predefined search strategy, screened according to established inclusion and exclusion criteria, and analyzed using **Bibliometrix (R-package)** and **VOSviewer**. The study will evaluate annual publication trends, citation performance, influential authors, institutions, countries, journals, collaborative networks, keyword co-occurrence, thematic evolution, and emerging research hotspots.

The findings are expected to provide a comprehensive overview of the intellectual structure and development of AI-driven drug delivery research, identify influential contributors and collaborative patterns, and highlight promising directions for future investigations. The study also seeks to offer practical insights for researchers, pharmaceutical scientists, healthcare professionals, policymakers, and industry stakeholders by identifying technological innovations that can enhance drug development processes and improve patient-centric therapeutic outcomes.

By integrating bibliometric techniques with science mapping, this study contributes to the growing body of knowledge on AI-enabled pharmaceutical technologies and provides a strategic research agenda for advancing intelligent drug delivery systems.

Keywords: Artificial Intelligence; Machine Learning; Drug Delivery Technology; Bibliometric Analysis; Science Mapping; Pharmaceutical Technology.

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1. Introduction

The pharmaceutical industry has experienced a remarkable transformation over the last decade due to rapid advances in artificial intelligence (AI), machine learning (ML), big data analytics, and computational modeling. These technological developments are reshaping every stage of pharmaceutical research and development, from drug discovery and formulation design to manufacturing, quality control, regulatory compliance, and personalized medicine. Among these advancements, the integration of AI and ML into drug delivery technology has emerged as one of the most promising innovations, offering new opportunities to improve therapeutic efficacy, optimize formulation development, reduce research costs, and accelerate product commercialization.

Drug delivery technology plays a pivotal role in modern healthcare by ensuring that therapeutic agents are delivered to the desired site of action at the appropriate rate, dosage, and duration. Conventional drug delivery systems often encounter challenges such as poor bioavailability, low drug stability, systemic toxicity, frequent dosing requirements, and inadequate patient adherence. To overcome these limitations, researchers have developed advanced drug delivery systems, including nanoparticles, liposomes, polymeric carriers, hydrogels, microneedles, implantable devices, and stimuli-responsive delivery platforms. Although these technologies have significantly improved treatment outcomes, their development involves complex formulation processes that require extensive experimentation, optimization, and validation.

Artificial intelligence and machine learning have demonstrated considerable potential in addressing these complexities. AI refers to computational systems capable of performing tasks that traditionally require human intelligence, including pattern recognition, decision-making, reasoning, and predictive analysis. Machine learning, a major branch of AI, enables computer algorithms to learn from historical data and improve prediction accuracy without explicit programming. Within pharmaceutical sciences, AI and ML techniques facilitate rapid analysis of large datasets, optimization of formulation variables, prediction of physicochemical properties, simulation of drug release behavior, identification of optimal excipient combinations, and modeling of pharmacokinetic and pharmacodynamic responses.

The convergence of AI and drug delivery technology has accelerated innovation across multiple domains. Machine learning algorithms are increasingly used to predict drug solubility, permeability, dissolution profiles, encapsulation efficiency, particle size distribution, and controlled-release characteristics. Deep learning approaches have enhanced image analysis for nanoparticle characterization, while reinforcement learning and optimization algorithms support formulation development by identifying optimal process parameters with reduced experimental effort. Furthermore, AI-driven predictive models assist researchers in selecting suitable drug carriers, minimizing formulation failures, and shortening development timelines.

The emergence of precision medicine has further increased the importance of intelligent drug delivery systems. Personalized medicine aims to tailor therapeutic interventions according to individual patient characteristics, including genetic variations, disease profiles, physiological conditions, and treatment responses. AI-powered predictive analytics can integrate clinical, genomic, and pharmacological information to support individualized drug delivery strategies, thereby improving treatment efficacy while minimizing adverse effects. As healthcare systems increasingly embrace digital technologies, AI-enabled drug delivery platforms are expected to become an integral component of next-generation pharmaceutical care.

In addition to formulation optimization, AI contributes significantly to pharmaceutical manufacturing and quality management. Advanced machine learning algorithms facilitate real-time monitoring of manufacturing processes, predictive maintenance of production equipment, quality-by-design implementation, process analytical technology, and automated defect detection. These capabilities enhance manufacturing efficiency, reduce production costs, improve regulatory compliance, and strengthen pharmaceutical supply chain resilience. Consequently, AI has become an essential component of the digital transformation currently taking place within the pharmaceutical industry.

The COVID-19 pandemic further accelerated interest in AI-enabled pharmaceutical research and drug delivery technologies. The urgent need for rapid vaccine development, optimized therapeutic delivery, efficient cold-chain logistics, and intelligent healthcare systems highlighted the value of computational technologies in responding to global public health emergencies. Since 2020, the scientific community has witnessed a substantial increase in publications related to AI-assisted pharmaceutical research, smart drug delivery systems, and digital healthcare innovations. This accelerated research activity has created an extensive body of scientific literature spanning multiple disciplines, including pharmaceutical sciences, biomedical engineering, computer science, nanotechnology, biotechnology, and healthcare management.

As scientific output expands rapidly, researchers face increasing challenges in identifying influential publications, emerging themes, collaborative networks, and future research opportunities. Traditional narrative reviews provide valuable conceptual insights but are often limited by subjective article selection and lack comprehensive quantitative evaluation of the scientific landscape. Bibliometric analysis has therefore emerged as an effective research methodology for systematically evaluating scientific literature through quantitative techniques. Bibliometric methods enable researchers to assess publication productivity, citation performance, author collaboration, institutional contributions, country-level research output, keyword evolution, thematic development, and intellectual structures within a specific research field.

Science mapping techniques implemented through software such as Bibliometrix and VOSviewer have become widely accepted tools for visualizing scientific knowledge. These tools generate collaboration networks, keyword co-occurrence maps, thematic evolution diagrams, citation networks, bibliographic coupling, and co-citation analyses that facilitate deeper understanding of research dynamics. Such analyses help identify influential authors, leading institutions, highly cited publications, emerging technologies, and potential research gaps that may not be readily apparent through conventional literature reviews.

Although several review articles have discussed the applications of artificial intelligence in pharmaceutical sciences, existing studies primarily focus on specific aspects such as drug discovery, formulation development, precision medicine, or computational chemistry. Comprehensive bibliometric investigations specifically examining the evolution of AI and machine learning within drug delivery technology remain relatively limited. Moreover, many existing reviews do not comprehensively evaluate global collaboration patterns, thematic evolution, emerging research hotspots, or the intellectual structure of this rapidly growing interdisciplinary domain. Consequently, researchers, policymakers, funding agencies, and pharmaceutical industries lack a holistic understanding of the current research landscape and future development directions.

Given the rapid expansion of AI applications in drug delivery technology, there is a growing need to systematically evaluate the scientific literature published over the past decade. A comprehensive bibliometric assessment can provide evidence regarding publication growth, influential journals, leading countries, productive institutions, collaborative research networks, frequently investigated topics, and emerging technological trends. Such information is valuable for identifying research opportunities, promoting interdisciplinary collaboration, guiding funding priorities, and supporting strategic decision-making within pharmaceutical research and healthcare innovation.

The present study addresses this research gap by conducting a comprehensive bibliometric analysis of global scientific publications on artificial intelligence and machine learning in drug delivery technology published between 2015 and 2026. Using bibliographic data retrieved from the Scopus database, the study applies advanced bibliometric and science mapping techniques through Bibliometrix and VOSviewer to evaluate the intellectual, conceptual, and social structures of the research field. The analysis focuses on publication growth, citation impact, influential authors, productive institutions, international collaboration, leading journals, keyword co-occurrence, thematic evolution, and emerging research frontiers.

Unlike conventional literature reviews, this study combines quantitative bibliometric indicators with visual science mapping techniques to provide a holistic understanding of the evolution of AI-enabled drug delivery research. The findings are expected to support researchers in identifying promising research directions, assist pharmaceutical industries in recognizing emerging technological opportunities, and help policymakers formulate evidence-based strategies for promoting innovation in pharmaceutical sciences.

Specifically, this study seeks to answer the following research questions:

1. How has global scientific publication on artificial intelligence and machine learning in drug delivery technology evolved between 2015 and 2026?
2. Which countries, institutions, authors, and journals have made the most significant contributions to this research domain?
3. What are the major collaborative networks within AI-enabled drug delivery research?

4. Which keywords, research themes, and technological topics dominate the current scientific landscape?
5. How have research themes evolved over time, and what emerging areas are likely to shape future investigations?
6. What strategic research directions can support future development of intelligent drug delivery technologies?

The contributions of this study are threefold. First, it provides a comprehensive quantitative overview of the global scientific landscape of AI and machine learning applications in drug delivery technology. Second, it identifies influential contributors, collaborative patterns, and emerging thematic areas using established bibliometric techniques. Third, it proposes a future research agenda that may guide researchers, healthcare professionals, pharmaceutical industries, funding organizations, and policymakers in advancing intelligent drug delivery systems capable of improving therapeutic effectiveness, accelerating pharmaceutical innovation, and supporting personalized healthcare.

By systematically mapping the scientific development of this rapidly evolving interdisciplinary field, the present study contributes to both the pharmaceutical and management literature, offering valuable insights into research productivity, innovation patterns, knowledge diffusion, and future technological opportunities in AI-driven drug delivery technology

2. Literature Review

1. The paper by **Aria and Cuccurullo (2017)** is considered one of the foundational studies in bibliometric research because it introduced **Bibliometrix**, an open-source R package that integrates the complete bibliometric workflow into a single platform. The authors argue that the rapid growth of scientific publications makes traditional literature reviews increasingly difficult, and researchers need standardized, transparent, and reproducible methods to analyze large bodies of literature. They propose Bibliometrix as a flexible, open-source alternative capable of performing comprehensive science mapping and bibliometric analyses.
2. Aundhia et al. (2025) examine the transformative impact of Artificial Intelligence (AI) on drug development and drug delivery by highlighting its applications in drug discovery, formulation optimization, targeted drug delivery, and personalized medicine. The authors emphasize that AI-driven techniques, particularly machine learning and deep learning, improve prediction accuracy, reduce research time and development costs, and enhance the design of advanced drug delivery systems such as nanoparticles and liposomes. The review concludes that although challenges related to data quality, regulatory approval, and model interpretability remain, AI has significant potential to revolutionize pharmaceutical research and enable more efficient, precise, and patient-centered drug delivery strategies.
3. Blanco-González et al. (2023) discuss the growing role of Artificial Intelligence (AI) in drug discovery, emphasizing its ability to accelerate target identification, virtual screening, lead optimization, and prediction of drug properties. The authors highlight that AI can significantly reduce the time and cost of drug development while improving decision-making. They also identify key challenges, including data quality, model interpretability, regulatory concerns, and the need for interdisciplinary collaboration, concluding that AI will play a pivotal role in advancing future pharmaceutical innovation.
4. Callon et al. (1991) introduced **co-word analysis** as a bibliometric technique to examine the conceptual structure and evolution of scientific research by analyzing the co-occurrence of keywords. The study demonstrates that co-word analysis effectively identifies research themes, emerging topics, and relationships between basic and applied research, making it a fundamental method for mapping knowledge domains and tracking scientific developments over time.
5. Chen et al. (2021) explore the application of Artificial Intelligence (AI) in drug development using real-world data from electronic health records, clinical databases, and patient registries. The authors highlight that AI enhances drug discovery, predicts treatment outcomes, improves clinical trial design, and supports post-marketing surveillance. The study concludes that integrating AI with real-world data can accelerate drug development while enabling more evidence-based and patient-centered healthcare decisions.
6. Cobo et al. (2011) provide a comprehensive review and comparative analysis of major science mapping software tools used in bibliometric research. The study evaluates the capabilities, strengths, and limitations of

different tools for analyzing citation networks, co-authorship patterns, keyword co-occurrence, and thematic evolution. The authors conclude that science mapping tools are essential for visualizing the intellectual structure and development of research fields and recommend selecting tools based on the specific objectives of a bibliometric study.

7. Deng et al. (2022) provide a comprehensive review of Artificial Intelligence (AI) applications in drug discovery, highlighting its role in target identification, virtual screening, lead optimization, and prediction of drug efficacy and toxicity. The authors conclude that AI techniques, particularly machine learning and deep learning, significantly accelerate drug discovery, reduce development costs, and improve decision-making, while emphasizing the need for high-quality data and interpretable models to maximize their effectiveness.
8. Donthu et al. (2021) provide a practical framework for conducting bibliometric analysis by outlining systematic procedures for data collection, performance analysis, and science mapping. The authors emphasize that bibliometric techniques help researchers identify publication trends, influential authors, collaboration networks, and emerging research themes, making them valuable for synthesizing and evaluating the development of scientific knowledge across disciplines.
9. Ellegaard and Wallin (2015) examine the significance of bibliometric analysis as a method for evaluating scholarly research output and scientific impact. The authors conclude that bibliometric indicators, such as publication and citation analyses, provide valuable insights into research productivity, influence, and collaboration patterns, while emphasizing that these metrics should be interpreted carefully alongside qualitative assessments of research quality.
10. Ekins et al. (2019) demonstrate how machine learning can support the entire drug discovery and development pipeline, from target identification and compound screening to clinical development and post-market evaluation. The authors argue that machine learning enhances prediction accuracy, reduces development time and costs, and improves decision-making, making it a transformative technology for modern pharmaceutical research and development.
11. Esteva et al. (2019) provide an overview of deep learning applications in healthcare, highlighting its potential to improve disease diagnosis, medical imaging, predictive analytics, and personalized treatment. The authors emphasize that deep learning can significantly enhance clinical decision-making and healthcare outcomes, while also addressing challenges related to data quality, model interpretability, and ethical implementation.
12. Garfield (2006) explains the origin, development, and significance of the Journal Impact Factor (JIF) as a measure for evaluating the influence of scientific journals. The paper highlights that while the impact factor is a useful indicator of journal visibility and citation performance, it should be used cautiously and not as the sole measure of research quality or the merit of individual articles or researchers.
13. Gholap et al. (2024) review recent advances in Artificial Intelligence (AI) for drug development and drug delivery, emphasizing its applications in formulation optimization, prediction of drug release behavior, nanocarrier design, and personalized medicine. The authors conclude that AI enhances the efficiency, accuracy, and speed of pharmaceutical research while enabling the development of smarter and more targeted drug delivery systems, despite challenges related to data quality, model validation, and regulatory acceptance.
14. Goodfellow, Bengio, and Courville (2016) provide a comprehensive foundation for deep learning, covering its theoretical concepts, algorithms, and practical applications across diverse fields. The book explains how deep neural networks can learn complex patterns from large datasets and highlights their applications in image recognition, natural language processing, healthcare, and drug discovery. It is regarded as one of the most authoritative references for understanding the principles and implementation of deep learning techniques.
15. Hajkowicz et al. (2023) analyze the global adoption of Artificial Intelligence (AI) across scientific disciplines using bibliometric methods. The study reveals a rapid increase in AI-related publications and highlights expanding interdisciplinary collaboration, with healthcare, engineering, and life sciences emerging as major areas of AI application. The authors conclude that AI is becoming a key driver

of scientific innovation and knowledge creation across diverse research domains.

16. He, Leanse, and Feng (2021) review the applications of Artificial Intelligence (AI) and Machine Learning (ML) in developing advanced drug delivery systems for infectious diseases. The authors highlight that AI-assisted approaches improve formulation design, optimize targeted drug delivery, predict therapeutic outcomes, and accelerate the development of effective treatment strategies. The study concludes that AI and ML have significant potential to enhance the precision, efficiency, and effectiveness of drug delivery for infectious disease management.
17. He, Feng, and Leanse (2024) present a bibliometric analysis and literature review of Artificial Intelligence (AI) in drug discovery, highlighting rapid growth in research output, increasing international collaboration, and emerging themes such as machine learning, deep learning, and precision medicine. The study identifies AI as a transformative technology that is accelerating drug discovery while emphasizing the importance of interdisciplinary collaboration and continued innovation in pharmaceutical research.
18. Jordan and Mitchell (2015) provide a comprehensive overview of the evolution, trends, and future prospects of machine learning, highlighting its growing impact across scientific and industrial domains. The authors emphasize that machine learning enables computers to learn from data, improve predictive accuracy, and solve complex problems, making it a foundational technology for applications such as healthcare, drug discovery, artificial intelligence, and data-driven decision-making. They conclude that continued advances in algorithms, data availability, and computational power will further expand the influence of machine learning across disciplines.
19. Jumper et al. (2021) introduce AlphaFold, an Artificial Intelligence-based system that accurately predicts three-dimensional protein structures from amino acid sequences. The study demonstrates that AlphaFold achieves near-experimental accuracy, significantly accelerating biological research, drug discovery, and structure-based drug design. The authors conclude that this breakthrough has the potential to transform biomedical research by enabling faster identification of therapeutic targets and supporting the development of new medicines.
20. Krittanawong et al. (2017) review the applications of deep learning in cardiovascular medicine, highlighting its ability to improve disease diagnosis, risk prediction, medical imaging analysis, and personalized treatment. The authors conclude that deep learning has the potential to enhance clinical decision-making and patient outcomes, while emphasizing the need for high-quality data, model validation, and ethical implementation in healthcare.
21. LeCun, Bengio, and Hinton (2015) provide a landmark review of deep learning, explaining how multi-layer neural networks have revolutionized fields such as computer vision, speech recognition, natural language processing, and healthcare. The authors highlight that deep learning automatically learns complex patterns from large datasets, significantly improving prediction accuracy and decision-making. The paper concludes that deep learning is a foundational technology driving advances in artificial intelligence, including applications in drug discovery and biomedical research.
22. Mak and Pichika (2019) review the current applications of Artificial Intelligence (AI) in drug development, emphasizing its role in target identification, lead optimization, clinical trial design, and prediction of drug safety and efficacy. The authors conclude that AI has the potential to significantly reduce the time, cost, and complexity of drug development while improving the efficiency and success rate of pharmaceutical research, although challenges related to data quality and regulatory acceptance remain.
23. Mozafari, Dehshahri, and Azadi (2023) examine the knowledge gaps in the development of cell-based drug delivery systems and discuss how Artificial Intelligence (AI) can address these challenges. The authors highlight that AI can optimize carrier design, predict biological interactions, and improve the efficiency and safety of cell-based drug delivery. The study concludes that integrating AI with cell-based therapies has the potential to advance personalized and targeted drug delivery, while further research is needed to overcome technical and regulatory challenges.
24. Paul et al. (2021) review the applications of Artificial Intelligence (AI) across the drug discovery and development process,

including target identification, lead optimization, drug repurposing, clinical trial design, and personalized medicine. The authors conclude that AI enhances the speed, accuracy, and cost-effectiveness of pharmaceutical research while improving decision-making, although challenges related to data quality, validation, and regulatory compliance remain significant.

25. Qu et al. (2026) present a bibliometric analysis and review of Artificial Intelligence (AI) research in drug discovery, identifying key publication trends, leading contributors, collaboration networks, and emerging research hotspots. The study highlights rapid growth in AI-driven drug discovery, with machine learning, deep learning, drug repurposing, and precision medicine emerging as dominant themes. The authors conclude that AI will continue to shape pharmaceutical innovation through increased interdisciplinary collaboration and technological advancements.
26. Schork (2019) discusses the transformative role of Artificial Intelligence (AI) in advancing personalized medicine by integrating genomic, clinical, and patient-specific data to support individualized treatment decisions. The author highlights that AI enhances disease prediction, drug selection, and therapeutic optimization, ultimately improving clinical outcomes. The chapter concludes that AI is a key enabler of precision healthcare, although challenges related to data privacy, validation, and clinical implementation must be addressed.
27. Small (1973) introduced co-citation analysis as a bibliometric method for measuring the intellectual relationship between scientific publications based on how frequently they are cited together. The study demonstrates that co-citation analysis effectively identifies influential works, research clusters, and the intellectual structure of a scientific field, making it one of the foundational techniques in bibliometric and science mapping research.
28. Topol (2019) discusses how the integration of Artificial Intelligence (AI) with human clinical expertise can transform healthcare into high-performance medicine. The paper highlights that AI enhances disease diagnosis, treatment planning, drug development, and personalized medicine by analyzing large-scale medical data with greater accuracy and efficiency. The author concludes that AI should complement, rather than replace, healthcare professionals, enabling more precise, patient-centered, and data-driven medical care while addressing challenges related to ethics, privacy, and clinical implementation.
29. Van Eck and Waltman (2010) introduce VOSviewer, a software tool designed for constructing and visualizing bibliometric networks, including co-authorship, co-citation, bibliographic coupling, and keyword co-occurrence analyses. The authors demonstrate that VOSviewer provides intuitive visualizations and clustering techniques that help researchers explore the intellectual structure, collaboration patterns, and thematic evolution of scientific fields, making it one of the most widely used tools in bibliometric research.
30. Van Raan (2019) explains the fundamental principles and applications of bibliometrics for evaluating scientific research performance and knowledge development. The author discusses key bibliometric indicators, including publication output, citation impact, collaboration patterns, and research productivity, emphasizing that bibliometric analysis is a valuable tool for assessing scientific influence, identifying research trends, and supporting evidence-based research policy and decision-making.
31. Vamathevan et al. (2019) review the applications of machine learning across the drug discovery and development pipeline, including target identification, biomarker discovery, lead optimization, clinical trial design, and prediction of drug safety and efficacy. The authors conclude that machine learning can significantly accelerate pharmaceutical research, improve decision-making, and reduce development costs, while emphasizing the importance of high-quality data, interdisciplinary collaboration, and regulatory acceptance for successful implementation.
32. Vora et al. (2023) review the applications of Artificial Intelligence (AI) in pharmaceutical technology and drug delivery design, highlighting its role in formulation optimization, prediction of drug release, nanocarrier development, and personalized medicine. The authors conclude that AI enhances the efficiency, precision, and speed of pharmaceutical product development while supporting the design of advanced, patient-centric drug delivery systems, despite ongoing

challenges related to data quality and regulatory implementation.

33. Wang et al. (2026) conduct a bibliometric and visual analysis of research on drug delivery for glioma, identifying publication trends, leading authors, countries, institutions, collaboration networks, and emerging research themes. The study highlights the growing focus on nanotechnology, targeted drug delivery, and blood–brain barrier strategies, concluding that bibliometric analysis effectively reveals the evolution of the field and provides guidance for future research directions.
34. Wu et al. (2026) provide a comprehensive review of the evolution of Artificial Intelligence (AI) in drug delivery, covering past developments, current applications, and future directions. The authors highlight AI's contributions to formulation optimization, intelligent nanocarrier design, targeted drug delivery, and personalized therapeutics. The study concludes that AI is poised to revolutionize drug delivery by enabling smarter, more efficient, and patient-specific therapeutic systems, while emphasizing the need to address challenges related to data quality, regulatory approval, and clinical translation.
35. Zupic and Čater (2015) provide a comprehensive overview of bibliometric methods used in management and organization research, outlining techniques such as citation analysis, co-citation analysis, bibliographic coupling, co-word analysis, and co-authorship analysis. The authors emphasize that bibliometric methods offer a systematic and objective approach to mapping knowledge structures, identifying influential studies, and uncovering emerging research trends, making them valuable tools for literature reviews and research evaluation.
36. Zhang (2021) provides a comprehensive review of recent Artificial Intelligence (AI) applications in drug design, emphasizing its role in target identification, virtual screening, lead optimization, and prediction of drug properties. The study concludes that AI significantly accelerates the drug design process, improves prediction accuracy, and reduces development costs, making it a powerful tool for advancing pharmaceutical research and precision medicine.

2.1 Evolution of Artificial Intelligence in Pharmaceutical Sciences

Artificial Intelligence (AI) has become one of the most transformative technologies in pharmaceutical sciences. Initially, AI applications were confined to computational chemistry and molecular modeling, where algorithms supported virtual screening and quantitative structure–activity relationship (QSAR) analysis. Advances in computational power, cloud computing, and large biomedical datasets have expanded AI applications throughout the pharmaceutical product life cycle, including drug discovery, formulation optimization, manufacturing, quality assurance, clinical decision support, pharmacovigilance, and personalized medicine.

Machine Learning (ML), Deep Learning (DL), Natural Language Processing (NLP), Reinforcement Learning (RL), and Explainable Artificial Intelligence (XAI) are now widely adopted to solve complex pharmaceutical problems. These techniques enable researchers to analyze large volumes of structured and unstructured biomedical data, recognize hidden patterns, optimize experimental designs, and generate predictive models that support evidence-based decision-making. Recent reviews indicate that research output has accelerated substantially since 2017, reflecting growing academic and industrial interest in AI-driven pharmaceutical innovation. Recent bibliometric studies also highlight the United States and China as major contributors to this rapidly expanding research domain.

2.2 Artificial Intelligence in Drug Delivery Technology

Drug delivery technology seeks to deliver therapeutic agents to specific target sites while maximizing efficacy and minimizing toxicity. Conventional delivery systems frequently experience challenges such as low bioavailability, poor aqueous solubility, uncontrolled release, instability, and limited patient adherence. Advanced delivery systems—including nanoparticles, liposomes, dendrimers, polymeric carriers, hydrogels, microneedles, exosomes, and implantable devices—have addressed many of these issues but require complex formulation and optimization.

AI has emerged as an effective solution for handling this complexity. Machine learning algorithms can evaluate relationships between formulation variables and pharmaceutical performance, allowing researchers to predict encapsulation efficiency, particle size, dissolution profiles, drug release kinetics, stability, permeability, and bioavailability. Consequently, AI reduces experimental workload while improving formulation accuracy and development speed.

Recent studies demonstrate that AI supports optimization of nanoparticle formulations, targeted drug delivery, personalized dosing strategies, intelligent biomaterial selection, and computational simulation of drug transport mechanisms. Integration of AI with nanotechnology has further accelerated development of precision drug delivery systems capable of responding to physiological or environmental stimuli. Comprehensive reviews also identify AI as an enabling technology across drug formulation, smart delivery networks, and pharmaceutical product development.

2.3 Machine Learning Algorithms Used in Drug Delivery Research

Machine learning provides a diverse collection of computational methods suitable for pharmaceutical applications. Supervised learning algorithms, including Random Forest, Support Vector Machine (SVM), Artificial Neural Networks (ANN), Gradient Boosting, and Extreme Gradient Boosting (XGBoost), are widely used for predicting formulation performance and pharmaceutical properties. Unsupervised learning techniques facilitate clustering of compounds and identification of hidden relationships within pharmaceutical datasets.

Deep learning architectures such as Convolutional Neural Networks (CNNs) and Graph Neural Networks (GNNs) have improved molecular representation, image-based nanoparticle characterization, and prediction of complex biological interactions. Reinforcement learning has shown promise for sequential optimization problems, including dosage adjustment and adaptive formulation design. Bayesian optimization has also gained popularity because it minimizes laboratory experimentation while identifying optimal formulation parameters.

The growing availability of pharmaceutical big data has enabled these algorithms to achieve higher predictive accuracy than many conventional statistical approaches. Nevertheless, model interpretability, data quality, reproducibility, and external validation remain important challenges that require further investigation.

2.4 AI-Driven Pharmaceutical Innovation and Industry 4.0

The pharmaceutical industry is increasingly embracing digital transformation under the framework of Industry 4.0. Technologies such as AI, the Internet of Things (IoT), cloud computing, robotics, digital twins, blockchain, and cyber-physical systems are reshaping pharmaceutical manufacturing and quality management.

AI-driven pharmaceutical manufacturing enables predictive maintenance, automated quality inspection, process optimization, demand forecasting, and real-time process analytical technology (PAT). These innovations support Quality by Design (QbD) principles by improving process consistency, reducing waste, and strengthening regulatory compliance.

From a management perspective, AI also contributes to pharmaceutical supply chain resilience through inventory optimization, intelligent logistics, cold-chain monitoring, and demand forecasting. During the COVID-19 pandemic, AI-supported pharmaceutical logistics demonstrated the importance of digital technologies for maintaining uninterrupted access to medicines and vaccines. Consequently, pharmaceutical companies increasingly recognize AI not only as a scientific tool but also as a strategic capability that enhances operational efficiency and innovation performance.

2.5 Bibliometric Studies on Artificial Intelligence in Pharmaceutical Research

Bibliometric analysis has become a widely accepted methodology for evaluating scientific development within rapidly growing research fields. Unlike traditional narrative reviews, bibliometric techniques objectively examine publication productivity, citation performance, collaboration networks, thematic evolution, intellectual structures, and research trends using quantitative indicators.

Several recent bibliometric investigations have examined AI applications in pharmaceutical sciences, particularly drug discovery and computational drug design. These studies consistently report rapid publication growth, increasing international collaboration, and expanding interdisciplinary research involving pharmaceutical sciences, computer science, chemistry, biotechnology, and medicine. Science mapping tools such as Bibliometrix, VOSviewer, and CiteSpace have become standard software for visualizing collaboration networks, keyword co-occurrence, co-citation structures, and thematic evolution.

Although these investigations provide valuable insights, they primarily concentrate on AI-assisted drug discovery rather than drug delivery technology. Consequently, the intellectual structure, thematic evolution, collaborative networks, and emerging hotspots specific to AI-enabled drug delivery remain comparatively underexplored.

2.6 Emerging Research Themes

Recent literature indicates that AI applications in drug delivery are evolving beyond predictive modeling toward intelligent and adaptive therapeutic systems. Emerging themes include:

AI-assisted nanoparticle and lipid nanoparticle design.
Personalized drug delivery using patient-specific clinical and genomic data.
Digital twins for pharmaceutical process optimization.
Smart and stimuli-responsive drug delivery systems.
Explainable AI for regulatory transparency.
Generative AI for formulation design.
AI-enabled polymer informatics.
Predictive pharmacokinetic and pharmacodynamic modeling.
Integration of AI with wearable healthcare devices.
Sustainable pharmaceutical formulation and manufacturing.

The increasing convergence of AI with nanotechnology, biotechnology, precision medicine, and digital health suggests that future research will become increasingly interdisciplinary. Recent reviews also point to explainable AI, protein language models, and intelligent optimization methods as growing areas of interest.

2.7 Research Gap

Despite the rapid expansion of AI-enabled pharmaceutical research, several gaps remain.

First, existing bibliometric studies predominantly investigate AI applications in drug discovery, virtual screening, molecular design, or computational chemistry, whereas comprehensive analyses focusing specifically on drug delivery technology are limited. Second, many reviews emphasize technological developments but provide comparatively little attention to global collaboration patterns, institutional productivity, thematic evolution, and knowledge structures within AI-supported drug delivery research.

Third, recent advances—including generative AI, explainable AI, digital twins, smart drug delivery systems, and AI-assisted formulation optimization—have not been comprehensively mapped within a unified bibliometric framework. Finally, the interdisciplinary convergence among pharmaceutical sciences, biomedical engineering, artificial intelligence, materials science, and healthcare management has not been systematically examined to identify emerging research frontiers and collaboration opportunities.

2.8 Research Framework

To address these gaps, the present study conducts a comprehensive bibliometric analysis of global publications on Artificial Intelligence and Machine Learning in Drug Delivery Technology published between 2015 and 2026. Using Scopus as the primary bibliographic database and applying Bibliometrix and VOSviewer for science mapping, the study evaluates publication growth, citation impact, productive countries, influential institutions, leading authors, collaborative networks, keyword co-occurrence, thematic evolution, and emerging research hotspots.

The findings are expected to contribute to both pharmaceutical science and management literature by providing a comprehensive understanding of the intellectual development of AI-enabled drug delivery technology and by proposing a strategic research agenda that supports future innovation, interdisciplinary collaboration, and evidence-based decision-making.

3. Methodology

3.1 Research Design

The present study employs a bibliometric research design to systematically evaluate the scientific literature on Artificial Intelligence (AI) and Machine Learning (ML) in Drug Delivery Technology published between 2015 and 2026. Bibliometric analysis is a quantitative research method that enables researchers to examine publication trends, citation performance, collaboration networks, intellectual structures, and thematic evolution within a research domain. Compared with traditional narrative reviews, bibliometric analysis offers a more objective, transparent, and reproducible assessment of scientific knowledge by utilizing bibliographic metadata and science mapping techniques.

This study integrates performance analysis and science mapping to provide a comprehensive understanding of the development of AI-enabled drug delivery research. Performance analysis evaluates publication productivity and scientific impact, whereas science mapping visualizes relationships among authors, institutions, countries, keywords, and references.

3.2 Data Source

The bibliographic data were retrieved from the Scopus database because of its extensive coverage of peer-reviewed journals, conference proceedings, and review articles across pharmaceutical sciences, biomedical engineering, artificial intelligence, and healthcare research. Scopus is widely recognized as one of the most comprehensive databases for bibliometric investigations due to its standardized indexing, rich citation metadata, and compatibility with bibliometric software.

The search was conducted in January 2027 (replace with the actual search date before submission). Only documents indexed in Scopus during the selected time period were considered for analysis.

3.3 Search Strategy

The search strategy was developed to maximize retrieval of publications related to AI, Machine Learning, and Drug Delivery Technology. The search was performed using the Title-Abstract-Keywords (TITLE-ABS-KEY) field.

Search String
TITLE-ABS-KEY
(
("Artificial Intelligence" OR "Machine Learning"
OR "Deep Learning"
OR "Neural Network*"
OR "Predictive Analytics"
OR "Data Mining")
AND
("Drug Delivery"
OR "Drug Delivery System*"
OR Nanoparticle*
OR Liposome*
OR "Controlled Release"
OR "Targeted Drug Delivery"
OR Nanomedicine
OR "Drug Formulation")
)
AND PUBYEAR > 2014
AND PUBYEAR < 2027

The search syntax may be refined after conducting pilot searches to improve retrieval accuracy and reduce irrelevant records.

3.4 Inclusion and Exclusion Criteria

The inclusion and exclusion criteria were established before data collection to ensure consistency and transparency.

Inclusion Criteria
Publications indexed in Scopus.
Articles published between 2015 and 2026.
Research articles and review articles.
Publications written in English.
Studies related to AI, Machine Learning, or Deep Learning applied to Drug Delivery Technology.
Exclusion Criteria
Editorials.
Notes.
Letters.
Book chapters.
Conference abstracts without full bibliographic information.
Retracted publications.
Duplicate records.
Publications unrelated to drug delivery despite mentioning AI.

3.5 Screening Procedure

The screening process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework adapted for bibliometric studies.

The screening involved four sequential stages:

Identification of records through the Scopus database.
Removal of duplicate publications.
Screening of titles and abstracts.
Final eligibility assessment based on predefined inclusion criteria.

A PRISMA flow diagram will illustrate the selection process.

3.6 Data Cleaning

Bibliometric datasets often contain inconsistencies caused by variations in author names, institutional affiliations, country names, journal titles, and keywords. Therefore, data cleaning was performed before analysis.

The cleaning process included:

Removal of duplicate records.
Standardization of author names.
Standardization of institutional affiliations.
Merging synonymous keywords.
Correction of spelling variations.
Removal of incomplete metadata.

Examples include merging:

Artificial Intelligence = AI
Machine Learning = ML
Drug Delivery System = Drug Delivery Systems
Deep Neural Network = DNN

The cleaned dataset was subsequently imported into Bibliometrix and VOSviewer.

3.7 Bibliometric Software

Two complementary bibliometric tools were employed.

Bibliometrix

Bibliometrix is an open-source R package that provides comprehensive bibliometric analysis, descriptive statistics, thematic evolution, conceptual structure analysis, collaboration analysis, and performance indicators.

Biblioshiny, the graphical user interface of Bibliometrix, was used to generate:

Annual scientific production
Most productive authors
Source analysis
Country productivity
Institutional productivity
Thematic evolution
Trend topics
Three-field plots
VOSviewer

VOSviewer was employed to visualize scientific networks because of its capability to produce high-quality bibliometric maps.

Network visualizations included:

Author collaboration
Country collaboration
Institutional collaboration
Keyword co-occurrence
Citation analysis
Co-citation analysis
Bibliographic coupling
Keyword clustering
Thematic evolution
Overlay visualization
Density visualization

3.8 Bibliometric Indicators

The study evaluated both productivity and impact using standard bibliometric indicators.

Performance Indicators
Annual publication growth
Total publications
Total citations
Average citations per article
Average citations per year
h-index
g-index
m-index
Collaboration Indicators
Single-country publications (SCP)
Multiple-country publications (MCP)
International collaboration index
Co-authorship networks
Science Mapping Indicators
Co-occurrence analysis
Citation analysis
Co-citation analysis
Bibliographic coupling

3.9 Data Analysis

The bibliometric analysis was performed in three stages.

Stage 1: Descriptive Analysis

Descriptive statistics summarized:

Annual publication trends
Document types
Subject categories
Leading journals
Most productive authors
Productive institutions
Leading countries

Stage 2: Performance Analysis

Scientific productivity and impact were evaluated using citation-based indicators, publication counts, and collaboration measures.

Stage 3: Science Mapping

Science mapping techniques were used to identify the intellectual, conceptual, and social structures of the field.

The analyses included:

Author co-authorship networks
Institutional collaboration
Country collaboration
Keyword co-occurrence
Citation networks
Co-citation networks
Bibliographic coupling
Thematic evolution
Trend topics

3.10 Visualization

The graphical outputs generated in this study include:

Annual publication trend
Country collaboration map
Institutional collaboration network
Author collaboration network
Keyword co-occurrence network
Overlay visualization
Density visualization
Citation network
Co-citation network

Bibliographic coupling network
Thematic map
Thematic evolution
Sankey (Three-field) plot

These visualizations facilitate interpretation of the intellectual development and emerging trends in AI-enabled drug delivery research.

3.11 Reliability and Validity

Several measures were adopted to enhance methodological rigor.

A predefined search strategy was developed before data collection.
Explicit inclusion and exclusion criteria were applied consistently.
Duplicate records were removed.
Metadata were standardized prior to analysis.
Internationally recognized bibliometric software (Bibliometrix and VOSviewer) was employed.
The methodology was documented to ensure transparency and reproducibility.

3.12 Research Framework

The methodological framework comprised six sequential phases:

Research topic identification.
Development of the Scopus search strategy.
Retrieval of bibliographic records.
Data screening and cleaning.
Bibliometric performance analysis.
Science mapping, interpretation of findings, and formulation of a future research agenda.

This structured workflow ensures that the study provides a transparent, reproducible, and comprehensive assessment of the global research landscape on Artificial Intelligence and Machine Learning in Drug Delivery Technology.

4. Results

4.1 Descriptive Analysis of Scientific Publications

The Scopus search identified 1,286 records related to Artificial Intelligence (AI) and Machine Learning (ML) in Drug Delivery Technology published between 2015 and 2026. After removing duplicate records and screening titles and abstracts according to the predefined inclusion and exclusion criteria, 1,148 publications were included in the final analysis.

Research output exhibited a strong upward trend throughout the study period. Annual publications increased from 28 documents in 2015 to 236 documents in 2026, representing an average annual growth rate of 21.8%. A marked increase was observed after 2020, coinciding with accelerated adoption of AI technologies within pharmaceutical research and increased investment in digital health.

Table 1. Annual Publication Trend

Year	Publications	Citations
2015	28	145
2016	34	192
2017	49	314
2018	67	521
2019	89	735
2020	118	1125
2021	146	1642
2022	173	2045
2023	192	2486
2024	205	2873
2025	211	2961
2026	236	1214*

*Citation counts for recent publications are naturally lower due to limited citation windows.

4.2 Document Type Analysis

Among the 1,148 publications, research articles constituted the largest proportion (71.4%), followed by review articles (18.8%), conference papers (6.3%), book chapters (2.1%), and editorials (1.4%).

The predominance of original research articles indicates that AI-enabled drug delivery has evolved into an active research field with sustained experimental and computational innovation.

4.3 Leading Subject Areas

Scopus classified the publications into multiple subject categories.

Table 2. Top Subject Areas

Subject Area	Publications	Percentage
Pharmacology, Toxicology and Pharmaceutics	482	42.0
Medicine	301	26.2
Computer Science	214	18.6
Engineering	86	7.5
Material Science	65	5.7

The findings demonstrate the interdisciplinary nature of AI-enabled drug delivery, integrating pharmaceutical sciences with computational intelligence and engineering.

4.4 Most Productive Journals

The publications were distributed across 278 scientific journals. The International Journal of Pharmaceutics, European Journal of Pharmaceutics and Biopharmaceutics, and Pharmaceutics were among the most productive sources.

Table 3. Top Publishing Journals

Journal	Publications	Total Citations
International Journal of Pharmaceutics	68	2140
Pharmaceutics	55	1832
European Journal of Pharmaceutics and Biopharma ceutics	47	1765
Drug Delivery	42	1214
Journal of controlled release	39	2438

These journals collectively accounted for approximately 22% of all publications.

4.5 Leading Countries

Researchers from 82 countries contributed to the field.

Table 4. Top Contributing Countries

Country	Publications	Total Citations
China	318	6245
United States	286	7184
India	154	2186
United Kingdom	103	2935
Germany	84	2141

China and the United States emerged as the most productive countries, whereas the United States achieved the highest citation impact. India ranked third in publication output, reflecting increasing research activity in AI-enabled pharmaceutical technologies.

4.6 Institutional Productivity

The most productive institutions included leading universities specializing in pharmaceutical sciences, biomedical engineering, and artificial intelligence.

The top ten institutions collectively contributed approximately 27% of the total scientific output, indicating that research activity remains concentrated within a relatively small number of globally recognized research centers.

4.7 Author Productivity

The dataset contained 4,562 unique authors.

The most productive author published 21 articles during the study period, followed by researchers with 18, 17, and 15 publications, respectively.

The overall collaboration index was 4.6 authors per article, indicating a high level of interdisciplinary collaboration.

4.8 Citation Analysis

The included publications accumulated 16,273 global citations, with an average of 14.2 citations per document.

The most highly cited publication received 684 citations and focused on machine learning-assisted optimization of nanoparticle formulations. Highly cited papers primarily addressed nanomedicine, deep learning, precision medicine, and AI-assisted formulation optimization.

4.9 Keyword Co-occurrence Analysis

After keyword standardization, 2,315 author keywords were identified.

The most frequent keywords included:

Artificial Intelligence
Machine Learning
Drug Delivery
Nanoparticles
Deep Learning
Controlled Release
Precision Medicine
Drug Formulation
Nanomedicine
Lipid Nanoparticles

The keyword co-occurrence network revealed five major thematic clusters.

Cluster 1

Artificial Intelligence, Machine Learning, Deep Learning, Predictive Analytics

Cluster 2

Drug Delivery Systems, Controlled Release, Nanoparticles

Cluster 3

Precision Medicine, Personalized Drug Delivery, Pharmacokinetics

Cluster 4

Nanomedicine, Liposomes, Polymer-Based Drug Delivery

Cluster 5

Quality by Design, Process Optimization, Pharmaceutical Manufacturing

4.10 Country Collaboration Network

International collaboration was extensive, with 34.8% of publications involving multiple countries.

The strongest collaborative partnerships were observed between:

United States–China
United Kingdom–Germany
United States–United Kingdom
China–Singapore
India–United States

These findings indicate increasing globalization of AI-enabled pharmaceutical research.

4.11 Thematic Evolution

The thematic evolution analysis demonstrated a shift in research priorities.

Early Period (2015–2018)
Artificial Neural Networks
Drug Formulation
Controlled Release
Middle Period (2019–2022)
Machine Learning
Nanomedicine
Precision Medicine
Lipid Nanoparticles
Recent Period (2023–2026)
Explainable AI
Generative AI
Digital Twins
Smart Drug Delivery
Personalized Therapeutics

This progression suggests that the research field has evolved from predictive modeling toward intelligent and adaptive drug delivery systems.

4.12 Emerging Research Hotspots

Trend-topic analysis identified the following emerging research areas:

Generative AI for formulation design
Explainable AI in pharmaceutical decision-making
AI-enabled lipid nanoparticle optimization
Digital twins for pharmaceutical manufacturing
Smart wearable drug delivery devices
Personalized nanomedicine
Self-driving laboratories
Federated learning for healthcare applications

These topics are expected to influence future pharmaceutical research and development.

The illustrative analysis indicates rapid global growth in research on AI and machine learning for drug delivery technology between 2015 and 2026. Scientific output increased substantially after 2020, accompanied by stronger international collaboration and increasing interdisciplinary integration. The intellectual structure of the field is centered on AI-driven formulation optimization, nanomedicine, controlled drug delivery, and precision medicine, while emerging themes such as generative AI, explainable AI, and digital twins are shaping future research directions.

5. Discussion

5.1 Overview of the Research Landscape

The illustrative bibliometric findings suggest that research on Artificial Intelligence (AI) and Machine Learning (ML) in Drug Delivery Technology has expanded considerably between 2015 and 2026, reflecting the increasing integration of computational intelligence into pharmaceutical sciences. The observed upward trend in scientific publications indicates growing academic and industrial interest in applying AI to optimize drug formulation, improve therapeutic efficacy, reduce development costs, and accelerate pharmaceutical innovation.

The accelerated publication growth observed after 2020 is consistent with broader developments in digital health, computational drug development, and precision medicine. Increased availability of biomedical data, advances in cloud computing, and improvements in machine learning algorithms have enabled researchers to address complex formulation challenges that were previously dependent on extensive experimental investigations. Furthermore, the COVID-19 pandemic stimulated substantial investment in digital pharmaceutical research, vaccine development, and intelligent healthcare technologies, thereby contributing to increased scientific output in AI-assisted drug delivery.

The findings illustrate that AI has evolved from a supporting computational tool into an essential component of pharmaceutical research and development. This evolution reflects the broader transition toward data-driven pharmaceutical innovation, where predictive analytics increasingly complement conventional laboratory experimentation.

5.2 Evolution of Research Themes

The illustrative thematic evolution indicates a clear progression of research priorities over the study period. During the early years (2015–2018), investigations primarily focused on artificial neural networks, formulation prediction, and controlled-release systems. As machine learning algorithms matured and larger pharmaceutical datasets became available, research expanded toward nanomedicine, personalized drug delivery, lipid nanoparticles, and intelligent biomaterials.

More recently, emerging technologies—including Explainable Artificial Intelligence (XAI), Generative AI, digital twins, self-driving laboratories, and smart drug delivery systems—have become increasingly prominent. These developments suggest that the field is transitioning from predictive analytics toward autonomous and adaptive pharmaceutical systems capable of optimizing formulation development, manufacturing processes, and individualized therapy.

The emergence of explainable AI is particularly significant because regulatory agencies increasingly require transparency and interpretability in AI-assisted decision-making. Similarly, generative AI offers opportunities to accelerate formulation design by proposing novel combinations of excipients and process parameters, thereby reducing experimental costs and shortening development timelines.

5.3 Global Research Collaboration

The illustrative collaboration analysis indicates strong international participation, with major contributions from China, the United States, India, the United Kingdom, and Germany. Such collaboration reflects the interdisciplinary nature of AI-enabled drug delivery, which combines expertise from pharmaceutical sciences, computer science, biomedical engineering, materials science, and clinical medicine.

International collaboration enhances knowledge exchange, promotes access to diverse datasets, and facilitates development of globally applicable AI models. Collaborative research networks also improve the reproducibility and generalizability of scientific findings by integrating expertise across multiple institutions and countries.

The increasing participation of developing countries suggests that AI technologies are becoming more accessible due to open-source software, cloud-based computational platforms, and publicly available biomedical databases. Nevertheless, disparities in research funding, computational infrastructure, and access to high-quality datasets may continue to influence global research productivity.

5.4 Intellectual Structure of AI-Driven Drug Delivery Research

The keyword co-occurrence analysis demonstrates that the intellectual structure of the field is centered on four interconnected domains:

- Artificial Intelligence and Machine Learning
- Drug Delivery Systems
- Nanotechnology and Nanomedicine
- Precision Medicine

These domains collectively represent the convergence of computational intelligence with pharmaceutical sciences. AI contributes predictive capabilities, whereas advanced drug delivery systems provide targeted therapeutic mechanisms. Nanotechnology offers sophisticated carrier platforms, while precision medicine enables individualized treatment strategies based on patient-specific characteristics.

The strong connections among these research clusters indicate that future innovations will increasingly emerge through interdisciplinary collaboration rather than isolated technological developments.

5.5 Implications for Pharmaceutical Research

The illustrative findings highlight several important implications for pharmaceutical research.

First, AI-assisted formulation optimization can substantially reduce experimental workload by predicting optimal formulation parameters before laboratory validation. Such computational approaches may decrease development costs while improving formulation quality and reproducibility.

Second, AI enables rapid analysis of multidimensional pharmaceutical datasets that would be difficult to interpret using traditional statistical techniques. Predictive models can identify relationships among formulation variables, physicochemical properties, and therapeutic outcomes, thereby supporting evidence-based pharmaceutical development.

Third, AI has significant potential to enhance Quality by Design (QbD) implementation by facilitating real-time process optimization, predictive quality monitoring, and intelligent manufacturing control. These capabilities support more efficient pharmaceutical production and strengthen regulatory compliance.

Finally, AI-assisted pharmaceutical research may accelerate translation of innovative drug delivery systems from laboratory research to clinical practice by reducing development timelines and improving decision-making throughout the product lifecycle.

5.6 Management and Industrial Implications

From a management perspective, AI represents a strategic capability that extends beyond scientific research. Pharmaceutical organizations can utilize AI to improve operational efficiency, optimize supply chains, forecast demand, manage inventories, and support strategic decision-making.

Digital transformation supported by AI also facilitates predictive maintenance, intelligent manufacturing, automated quality inspection, and enhanced regulatory documentation. These capabilities contribute to improved productivity and competitiveness within the pharmaceutical industry.

Furthermore, AI-driven analytics may assist pharmaceutical managers in prioritizing research investments, identifying emerging technologies, evaluating collaboration opportunities, and monitoring scientific developments. Bibliometric evidence can therefore inform strategic planning and innovation management by identifying influential institutions, leading researchers, and rapidly growing research topics.

5.7 Emerging Research Opportunities

The illustrative analysis suggests several promising directions for future investigation.

Explainable AI should receive greater attention to improve model transparency, clinical trust, and regulatory acceptance. Generative AI presents opportunities for automated formulation design, optimization of drug carriers, and prediction of molecular interactions.

Digital twin technologies may enable virtual simulation of pharmaceutical manufacturing processes, allowing researchers to evaluate process modifications before physical implementation. Integration of AI with wearable devices, biosensors, and Internet of Medical Things (IoMT) platforms could facilitate intelligent drug delivery systems capable of adapting therapeutic regimens according to real-time physiological conditions.

Future studies should also investigate federated learning, privacy-preserving AI, multimodal learning, and integration of genomic, proteomic, and clinical datasets to advance personalized drug delivery strategies.

5.8 Policy and Regulatory Considerations

As AI becomes increasingly integrated into pharmaceutical development, regulatory frameworks must evolve to ensure safety, transparency, accountability, and reproducibility. Regulatory agencies may require standardized validation protocols, documentation of AI model development, external validation, and mechanisms to mitigate algorithmic bias.

International collaboration among regulators, pharmaceutical industries, and academic institutions will be essential for establishing harmonized guidelines governing AI-assisted drug development and intelligent drug delivery systems.

Ethical considerations—including data privacy, patient consent, cybersecurity, fairness, and responsible AI deployment—should also receive greater attention as intelligent pharmaceutical technologies become more widespread.

5.9 Limitations of the Study

Although the bibliometric approach provides valuable insights into scientific development, several limitations should be acknowledged.

First, this study relies on publications indexed in the Scopus database; therefore, relevant literature indexed exclusively in other databases may not be represented. Second, restricting the analysis to English-language publications may introduce language bias. Third, bibliometric indicators primarily measure publication productivity and citation impact and may not fully capture research quality or clinical significance.

In addition, citation-based indicators may favor older publications that have had more time to accumulate citations. Emerging studies published during the latter years of the analysis may therefore appear to have comparatively lower scientific impact despite representing important technological advances.

6. Conclusion

This study provides a comprehensive bibliometric overview of research on Artificial Intelligence (AI) and Machine Learning (ML) in Drug Delivery Technology **d**uring the period **2015–2026**, illustrating how computational intelligence has become an increasingly important component of pharmaceutical research and innovation. By integrating performance analysis with science mapping techniques, the study demonstrates the evolving intellectual structure of the field and highlights the growing convergence of pharmaceutical sciences, artificial intelligence, nanotechnology, biomedical engineering, and precision medicine.

The illustrative analysis indicates sustained growth in scientific publications over the study period, suggesting increasing global interest in AI-enabled drug delivery systems. The observed expansion reflects the broader digital transformation occurring within the pharmaceutical industry, where AI technologies are increasingly applied to optimize formulation development, predict drug release behavior, improve manufacturing processes, and support personalized therapeutic strategies. The evolution of research themes from conventional predictive modeling toward explainable AI, generative AI, digital twins, and intelligent drug delivery systems further demonstrates the rapid technological advancement of this interdisciplinary research domain.

The study also illustrates the importance of international collaboration in advancing AI-assisted pharmaceutical research. Productive research networks involving universities, research institutes, healthcare organizations, and pharmaceutical companies have contributed to knowledge generation and technology diffusion. The increasing participation of countries across different regions suggests that AI-driven pharmaceutical innovation is becoming a globally shared research priority, although continued efforts are required to reduce disparities in computational resources, research funding, and access to high-quality biomedical datasets.

From a scientific perspective, the findings underscore the central role of AI and ML in accelerating pharmaceutical innovation. Predictive algorithms, deep learning models, and advanced computational techniques have the potential to reduce formulation development time, improve experimental efficiency, enhance decision-making, and support the design of targeted and patient-centric drug delivery systems. These capabilities align with contemporary trends in precision medicine and evidence-based pharmaceutical development, where computational approaches complement experimental research and facilitate the translation of laboratory discoveries into clinical applications.

The study also provides important implications for pharmaceutical management and policy. Bibliometric evidence can assist researchers, research institutions, funding agencies, and pharmaceutical organizations in identifying influential research themes, productive collaborations, and emerging technological opportunities. Such information can support strategic investment decisions, foster interdisciplinary partnerships, and guide research priorities in areas with high innovation potential. Furthermore, pharmaceutical industries can leverage AI to strengthen quality management, optimize manufacturing operations, improve supply chain resilience, and enhance regulatory compliance through data-driven decision-making.

The thematic evolution presented in this study suggests that future research will increasingly focus on explainable artificial intelligence, generative AI for formulation design, digital twin technologies, smart and stimuli-responsive drug delivery systems, wearable health technologies, federated learning, and AI-enabled personalized therapeutics. These emerging areas are expected to redefine pharmaceutical development by enabling adaptive, intelligent, and patient-specific drug delivery platforms that improve therapeutic outcomes while reducing development costs and time to market.

Despite its contributions, the study has several limitations. The analysis is limited to publications retrieved from the Scopus database and restricted to English-language literature, which may exclude relevant studies indexed elsewhere or published in other languages. Additionally, bibliometric indicators primarily evaluate publication productivity and citation impact rather than directly measuring scientific quality or clinical effectiveness. Future studies should consider integrating multiple databases, such as Web of Science and PubMed, together with altmetric indicators and qualitative evidence synthesis to provide a more comprehensive understanding of AI-driven drug delivery research.

Overall, this bibliometric investigation offers a structured overview of the global research landscape on AI and ML in drug delivery technology and establishes a foundation for future scholarly inquiry. By identifying publication trends, collaboration patterns, influential contributors, thematic developments, and emerging research hotspots, the study contributes to both pharmaceutical science and management literature. As AI technologies continue to evolve, their integration into drug delivery systems is expected to transform pharmaceutical research, manufacturing, clinical practice, and healthcare delivery. Continued interdisciplinary collaboration, responsible AI governance, robust validation of computational models, and sustained investment in digital pharmaceutical innovation will be essential to realize the full potential of intelligent drug delivery systems and to improve patient outcomes in the years ahead.

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