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Future Journal of Pharmaceutical Sciences (2024) 10:58
https://doi.org/10.1186/s43094-024-00632-2

Future Journal of Pharmaceutical Sciences

CASE STUDY

Open Access

Evaluating the effect of artificial intelligence on pharmaceutical product and drug discovery in China

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Abstract

The pharmaceutical sector has recently witnessed a transformative improvement and shift toward artificial intelligence (AI) in its drug and pharmaceutical delivery process and procedures. Hence, this research delves into the benefits and obstacles pharmaceutical firms face in utilizing AI in China. Globally, China is recognized as a dominant pillar in research and development in the pharmaceutical industry. The country has incorporated AI approaches and technologies to improve the drug industry's cost, efficiency and development. Therefore, this study applies the case study method and evaluation of prior studies to assess AI's potential benefits and challenges in the drug and pharmaceutical enterprises. The research provided an in-depth evaluation of AI in the various phases of the drug discovery process. The research outcome indicated that AI's benefits include drug repurposing, target identification, clinical trial optimization, quality assurance, and control and efficient drug distribution method. However, the analysis revealed that China faces several challenges that impact the pace and extent of integration of AI in its pharmaceutical industry. These challenges include a lack of standardized data, a shortage of skilled labor or professionals, and data and privacy concerns. In addition, the research provides three case studies that focused on f XtalPi-AI-Enhanced Drug Discover, BioMap: Accelerating Drug Development Through AI and iCarbonX: AI-Driven Precision Medicine and provided a comprehensive analysis of how these firms have used AI to stimulate their drug discovery process. The study also provides policies that can help improve the integration of AI in the pharmaceutical and drug delivery process.

Keywords Drug repurposing, Pharmaceutical industry, Artificial intelligence, Machine learning, Drug discovery

Background

In recent years, integrating artificial intelligence (AI) into various industries has catalyzed transformative changes, with the pharmaceutical sector no exception [25]. This study delves into the profound implications of AI in drug discovery and development, with a specific focus on pharmaceutical companies operating in China. Sufyan, Shokat, and Ashfaq [44] asserted that as technological advancements continue redefining traditional methodologies, it becomes imperative to assess the comparative strategies employed by pharmaceutical enterprises in harnessing AI to enhance drug discovery and development processes. Lengthy and resource-intensive drug development pipelines have long characterized the pharmaceutical industry. The introduction of AI promises to expedite these processes, potentially revolutionizing the landscape of drug discovery [29]. However, the adoption and implementation of AI technologies vary among pharmaceutical companies, and a comparative analysis provides an understanding of the diverse approaches employed by industry players in China [29]. This research seeks to unravel the intricacies of AI utilization,

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evaluating the impact on efficiency, cost-effectiveness, and overall success rates in drug discovery and development. Thus, this research provides a novel approach that can help understand the opportunities and challenges faced by pharmaceutical in China. Moreover, as indicated by Kim et al. [20], China has become a center for the advancement of drugs. As AI applications advance in sophistication, it will become strategically imperative for firms looking to gain a competitive advantage to integrate them into their drug development processes.

Moreover, implementing AI tools, including machine learning and data analytical approaches, is revolutionizing drug and pharmaceutical enterprises to identify and initiate a new therapeutic in contemporary times [19]. Compared to the traditional methods used for drug discovery and pharmaceutical process, Sultana and Rangareddy [46] recounted that AI has offered firms the ability to process huge amounts of clinical, biological, and chemical data in a timely and sustainable manner. As the demand for novel and effective therapeutics continues to rise, so does the pressure on pharmaceutical companies to innovate and streamline their drug discovery and development pipelines. AI presents a unique opportunity to augment human capabilities, offering the potential to uncover hidden patterns in data, predict potential drug candidates, and optimize clinical trial designs [3]. This exploration into the utilization of AI in drug discovery and development processes among pharmaceutical companies sheds light on the current state of the industry but also lays the groundwork for understanding the future trajectory of pharmaceutical innovation in the era of artificial intelligence [3].

The research problem at the core of this investigation revolves around identifying the key determinants that influence the adoption and efficacy of AI in drug discovery among pharmaceutical companies in China. By conducting a comparative analysis, we aim to uncover patterns, trends, and success factors that distinguish the strategies of various enterprises. Moreover, this study seeks to address potential challenges and ethical considerations associated with implementing AI in drug development, contributing to a comprehensive understanding of the evolving landscape in the context of the Chinese pharmaceutical industry. As AI technologies evolve rapidly, staying abreast of the dynamic relationship between pharmaceutical companies and these innovations is paramount [5]. The findings of this research endeavor are poised to offer valuable insights not only for industry stakeholders but also for policymakers, researchers, and the broader scientific community. Ultimately, by scrutinizing the impact of AI in drug discovery and development within the unique context of Chinese pharmaceutical companies, this study contributes to the ongoing discourse on the role of artificial intelligence in shaping the future of healthcare and innovation.

This research significantly contributes to the evolving field of pharmaceuticals and artificial intelligence. By focusing specifically on China, the study provides valuable insights into the utilization of AI in drug discovery and development processes within the Chinese pharmaceutical industry. This geographical focus is crucial, as China has emerged as a major player in the global pharmaceutical market, and understanding how AI is integrated into its drug development practices is essential for academic and industry stakeholders [51]. The novelty of this research lies in its comparative analysis, which allows for a comprehensive understanding of the different approaches adopted by pharmaceutical companies in China regarding AI in drug discovery. The study explores various AI techniques, algorithms, and technologies these companies employ, shedding light on the diversity of strategies within the Chinese pharmaceutical sector. This comparative aspect contributes to the existing body of knowledge by highlighting variations in AI adoption and implementation across different companies, offering a nuanced perspective on AI integration in drug development.

The practical significance of the research is evident in its potential to inform policymakers, industry professionals, and researchers about the current landscape of AI in drug discovery in China. The findings can guide decision-makers in developing targeted policies and strategies to foster AI's responsible and effective use in the pharmaceutical sector. Moreover, pharmaceutical companies can benefit from the insights by understanding their counterparts' successful AI applications and challenges, potentially optimizing their drug discovery and development processes. This research holds practical implications for advancing the intersection of artificial intelligence and pharmaceuticals, with potential global implications given China's growing influence in the industry.

Literature review

AI: a transformative tool for advancing pharmaceutical product lifecycle

AI has emerged as a transformative force in advancing the pharmaceutical product life cycle across various stages, from drug discovery to post-market surveillance [53]. One notable contribution of AI is in drug discovery, which accelerates the identification of potential drug candidates. By leveraging machine learning algorithms, AI can analyze vast datasets, including genomic information and chemical properties, to predict how different compounds might behave and interact [9]. This expedites the discovery process, significantly reducing the time and costs traditionally associated with bringing

a new pharmaceutical product to market. In the development phase, AI is crucial in optimizing clinical trials [2]. Machine learning algorithms can analyze patient data to identify suitable trial candidates, predict potential adverse effects, and optimize the trial design. This enhances the efficiency of clinical trials and improves patient outcomes by ensuring that the right individuals are enrolled, leading to more robust and reliable results [33]. Additionally, AI can assist in the monitoring and analysis of real-world evidence, providing insights into the long-term efficacy and safety of pharmaceutical products [43].

Once a drug is approved and enters the market, AI contributes to its life cycle by enhancing manufacturing processes [17]. AI-powered systems can monitor and optimize production, ensuring consistency and quality while minimizing waste. Predictive maintenance powered by AI can also reduce downtime in manufacturing facilities, improving overall efficiency [40]. These manufacturing advancements benefit pharmaceutical companies and contribute to a more reliable and accessible supply of medications for patients. In the post-market phase, AI facilitates pharmacovigilance and drug safety monitoring. According to Deng et al. [12], AI can promptly identify possible adverse responses and new security vulnerabilities by examining vast amounts of data, such as online communities and medical records.

AI can quickly detect potential adverse reactions and emerging safety concerns by analyzing large-scale data, including electronic health records and social media [12]. This makes it possible for pharmaceutical firms and regulatory organizations to act quickly, protecting the welfare of patients and upholding the general public's trust in pharmaceuticals. Over every phase of the life cycle, a more proactive and instantaneous policy regarding pharmaceutical security is made possible by AI's constant surveillance features. [7]. Floresta et al. [14] revealed that AI helps provide personalized medicine by evaluating the patient data to recognize specific biomarkers and genetic markers that may affect the therapy responses. This enables the improvement of customized or targeted medicines that optimize efficacy while minimizing the adverse effects.

Furthermore, AI aids in personalized medicine by analyzing patient data to identify specific genetic markers and biomarkers that can influence drug response. This allows for the development of targeted therapies tailored to individual patients, maximizing efficacy while minimizing adverse effects [14]. A substantial advancement in the life progression of medical products, tailoring therapy regimes based on a patient's genetic profile, represents an essential turning point in the medical field. According to Gupta et al. [15], AI can greatly accelerate the lifespan of pharmaceutical products. Knake [21] advances the discussion by indicating that AI has an enormous effect on every stage of the product life cycle, from accelerating the discovery of new drugs to streamlining clinical trials, boosting post-market monitoring and facilitating targeted therapy. As technology evolves, the pharmaceutical industry is poised to benefit from further innovations and improvements, ultimately leading to more efficient, effective, and patient-centric healthcare solutions [42]. In Fig. 1, Paul et al. [36] identified various AI networks and decision tree algorithm that helps improve pharmaceutical products.

Artificial intelligence: a sustainable approach to drug discovery

AI has emerged as a sustainable and revolutionary approach to drug discovery, offering unprecedented opportunities to streamline and enhance the traditionally time-consuming and resource-intensive process [48]. Hence, Bhattamisra et al. [6] mentioned that AI's important enhancement to drug development is its speedy digestion of enormous amounts of medical and scientific information. Thus, AI enables health practitioners to identify prospective drug candidates more accurately and efficiently than they could using the conventional approach when they employ ML. Thus, complex compositions can be examined and explored using ML. AI's capacity to substantially reduce the cost and time connected with bridging new drugs to the market demonstrates the sustainability of this kind of drug delivery process. Therefore, AI expedites the initial drug discovery phase by promptly recognizing novel compounds and forecasting their physiological impact on patients. AI's capacity to significantly reduce the time and cost associated with bringing new drugs to market demonstrates the sustainability of this kind of drug development. AI expedites the initial phases of drug discovery by promptly recognizing novel compounds and forecasting their physiological effects. This increases the likelihood of successful and noteworthy pharmaceutical product launches and helps pharmaceutical businesses allocate resources more wisely, both of which support stability in the healthcare sector.

The sustainable aspect of AI in drug discovery is evident in its potential to significantly reduce the cost and time required to bring new drugs to market. By expediting the identification of promising compounds and predicting their biological activity, AI accelerates the initial phases of drug discovery. This allows pharmaceutical companies to allocate resources more efficiently and increases the likelihood of bringing successful and impactful drugs to market, promoting sustainability within the pharmaceutical industry [47]. Furthermore, AI contributes to

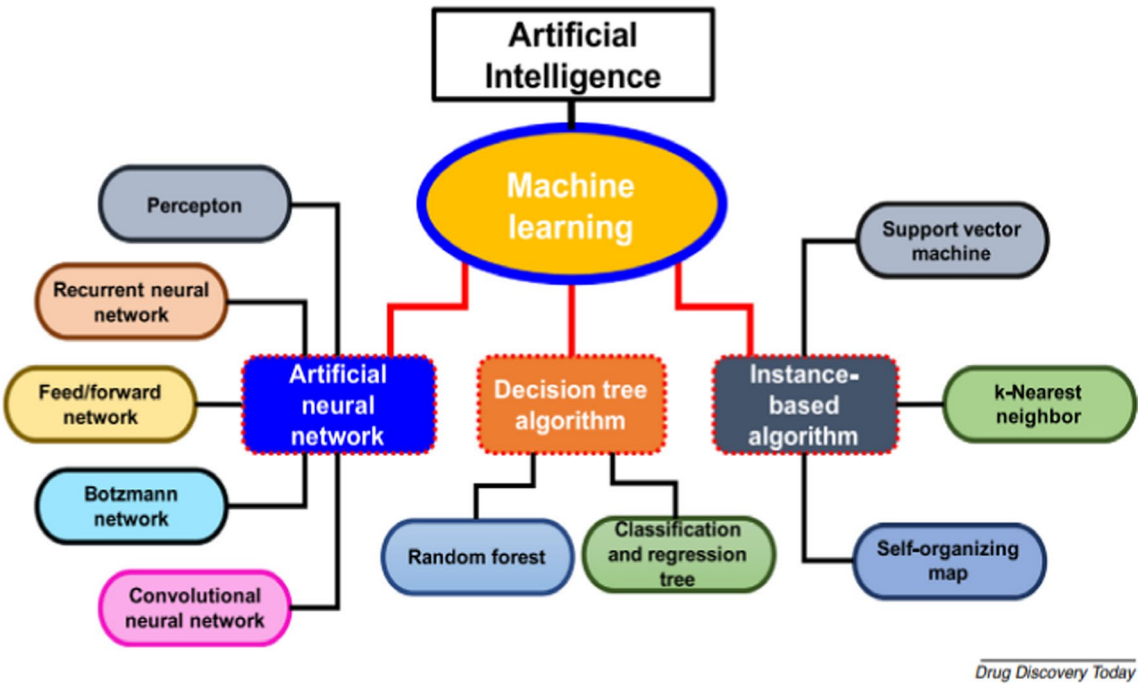

Fig. 1 AI algorithm in drug development. *Source*: Paul et al. [36]

sustainability by facilitating a more targeted and personalized approach to drug development. Machine learning models can analyze patient data, identifying specific genetic markers and biomarkers influencing individual medication responses [35]. This personalized medicine approach not only enhances the effectiveness of treatments but also minimizes adverse effects, reducing the overall environmental impact associated with the production and disposal of pharmaceuticals. In addition to its role in the early stages of drug discovery, AI supports sustainability in optimizing clinical trials [32]. By analyzing patient data, AI can help identify suitable trial candidates, predict potential adverse effects, and optimize trial designs. This ensures that clinical trials are more efficient, with reduced resource requirements and a higher likelihood of success. Streamlining clinical trials contributes to the overall sustainability of drug development processes [4].

Hence, the integration of AI in drug discovery also aligns with sustainable practices by improving the efficiency of drug manufacturing. AI-powered systems can monitor and optimize production processes, reducing waste and ensuring consistent product quality [4]. Predictive maintenance, enabled by AI, minimizes downtime in manufacturing facilities, contributing to a more sustainable and resource-efficient pharmaceutical production ecosystem [24]. Moreover, AI enhances sustainability in drug discovery through its contribution to pharmacovigilance and drug safety. By continuously analyzing real-world data, including electronic health records and social media, AI can quickly detect and assess potential adverse reactions and safety concerns [49]. This proactive monitoring ensures patient safety and builds trust in pharmaceutical products, promoting the industry's long-term sustainability. Accordingly, integrating AI in drug discovery represents a sustainable approach that addresses various challenges in the pharmaceutical industry [24]. AI's impact is multifaceted, from expediting drug discovery and optimizing clinical trials to supporting personalized medicine and improving manufacturing efficiency. As the field continues to evolve, the sustainable application of AI in drug discovery holds the promise of transforming the pharmaceutical industry toward more efficient, effective, and environmentally conscious practices [45]—Table 1 provides a list of some prominent AI tools used in drug discovery.

Advancing pharmaceutical product and drug discovery in China: the role of AI

AI is transforming China's life science and healthcare enterprises as it has become essential for creating medication and pharmaceutical products. Given China's growing pharmaceutical industry, it has recognized the potential of AI to revolutionize conventional drug research methods, leading to improved creativity and efficiency [45]. AI has significantly improved China's

Table 1 Examples of AI tools in drug discovery

AI tools in drug discovery	Explanation	References
IBM Watson for drug discovery	IBM Watson for Drug Discovery leverages AI to analyze biomedical literature, clinical trial data, and other relevant information to help researchers identify potential drug candidates and biomarkers	Chen et al. [10] and Hatz et al. [18]
Atomwise	Atomwise uses deep learning for the virtual screening of potential drug compounds. It analyzes molecular structures to predict their binding affinity with target proteins, expediting the identification of potential drug candidates	Carpenter and Huang [8]
DeepChem	DeepChem is an open-source platform that provides a collection of deep-learning tools for drug discovery	Korshunova et al. [23]
In silico medicine	In silico medicines aims to provide aging research and medicine discovery by applying AI. It also utilizes biological data and seeks promising medication options that focus on sickness, which comprises neurological conditions and cancer	Shaker et al. [41]
Recursion pharmaceuticals	Recursion Pharmaceuticals screens and analyzes biological pictures with artificial intelligence (AI) to find possible medication prospects. Their approach enables rapid screening of biological abnormalities by combining machine learning and computer vision	Malandraki-Miller and Riley [31]
OpenEye scientific software	OpenEye provides a suite of AI tools for cheminformatics research and structural architecture. Their software helps with drug candidate optimization, biological attribute forecasting and chemical-based dataset assessment	Cox and Gupta [11] and Rifaioglu et al. [38]
Schrodinger	Schrodinger offers a system for molecular interaction modeling, digital screening, and discovery of medicines package that integrates AI. It helps scientists optimize tiny compounds to create medications and estimate binding capacities	Adelusi et al. [1]

drug discovery process by speedily and accurately analyzing large amounts of data, accelerating the recognition of promising potential medicines.

According to Deshmukh [13], in the drug discovery process, AI algorithms can be used to evaluate complex chemical information and biological analysis comprising proteomics, genomics and chemical composition. Chinese medicinal product companies use AI to improve the accuracy of target authentication, which raises the effectiveness rate of pharmaceutical research initiatives [28]. The application of AI in this phase is particularly crucial for addressing diseases prevalent in China and globally, providing a tailored and efficient approach to drug development. Furthermore, AI is optimizing the clinical trial process in China, another critical phase in pharmaceutical product development. Machine learning algorithms are employed to analyze patient data, identify suitable clinical trial participants, and predict potential adverse effects [28]. This personalized approach to clinical trials accelerates the testing process. It ensures that drugs are tailored to diverse genetic profiles, contributing to developing more effective and safer pharmaceutical products [30].

China's commitment to AI in pharmaceuticals extends to manufacturing processes. AI-powered systems are being integrated into production facilities to monitor and optimize manufacturing, ensuring consistency, quality, and efficiency [39]. Predictive AI-powered maintenance minimizes downtime, contributing to China's more reliable and sustainable pharmaceutical manufacturing ecosystem. These advancements benefit local pharmaceutical companies and position China as a global leader in adopting cutting-edge technologies for drug production [39]. AI can quickly identify potential adverse reactions and safety concerns by analyzing real-world data from diverse sources, including electronic health records and social media. This continuous monitoring enhances patient safety and regulatory compliance, contributing to the sustainable growth of the pharmaceutical industry in China [36].

Moreover, AI is fostering international collaborations and partnerships in drug discovery. Chinese pharmaceutical companies are increasingly collaborating with global AI and biotech firms to access cutting-edge technologies and expertise [22]. These collaborations facilitate knowledge exchange, talent development, and the integration of diverse perspectives, ultimately contributing to a more robust and globally connected pharmaceutical ecosystem in China [16]. Therefore, the integral role of AI in advancing drug discovery and pharmaceutical products in China underscores the nation's commitment to embracing innovative technologies [24]. AI is reshaping the entire pharmaceutical product life cycle, from accelerating drug discovery and optimizing clinical

trials to improving manufacturing processes and ensuring post-market safety [34]. As China continues to invest in research, development, and collaborations, the synergy between AI and pharmaceuticals is poised to drive transformative changes in healthcare, benefiting both the nation and the global community [26].

A case study on the utilization of AI in drug discovery and development processes among pharmaceutical companies

Case of iCarbonX: AI-driven precision medicine

iCarbonX, a prominent entity in the Chinese healthcare sector, specializes in AI-driven precision medicine, leveraging advanced technologies to analyze diverse datasets, including genomics, lifestyle factors, and clinical records. By forming strategic alliances with academic institutions, iCarbonX collects large amounts of genomic data and uses AI algorithms for predictive modeling to find individual treatment plans. Machine learning is then used to detect biomarkers and help create targeted medicines. A global pioneer in precision medicine, iCarbonX can now produce medicines with more efficacy and fewer side effects thanks to the successful integration of AI. This has led to advancements in personalized medicine. But the business also has to deal with issues like data protection, moral dilemmas, and the need for smooth communication between AI specialists and healthcare professionals. Constant endeavors center on guaranteeing adherence to regulations and fostering public confidence. [26]. Figure 2 shows IsoLight, a precision medical tool invented by iCarbonX for profiling the cells of single-cell chips and software products.

Case of BioMap: accelerating drug development through AI

The dynamic biotechnology startup BioMap was founded in China and is dedicated to utilizing state-of-the-art AI-driven methods to hasten medication development. With a focus on efficiency enhancement, the company uses artificial intelligence (AI) to assess complicated biological datasets, including pharmaceutical interactions, proteomics, and genomes. BioMap's strategy approach combines AI algorithms for lead optimization and target discovery with real-time data analytics and predictive modeling to speed up drug development. Collaborations between AI firms and academic institutions expand their technological capabilities. Because of this, BioMap's implementation of AI has significantly decreased the time and expenses related to drug development, allowing for the quicker identification of viable drug candidates and creating a more effective development pipeline. The firm has successfully brought innovative treatments to market in a record time. Notwithstanding these achievements, BioMap still has issues with its AI infrastructure's scalability and integration of various datasets. To keep personnel updated on the latest developments in AI technology, ongoing efforts are being made to solve these issues and provide them with ongoing education and training. A sample picture of the BioMap tool used for accelerating the drug development process is captured in Fig. 3.

Case of XtalPi: AI-enhanced drug discovery

XtalPi, a pioneering pharmaceutical technology company in China, specializes in advancing drug discovery through AI-enhanced methodologies. Their strategic focus is leveraging computational approaches to optimize drug formulations and accurately predict properties. XtalPi's distinctive approach integrates quantum mechanics and AI algorithms, enabling the modeling of molecular interactions, prediction of drug solubility, and optimization of drug formulations. Through partnerships with global pharmaceutical firms, XtalPi enhances its access to diverse datasets, facilitating virtual screening of compounds and expediting the lead optimization process. Moreover, Xtalpi has listed these objectives as their

Fig. 2 IsoLight precision medical tool

Fig. 3 BioMap AI tool for drug delivery

mandate in improving health care and drug delivery systems, and they include:

(1) Target characterization and identification of binding modes
(2) Ideation and exploration of novel chemical space
(3) Accurate forecasting of potency and properties
(4) Formulation, synthesizing and evaluation strategies
(5) AI-enhanced physics based on computational modeling

The incorporation of AI at XtalPi has transformed drug discovery, markedly reduced preclinical development timelines, and identified more stable and effective drug formulations. Despite these successes, XtalPi grapples with challenges related to the intricate nature of quantum mechanics simulations and the continual validation of AI models. Ongoing efforts are directed at ensuring seamless integration with existing pharmaceutical workflows [37]. Figure 4 indicates the collaborative approach adopted by Xtalpi with partners to power macromolecule programs that can create custom-based solutions integrated into their AI machine called the ID4 platform.

Evaluating the benefits and challenges of AI in the drug discovery and pharmaceutical product

Potential benefits of AI in drug discovery and pharmaceutical product

Drug repurposing

AI is essential to drug repurposing because it provides a strong and creative method for finding novel therapeutic applications for already-approved medications. AI's capacity to evaluate large and varied historical data, comprising genetic, surgical, and pharmacologic statistics, is one of the primary benefits of medication repurposing [52]. AI algorithms can find possible interconnections and links through examination that might not be readily evident using more conventional techniques. AI can quickly treat existing medications with an opportunity to alleviate various ailments by employing ML models to go through complex data and unearth novel findings [52]. Specialists can bypass some phases of expansion, such as assurance of safety, which was already completed after the drug's first acceptance, by using AI to repurpose existing pharmaceuticals [20]. To meet patients' immediate healthcare demands, it is very important to streamline the clinical trial process because it enables clients to receive therapies more quickly.

Sufyan et al. [44] denoted that AI systems can track subtle patterns and connections in data that may escape human scrutiny. Thus, the ability to make coincidental discoveries broadens the scope of repurposing medication, revealing possible remedies for ailments other than those for which they were originally designed. Moreover, AI-driven medication repurposing multidisciplinary perspective facilitates a more comprehensive comprehension of the biological causes of disease, opening the door to novel and unanticipated methods for therapy [19]. In summary, AI is essential for drug repurposing because it can transform the drug development process by providing quicker, more efficient and creative measures to find new therapeutic uses for already-approved medications. This has the potential to find novel answers to urgent medical challenges and expedite the delivery of therapies to patients.

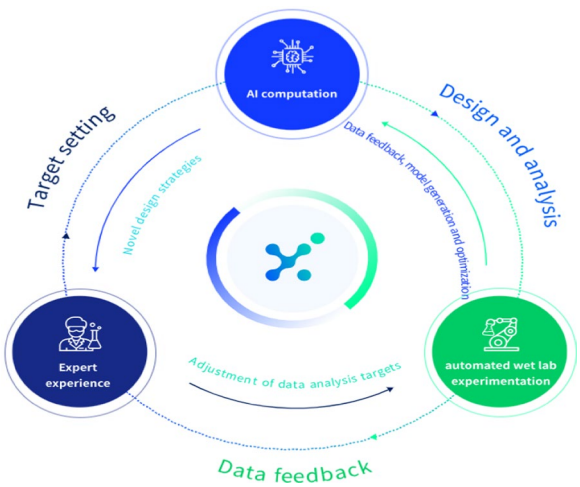

Fig. 4 AI machine-ID4 platform

Target identification

The technique of finding a medicine involves a critical called pinpointing the target. Because of its numerous advantages, AI plays a significant role in the success and efficacy of this procedure. Since AI can sift through vast amounts of complex biological information and data, it is essential for target identification [22]. AI algorithms can find possible treatment targets more speedily than conventional techniques since they can evaluate proteomics, genomes and other omics data. Moreover, AI helps find fresh pathways and interconnections in information essential to the target assessment process. ML algorithms recognize patterns and correlations that may be challenging for human researchers to identify [28]. This capability allows AI to reveal potential targets that may have been overlooked using conventional approaches. By simultaneously considering many factors, AI enhances the comprehensiveness and accuracy of target identification, opening up new avenues for developing targeted and effective therapeutic interventions.

The essence of AI in target identification is further underscored by its role in personalized medicine. AI can analyze large-scale patient data, including genetic information, to identify specific disease-associated biomarkers [26]. This personalized approach allows for identifying effective targets in treating a particular disease and is tailored to individual patient profiles, potentially improving treatment outcomes and minimizing adverse effects [27]. In essence, AI in target identification brings a level of precision and efficiency that has the potential to revolutionize the drug discovery process and pave the way for more effective and personalized therapeutic interventions [50].

Clinical trial optimization

ML algorithms can analyze diverse data sources, including electronic health records and real-world data, to identify suitable candidates for clinical trials. By streamlining the recruitment process and matching patients with specific trial criteria, AI accelerates the enrolment phase, reducing delays and ensuring that trials progress more swiftly [16, 22, 36]. Another critical role of AI in clinical trial optimization is in the design and management of trials. AI systems can assess historical data, enhance trial protocols and predict medical challenges confronting patients. AI also help to maximize client satisfaction and participation in clinical studies. AI provided the platform to evaluate patient input from various reports, including patient forums and social media platforms, using sentiment analysis and processing of natural language. With these insightful data on patient experience, trial administrators will be better equipped to quickly resolve issues, strengthen their interaction plans and increase participant engagement. By providing a data-driven, patient-centered approach, the integration of AI in clinical trial optimization marks a paradigm shift and the ability to expedite procedures, lower costs and more quickly bring novel therapies to the marketplace [24, 26, 34].

Quality control and assurance through AI

Mahato [30] revealed that with its enhanced ability to improve efficiency, precision, and the overall quality of the product, AI is becoming a more vital component of quality assurance and control throughout a wide range of industries. AI ensures that products satisfy strict requirements by automating quality control operations in production. Large production of data sets can be evaluated by ML algorithms to locate abnormalities and trends, enabling real-time prompt corrections and monitoring. This predictive capability helps improve the overall quality of the production process by assisting in the detection and prevention of possible flaws [52]. In pharmaceuticals and healthcare, AI transforms quality assurance by streamlining processes and ensuring compliance with rigorous standards. Large volumes of data about pharmaceutical production, testing in labs, and experimental treatments can be analyzed by AI-powered systems, which can then spot variations and discrepancies from forecasted outcomes. This lowers the potency that client will receive defective medicals by enabling prompt identification of such issues [20]. Additionally, AI contributes to regulatory compliance by automating documentation processes, facilitating easier traceability, and ensuring that every step in the production and testing phases aligns with established quality standards.

Kulkov [25] reported that using AI software to control and quality assurance medical products is a common practice. Testing tools engineered by AI can automatically find vulnerabilities in the software, security issues, and operational problems. Thus, software development cycles can be accelerated while upholding rigorous standards of quality because of these technologies' ability to carry out complicated test situations more quickly than conventional approaches. Likewise, Hasselgren and Oprea [17] espoused that through ML, these systems can learn from previous testing situations and improve their ability to recognize possible problems with every iteration. This improves the effectiveness of the testing procedure while also adding to the general resilience and dependability of software offerings.

AI in drug distribution

AI is instrumental in route optimization and logistics planning. Through advanced algorithms and machine learning models, AI can analyze various factors such as traffic conditions, weather, and transportation costs to optimize the delivery routes of pharmaceutical products. This ensures timely and cost-effective distribution and minimizes the environmental impact associated with transportation. AI-driven route optimization can lead to more sustainable drug distribution practices, aligning with broader efforts to reduce carbon footprints in the pharmaceutical industry [9]. Additionally, AI improves the accuracy and efficiency of order fulfillment processes in drug distribution. AI-powered automated systems can handle order processing, packing, and labeling with high precision, reducing the likelihood of errors and enhancing overall operational efficiency [2]. These AI-driven systems can adapt to fluctuating demand, prioritize critical orders, and provide real-time tracking information, ensuring that healthcare providers and patients receive the proper medications at the right time. Integrating AI in drug distribution is thus instrumental in achieving precision, reliability, and sustainability in the pharmaceutical supply chain [33].

Ongoing challenges facing the implementation of AI among pharmaceutical industries in China

While promising, the adoption of artificial intelligence (AI) in the pharmaceutical industry in China faces several challenges that impact the pace and extent of integration. One primary challenge is the *lack of standardized data*. The pharmaceutical sector has vast and diverse datasets, including clinical trial data, patient records, and genomic information. The absence of standardized formats and interoperability issues among these datasets can impede the seamless integration of AI solutions, making it challenging for pharmaceutical companies to harness the full potential of AI in data-driven decision-making processes [17, 40, 43].

Moreover, the *demand for experts proficient in pharmaceutical sciences* and AI technologies exceeds the current supply [12]. The development, application, and upkeep of AI-driven approaches in drug research, clinical trials, and other pharmaceutical industries are hampered by this shortage. It will take targeted educational initiatives and training programs to close this talent gap and give experts the multidisciplinary skills necessary for sustainable AI integration [7]. Regulatory issues further hamper the extensive use of AI in the Chinese pharmaceutical sector. The healthcare industry's legal framework is always changing, and pharmaceutical companies need to maneuver through intricate procedures to maintain conformance. Adoption may be slowed by the absence of precise and uniform criteria, which could lead to ambiguities and delays when applying for regulatory clearances for AI-driven technologies. [14].

Privacy and data security concerns also pose a big obstacle to using AI in healthcare. There is a greater emphasis on guaranteeing data privacy and protection since healthcare data, such as genetic knowledge and records of patients, are delicate [14]. To alleviate these concerns and promote the broad adoption of AI in pharmaceutical operations, businesses need to invest in cybersecurity safeguards and build confidence with all relevant parties, including clients and regulatory authorities. [15]. Therefore, even if AI has a lot of prospective advantages for the Chinese pharmaceutical business, its wide-ranging implementation will need to address issues, including data harmonization, talent shortages, regulatory complications, and data security concerns [48].

Research conclusion and policy directions

Conclusions

Exploring the influence of AI in drug discovery and the development of pharmaceutical enterprises in China has revealed a substantial shift toward using innovative approaches to promote and enhance the health sector in the country. The current analysis has provided a comprehensive understanding of the potential transformative of applying AI tools in reducing cost, enhancing efficiency and streamlining drug development pipeline policies. The current assessment has revealed that the strategic application and adoption of AI reflects an expanding recognition of its capacity to expedite the invention of new therapeutics, thereby improving and advancing health care and medical science. In addition, this research has shed light on the assumption that China's drug and pharmaceutical industry is at the forefront of outlining cutting-edge tools for research and development which can foster a culture of collaboration and innovation. The report emphasizes the tremendous steps Chinese pharmaceutical businesses have taken in incorporating AI. Still, it also emphasizes the necessity for continued research, international cooperation, and regulatory frameworks to address issues and guarantee AI's moral and responsible application in drug creation. Amidst the paradigm shift in the pharmaceutical industry, stakeholders need to exercise caution when navigating the ethical, legal, and societal ramifications of incorporating artificial intelligence (AI) into the complex drug development processes. In the end, the comparative research indicates that the pharmaceutical business could undergo a revolution if AI technologies are successfully incorporated, with China establishing itself as a key participant in this revolutionary process.

Policy directions

Based on the study's outcome, the research proposes that certain policy recommendations must be implemented to optimize AI's impact on drug discovery. Firstly, fostering collaboration between pharmaceutical companies and research institutions is crucial. Establishing a framework for data sharing and joint projects can leverage collective knowledge and resources, accelerating the pace of drug discovery.

Secondly, there is a need for standardized regulatory guidelines governing the ethical use of AI in pharmaceutical research. Developing a comprehensive set of regulations ensures the responsible and transparent deployment of AI technologies, addressing concerns related to data privacy, bias, and the potential misuse of AI-generated insights. Establishing clear ethical boundaries allows trust in AI applications within the drug development process to be cultivated among industry stakeholders and the public. Furthermore, incentivizing AI research and development through government policies can stimulate innovation. Offering tax breaks or research grants to pharmaceutical companies investing in AI technologies encourages the industry to explore and implement cutting-edge solutions. This bolsters the competitive edge of Chinese pharmaceutical companies

in the global market and positions the nation as a leader in AI-driven drug discovery.

Moreover, educational initiatives should be prioritized to bridge the gap between AI developers and pharmaceutical researchers. Promoting interdisciplinary programs that combine expertise in both AI and pharmaceutical sciences can cultivate a new generation of professionals equipped to harness the full potential of AI in drug discovery. Collaboration between academic institutions and industry players can facilitate knowledge exchange, fostering an environment conducive to continuous learning and adaptation. In addition, creating a centralized AI platform that aggregates and anonymizes data from various pharmaceutical companies can enhance the industry's collective intelligence. This platform could serve as a hub for shared insights, best practices, and AI algorithms, using advancements in drug discovery on a broader scale. Such a collaborative approach mitigates the fragmentation of efforts and maximizes the benefits of AI technologies across the entire pharmaceutical ecosystem.

Lastly, ongoing monitoring and evaluation mechanisms should be established to assess the impact of AI interventions in drug discovery and development. Regular audits can ensure compliance with ethical standards, measure implemented policies' effectiveness, and identify improvement areas. This adaptive approach enables the refinement of policies based on real-world outcomes, ensuring that the integration of AI in pharmaceutical processes aligns with societal expectations and ethical considerations. In conclusion, a comprehensive and collaborative approach, anchored by robust regulations and incentives, is essential to harness the full potential of AI in drug discovery among pharmaceutical companies in China.

Limitations and future research directions

Integrating AI in drug discovery and development has undeniably revolutionized the pharmaceutical landscape, particularly in China. However, this technological advancement is not without its limitations. One major challenge lies in the availability and quality of data for training AI models. The success of AI algorithms in drug discovery heavily depends on access to comprehensive and reliable datasets, which can be a bottleneck in regions where data sharing and standardization practices may vary. Additionally, the interpretability and explainability of AI-generated insights remain significant concerns, especially in the highly regulated field of pharmaceuticals. Future research in this domain should address these limitations by establishing robust data-sharing frameworks, improving the transparency of AI algorithms, and enhancing the collaboration between pharmaceutical companies, research institutions, and regulatory bodies. Moreover, exploring the potential ethical implications of AI-driven drug discovery and development is crucial to ensuring responsible and equitable deployment of these technologies in advancing healthcare solutions.

Author contributions
AKS did conceptualization and data curation; FN performed formal analysis and funding acquisition.

Funding
No funding was received.

Data availability
The manuscript has no associated data.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors reviewed and approved the manuscript for publication.

Competing interests
No potential conflict of interest was reported by the author.

Received: 19 January 2024 Accepted: 2 April 2024
Published online: 08 April 2024

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