Published: 28th June 2025

ANACHEM JOURNAL
ISSN: 2006-5221 (Online)

THE ROLE OF ARTIFICIAL INTELLIGENCE IN HERBAL MEDICINE FORMULATIONS: A REVIEW

[*1]Aghanwa, C.I., [1]Obiefuna, J.N. and [1]Akinyele, A.B.

[1]Department of Pure and Industrial Chemistry, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria.

*Corresponding author's e-mail: ci.aghanwa@unizik.edu.ng.

DOI: ***https://doi.org/10.5281/zenodo.15734072***

ABSTRACT

This review examines the increasing influence of artificial intelligence (AI) on ensuring and improving the quality of herbal medicine. It discusses how machine learning, deep learning, and other AI-based techniques are being utilized to improve the identification of medicinal herbs, standardize quality, optimize formulations, and predict interactions between drugs and herbs. These technologies are crucial in addressing ongoing challenges in herbal medicine, including inconsistent quality, adulteration, and a lack of scientific validation. Recent AI advancements include standardizing herbal products, improving treatment recommendations for conditions like hypertension, and supporting the development of formulations that comply with Good Manufacturing Practice (GMP). AI systems also enable personalized treatment by analysing complex relationships between symptoms and herbal components. However, obstacles remain. Major limitations include the scarcity of high-quality, well-maintained datasets, the structural complexity of herbal compounds, high computational requirements, and concerns regarding data privacy and ethics. Furthermore, the "black box" nature of many AI models can make their decision-making processes opaque and difficult to trust. Despite these challenges, AI presents promising opportunities to enhance the safety, reliability, and effectiveness of herbal medicines by integrating traditional knowledge with modern, data-driven approaches. Achieving its full potential will require increased transparency in AI algorithms, improved data quality, robust ethical safeguards, and collaboration among technology specialists, scientists, and practitioners of traditional medicine.

Keywords: Artificial intelligence, herbal medicine, herbal formulation, machine learning, quality control, neural networks

INTRODUCTION

In recent times, there has been a growing recognition of the importance of good nutrition in maintaining health, which underscores the value of herbs (Altun *et al.,* 2022). Herbs are highly valued for their healing abilities in a range of ailments, thanks to the active compounds they contain (Sharma *et al.,* 2025). Throughout the world, medicinal plants have been utilised in treatments for centuries and continue to play a vital role in traditional healing practices (Gebre *et al.,* 2023). An increasing number of people are turning to herbal remedies from natural sources because they generally have

fewer side effects and offer numerous health benefits (Sharma *et al.,* 2025).

According to Jiang & Deng (2025), herbs exhibit notable differences in their hue, texture, and fragrance. The identification of herbs predominantly employs organoleptic approaches, which significantly rely on the proficiency of botanists. Furthermore, various chemical, phytochemical, and analytical methodologies, including streamlined analytical processes, are utilized to assess the quality of herbal components (Che Soh *et al.,* 2017). Nonetheless, the increasing morphological resemblances among flora species within the same familial group have complicated precise identification due to the overlap in their physical traits (Che Soh *et al.,* 2017).

Herbal remedies pose several challenges, particularly in accurately identifying and verifying their ingredients (Zhou *et al.,* 2024). Traditional methods, such as examining the herb and assessing its taste and smell, are often slow, subjective, and heavily reliant on expert knowledge. Consequently, they are prone to errors (Huang *et al.,* 2023). These shortcomings can lead to misidentification, adulteration, contamination, and inconsistencies in the formulation of herbal products (Boer *et al.,* 2015).

Despite the increasing popularity of herbal medicines, concerns persist about their quality and efficacy. In India, the herbal market is projected to reach INR 1,900 billion, with an annual growth rate of approximately 19% (Sharma *et al.,* 2025). On a global scale, the herbal medicine market was estimated at USD 233.08 billion in 2024 and is expected to reach USD 437 billion by 2032 (Fortune Business Insights, 2025). As worldwide utilization of herbal drugs rises, anxieties regarding their safety also increase, often arising from the inferior quality of raw materials or end products. To tackle these challenges, incorporating artificial intelligence (AI) into identification and quality control processes is emerging as a promising strategy to improve the accuracy, efficiency, and safety of developing herbal medicines.

In contrast to humans, AI-driven technologies are expected to possess the capability to accurately distinguish between various species (Ibrahim *et al.,* 2023). These systems can achieve remarkable precision in identifying leaf species and diagnosing plant diseases across a broad spectrum (Dagwale & Adakane, 2023). AI methodologies are adept at recognizing 95 species of medicinal plants, contributing to Ayurvedic formulations and reducing reliance on subjective identification methods (Soni *et al.,* 2023).

Recent scholarly investigations have demonstrated the potential of AI, including frameworks such as neural networks and reinforcement learning, in developing and optimizing herbal blends tailored for specific medical conditions, such as hypertension and chronic diseases. These AI models analyse extensive datasets concerning plant attributes, interactions, and clinical outcomes to propose formulations that enhance therapeutic efficacy while reducing adverse effects, thereby improving patient outcomes and ensuring safety (Syzdykova *et al.,* 2025; Yang *et al.,* 2024). Embracing new technologies can reduce both time and cost while also fostering a better understanding of the relationship between herb formulation design and production elements (Navya *et al.,* 2022).

Artificial intelligence (AI) has the potential to enhance the precision and effectiveness of herbal treatment standardisation, thereby paving the way for more reliable and potent remedies (Sharma *et al.,* 2025). AI-driven recommendation systems are improving the accuracy of herbal prescriptions in traditional medicine. These systems can decode complex, multidimensional relationships between symptoms, conditions, and herbs, surpassing traditional methods and providing more personalised and effective therapeutic suggestions (Li *et al.,* 2022). Despite the significant opportunities AI presents for increasing efficiency and facilitating informed decision-making in drug development, challenges remain, including limited access to data, model interpretation, and compliance with regulatory requirements (Noorain *et al.,* 2023).

ARTIFICIAL INTELLIGENCE AND HERBAL MEDICINES

Artificial Intelligence is described as a branch of computer science that focuses entirely on solving problems and creating machines capable of performing tasks that would otherwise require human intelligence and operators (Sethuraman, 2020). Here, AI is broadly characterised as a field concerned with the development and implementation of algorithms for analysing, learning from, and interpreting information. AI encompasses various branches of machine learning, logic and probabilistic theories, pattern recognition, and biologically inspired methods, such as neural networks, evolutionary computing, or fuzzy models, collectively known as "computational intelligence" (Man *et al.,* 2001).

As AI becomes increasingly interwoven with medicine in various fields, we are witnessing a steady shift in healthcare and biomedical research patterns (Adeluwa *et al.,* 2021). The traditional medical field is undergoing a rapid adoption of AI, including in complementary and alternative medicine (CAM) (Coleman *et al.,* 2020; Khan *et al.,* 2021).

Artificial intelligence has the potential to enhance the detection and quality mapping of traditional herbal medicines, leading to more advanced methods for their identification and verification (Baldi *et al.,* 2024). The TCMFP approach, an innovative system for predicting traditional Chinese medicine formulas, can effectively forecast the optimal herbal combinations for treating ailments such as Alzheimer's, asthma, and atherosclerosis. This approach integrates the principles of traditional Chinese medicine with artificial intelligence and network science algorithms (Tong *et al.,* 2023).

Artificial intelligence tools, such as neural networks, can analyze botanical data, interactions, and therapeutic outcomes to create optimized herbal formulations. For example, AI-generated compounds for regulating blood pressure have been designed to enhance efficacy and reduce side effects, demonstrating the potential for improved patient outcomes in cardiovascular health (Syzdykova *et al.,* 2025).

AI can provide a deeper understanding of how drugs interact with herbal products and identify potential links that may pose risks (Sakkalis *et al.,* 2025). It can also forecast standard curves for herbal remedies with an impressive accuracy of 95.67%, enhancing the precision and effectiveness of standardizing these natural treatments (Chamoli *et al.,* 2025).

CURRENT TRENDS IN ARTIFICIAL INTELLIGENCE FOR HERBAL MEDICINE FORMULATION

The integration of artificial intelligence (AI) into the development of herbal medicines is rapidly transforming the field, offering unparalleled precision, celerity, and insight. AI technologies such as machine learning, deep learning, and network-based algorithms are being employed in diverse areas, such as:

a) Enhancing Standardization and Quality Control in herbal medicine formulation

Artificial intelligence models are currently used in forecasting normative curves for phytopharmaceuticals, significantly improving the accuracy and effectiveness of determining the concentrations of active constituents compared to traditional methods. This technological advancement optimises experimental processes and facilitates the development of more reliable and potent botanical remedies, thereby addressing the complexity and variability inherent in plant-derived medications more effectively. (Chamoli *et al.,* 2025).

b) **Optimising Herbal Formulations:** Recent studies have shown that AI tools, such as neural networks and reinforcement learning, are being employed to design and optimize herbal blends for conditions like hypertension. These models analyze large datasets to create effective and safe formulations, thereby improving patient outcomes. (Syzdykova *et al.,* 2025; Yang *et al.,* 2024).

c) **Intelligent Prescription and Recommendation Systems:** AI recommendation frameworks employing multi-graph convolutional networks combined with genetic algorithms significantly improve the precision of herbal prescriptions within the realm of traditional medicine. These models adeptly capture intricate associations among symptoms, syndromes, and medicinal herbs, thus exceeding the capabilities of conventional algorithms to deliver more individualized and efficacious treatment recommendations (Li, *et al.,* 2022; Tong *et al.,* 2023).

d) **Mechanistic Insights and Drug-Herb Interaction Assessment in herbal therapies:**

Artificial intelligence plays a crucial role in clarifying the mechanisms of action of herbal medicines and predicting potential drug interactions. By integrating comprehensive biological and pharmacological datasets, AI algorithms can identify molecular targets, pathways, and risks of interactions, thereby enhancing the safety and informed use of herbal products within clinical settings (Sakkalis *et al.,* 2025; Leung *et al.,* 2022).

e) **Data-Driven Approaches and Big Data Integration:**

Utilizing AI models trained on extensive clinical and insurance datasets facilitates the development of GMP-certified herbal formulations grounded in empirical evidence. These approaches integrate the expertise of medical practitioners with the analytical power of big data to provide therapies that are safe, of superior quality, and tailored to individual needs, which is especially advantageous for addressing intricate or uncommon diseases.(Chen & Wang, 2024; Zhu *et al.,* 2023).

EXAMPLES OF ARTIFICIAL INTELLIGENCE DESIGN MODELS USED IN HERBAL MEDICINE FORMULATION

Numerous artificial intelligence paradigms and techniques have been developed to address challenges such as ensuring the accuracy of prescriptions, maintaining quality assurance, and predicting interactions between pharmaceuticals and herbal

compounds. Recent advancements in artificial intelligence have predominantly focused on three areas: machine learning, deep learning, and large language models (Hou *et al.,* 2025).

a. **Machine Learning Models** (MLM) are statistical frameworks capable of discerning intrinsic patterns within data and extending their applicability to previously unobserved data, all without adhering to explicit directives (Hou *et al.,* 2025).

- Standard Curve Prediction: Machine learning models facilitate the prediction of standard curves for herbal medicines, enhancing the accuracy and speed of measuring active compound levels compared to traditional methods (Chamoli *et al.,* 2025).

b. **Classification Models**: Models such as logistic regression, support vector machines (SVM), k-nearest neighbours (KNN), decision trees (DT), random forests (RF), and Light GBM are employed to categorise and verify herbal medicines utilising hyperspectral imaging data.(Yang *et al.,* 2024;Baldi, *et al.,* 2024).

- Support Vector Machines (SVM): It is used for categorizing herbs, focusing on identifying those with traits such as reducing inflammation, combating oxidation, or fighting microbes based on their chemical makeup. A practical example is employing a multi-class SVM to sort traditional herbal remedies found in clinical records (Yang *et al.,* 2024).
- Random Forest (RF) & Decision Trees: Popular Renowned for forecasting the therapeutic outcomes of herbal mixtures or simulating herb–drug interactions, RF algorithms offer a robust predictive capability. These algorithms facilitate the integration of phytochemical profiles alongside pharmacologic pathways to ensure reliable projections (Baldi *et al.,* 2024; Spanakis,2023).
- Convolutional Neural Networks (CNN): used to examine visual characteristics of patients, such as facial or tongue images, to suggest personalized herbal treatments.
- Recurrent Neural Networks (RNNs) / LSTM: This is particularly applicable to systematic treatment planning, especially for chronic ailments. An example of this is Prescdrl. PrescDRL is a progressive herbal prescription refinement model and a profound reinforcement learning framework that amalgamates an LSTM-like mnemonic architecture to enhance long-term herbal prescription strategies for diabetes. It exhibited remarkable improvements in single-step rewards (approximately 117–153%) relative to medical practitioners, emphasising long-term efficacy over maximising reward at each interval, thus ensuring superior patient outcomes with up to a 63% enhancement in recall compared to expert physicians. PrescDRL yielded a heightened therapeutic impact, with the single-step reward advancing by 117% and 153% in comparison to medical professionals. Moreover, PrescDRL surpassed the benchmark in prescription forecasting, with precision increasing by 40.5% and recall rising by 63%. (Yang *et al.,*2023).
- Reinforcement Learning (RL) / Deep RL: employed in dynamic treatment planning where AI agents

propose evolving prescriptions over multiple visits (Yang *et al.,* 2023).

C. **Deep Learning and Neural Networks**: Deep learning and neural networks are a specialized branch within the field of machine learning, distinguished by the use of deep neural networks that consist of many layers, often numbering over a hundred. The structure of the components that make up deep learning models includes fully connected layers, Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), Graph Neural Networks (GNN), attention mechanisms, and others (Hou *et al.,* 2025). CNNs are typically favoured for handling visual data, like images, while RNNs excel at processing sequential information, such as text.

- Deep Learning for Interaction Prediction: Deep learning frameworks, which include large language models (LLMs), Natural Language Processing (NLP) methods, and variational graph autoencoders (VGAEs), are used to predict how herbal treatments and drugs interact, improve formulation strategies, and support precision medicine (Jin *et al.,* 2025).
- Large language models (LLMs) are advanced deep learning structures that typically comprise millions of parameters. The transformer is the key element most commonly used to build LLMs.These models are trained using vast amounts of text through a self-supervised approach. At their core, LLMs work as statistical probabilistic systems, assigning probabilities to sequences of words. Their primary goal is to enhance the likelihood of generating word sequences that resemble human-produced language, thereby helping them understand how humans naturally communicate.
- BERT/GPT: The application of BERT/GPT models (Bidirectional Encoder Representations from Transformers/Generative Pre-trained Transformers) is becoming more prevalent in the semi-automation of extracting formula information or clinical practice patterns from extensive collections of herbal medicine literature.
- Named Entity Recognition (NER) and textual analysis elucidate botanical nomenclature, methods of formulation, and customary therapeutic applications within historical documents or scholarly articles, adopting a more formal academic expression.(Hou *et al.,* 2025)

D. **ChatGPT Neural Network**: Artificial neural networks similar to ChatGPT have been used to assess plant data and create optimized herbal combinations for illnesses like high blood pressure, improving both effectiveness and safety (Syzdykova *et al.,* 2025).

E. **Network-Based and Graph Models**

- Multi-Graph Convolutional Networks (MGCN): These models capture the complex and multi-layered relationships between symptoms, syndromes, and herbal remedies, which significantly boost the accuracy of recommendations for herbal treatments (Li *et al*, 2022).
- Graph Neural Networks (GNN): Designed to represent complex relationships among herbal components, phytochemicals, and biological targets. A study conducted in 2024 employed GNNs to assess the balanced compositions in Traditional Chinese Medicine (TCM) recipes, unveiling interaction patterns from 6,080 ancient herbal preparations (Zeng & Jia, 2024).

F. **Knowledge Graphs and Network Target Scoring:**

AI frameworks, such as DeepTCM and TCMFP, employ knowledge graphs alongside network science techniques to emulate interactions between herbs and targets, as well as between genes and diseases. They anticipate ideal herbal formulations, evaluate traditional medicine compatibility standards, and identify contraindications, including incompatible herb pairs in Traditional Chinese Medicine. Graph Neural Network models construct computational "compatibility graphs" that depict interactions between cytochrome and targets, as well as between herbs. These models amalgamate traditional wisdom with contemporary pharmacological information (Zhu *et al.,* 2023; Tong *et al.,* 2023).

ADVANTAGES OF AI IN HERBAL MEDICINE FORMULATION

(i) Overcoming the identification problem of herbal drugs: Recognizing traditional herbal samples is often a tough task and heavily depends on the sensory skills and expertise of the botanist or specialist involved. AI technology enhances the speed and accuracy of identifying medicinal herbs (Gao & Liu, 2024).

(ii) Ensuring quality and safeguarding against adulteration: The surge in the popularity of herbal medicine following the COVID era heightens the risk of adulteration in herbal pharmaceuticals, which can ultimately result in health complications for consumers. Artificial intelligence-enabled technology enhances quality assurance by providing a comprehensive approach to identifying and verifying herbal medications, effectively detecting potential adulterants and contaminants (Chu *et al.,* 2022).

(iii) The combination of AI with the distinct characteristics of herbal medicine is poised to bring breakthroughs. This approach empowers everyday individuals and key players to distinguish authentic herbal products from any tampering, thereby ensuring their safety and effectiveness.

(iv) It promotes the use of traditional herbal medicine (THM) products that are validated by Good Manufacturing Practice (GMP) standards (Chen & Wang, 2024).

(v) The utilization of artificial intelligence in preventive healthcare, aimed at diminishing the risk of diseases through early intervention, is crucial for improving patient outcomes and protecting public health (Hou *et al.,* 2025).

(vi)The integration of AI with herbal medicine synergizes remarkably to accelerate the discovery of new treatment combinations and enhance the understanding of the intricate interactions between plant compounds and their biological targets (Kumbhar *et al.,* 2024).

LIMITATION OF ARTIFICIAL INTELLIGENCE TECHNIQUES IN HERBAL MEDICINE

Utilizing machine learning models within AI-centric methods for identity verification and authentication of herbal medicines offers several benefits, including increased speed and accuracy. However, these ML-based strategies for detecting and validating herbal drugs come with several drawbacks, listed below:

(i) Quantity and quality of data: There is a noticeable shortage of high-quality, well-annotated datasets related to herbal remedies. When data is insufficient, it can result in underfitting, meaning the model struggles to recognize the underlying patterns within the data. Given that herbal treatments are sourced from various origins and locations, they

introduce significant diversity to the dataset (Zuo *et al.,* 2021).

(ii) Selection and extraction of complex features: Many herbal medicines have very complex structures that make it very difficult for ML models to identify the unique pattern for their identification. Noises that are generally attached to the data of medicine are also an important factor that limits the application of ML (Machine learning) models (Rahmani *et al.,* 2021).

(iii) Lack of computational resources: Models in machine learning generally necessitate advanced computational resources, constituting a significant hindrance to their utility. Furthermore, scalability to larger dimensions often emerges as a challenge due to the inadequate availability of essential digital resources (Nguyen & Truong, 2024).

(iv)Ethical considerations during the application of AI in traditional herbal medicines are vital pillars of healthcare. Integrating AI into the healthcare system raises ethical concerns, particularly regarding data privacy and the trustworthiness of AI's decision-making capabilities. There are potential risks of data breaches and unlawful access to sensitive information collected by AI systems (Mwogosi, 2025).

(v) Errors and inaccuracies in the AI-based model can eventually lead to incorrect identification or authentication that can put the user at high risk. Robust testing, validation, continuous monitoring, and clear policies for AI systems are crucial (Chu *et al.,* 2022). Even while AI can't take the role of clinical judgment entirely, it may nonetheless assist physicians in making better choices.

(vi) Need for transparency: Most AI models operate as black boxes, making it difficult to understand the decision-making process of safety and reliability (Rane *et al.,* 2024).

(vii) AI systems can sometimes display bias because the data used to train them or the way they make decisions is skewed, resulting in uneven outcomes in medical care. The lack of transparency is a challenge with AI technologies, as they often operate like black boxes, making it difficult to understand how they arrive at their decisions (Hammood, 2023).

CONCLUSION

AI is reshaping herbal medicine by blending age-old wisdom with cutting-edge technology, resulting in more reliable, safer, and efficient treatments. It utilizes machine learning and neural networks to enhance prescription accuracy and quality assurance. Tackling biases and safeguarding data are vital to maintain fairness in AI-driven initiatives. Although AI provides tailored and precise solutions, its effectiveness hinges on harmonizing innovation with ethics, establishing clear guidelines, and fostering teamwork in research.

RECOMMENDATIONS

To maximize the benefits of AI in herbal medicine formulation, the following steps are recommended:

a.) Integration of Traditional Knowledge with Modern AI: Build hybrid models that integrate ethno-botanical wisdom with clinical and molecular datasets.

b.) Develop standardized digital ontologies for herbal medicine systems like Ayurveda, TCM, and Kampō.

c.) Establishment of Robust Databases: Create comprehensive, open-access databases combining herbal composition, phytochemical profiles, toxicity data, and clinical outcomes to improve AI training accuracy.

d) Cross-Disciplinary Collaboration: Encourage partnerships among AI experts,

pharmacologists, ethnobotanists, and traditional healers to ensure culturally informed and scientifically rigorous models.

e.) Regulatory Framework Development: Update regulatory standards to support AI-augmented herbal product development, including validation protocols for AI-predicted formulations.

f.) User-Friendly Platforms: Develop AI-powered tools accessible to clinicians and herbalists for personalized formulation, real-time diagnosis, and evidence-based recommendations.

g.) Ethical and Cultural Sensitivity: Ensure AI applications respect the cultural origins of traditional medicine and promote fair intellectual property practices regarding indigenous knowledge.

REFERENCES

Adeluwa, T., McGregor, B. A., Guo, K., & Hur, J. (2021). Predicting drug-induced liver injury using machine learning on a diverse set of predictors. *Frontiers in Pharmacology,* 12, 648805.

Baldi, A., Naman, S., & Sharma, S. (2024). Recognition and quality mapping of traditional herbal drugs: way forward towards artificial intelligence. *Traditional Medicine Research, 10(1), 2.* https://doi.org/10.53388/tmr20240416001.

Boer, H., Ichim, M., & Newmaster, S. (2015). DNA Barcoding and Pharmacovigilance of Herbal Medicines. Drug Safety, 38, 611-620. https://doi.org/10.1007/s40264-015-0306-8.

Chamoli, V., Raina, D., & Mall, P. (2025). Artificial Intelligence -Powered Precision: Predicting Standard Curves for Herbal Medicines. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.5083338.

Che Soh, A., Yusof, U. K., Radzi, N. F. M., Ishak, A. J., & Hassan, M. K. (2017). Classification of aromatic herbs using artificial intelligent technique. *Pertanika Journal of Science & Technology,* 25.

Chen, M., & Wang, S. (2024). Herbal Medicine for Rare Diseases. . https://doi.org/10.1201/9781032726625.

Chu, H., Moon, S., Park, J., Bak, S., Ko, Y., & Youn, B. Y. (2022). The use of artificial intelligence in complementary and alternative medicine: A systematic scoping review. *Frontiers in pharmacology*, 13, 826044.

Coleman, B. C., Fodeh, S., Lisi, A. J., Goulet, J. L., Corcoran, K. L., Bathulapalli, H., & Brandt, C. A. (2020). Exploring supervised machine learning approaches to predicting Veterans Health Administration chiropractic service utilization. *Chiropractic & manual therapies,* 28, 1-13.

Dagwale, S. S., & Adakane, P. (2023). Prediction of Leaf Species & Disease using AI for Various Plants. *International Journal for Multidisciplinary Research*, 5(3). https://doi.org/10.36948/ijfmr.2023.v05i03.4169

Fortune Business Insights (May,2025).Herbal Medicine Market Size, Share & Industry Analysis, By Form (Powder, Liquid & Gel, and Tablets & Capsules), By Application (Pharmaceutical & Nutraceutical, Food & Beverages, and Personal Care & Beauty Products), and Regional Forecast, 2025-2032 Last Updated: June 02, 2025 Source: https://www.fortunebusinessinsights.com/herbal-medicine-market-106320

Gao, Y. and Liu, M. (2024). Application of machine learning based genome sequence analysis in pathogen identification. *Frontiers in Microbiology,* 15. https://doi.org/10.3389/fmicb.2024.1474078

Hammood, Z. (2023). artificial intelligence in applied medicine. *Barw Medical Journal*. https://doi.org/10.58742/xby1yt29

Hou, C., Gao, Y., Lin, X., Wu, J., Li, N., Lv, H., & Chu, W. C. (2025). A review of recent artificial intelligence for traditional medicine. *Journal of traditional and complementary medicine,* 15(3), 215–228. https://doi.org/10.1016/j.jtcme.2025.02.009

Huang, J., Kong, W., Liu, F., Wang, W., Yang, R., Zhao, Y., Peng, J., Zhang, C., & Chen, R. (2023). Trends in digital detection for the quality and safety of herbs using infrared and Raman spectroscopy. *Frontiers in Plant Science,* 14. https://doi.org/10.3389/fpls.2023.1128300.

Ibrahim, N., Musleh, D., Alkharraa, M., Alkhulaifi, D., Rahman, A., & Gabr, D. (2023). Transfer Learning Approach to Seed Taxonomy: A Wild Plant Case Study. *Big Data Cogn. Comput.,* 7, 128. https://doi.org/10.3390/bdcc7030128.

Jiang, X. and Deng, H. (2025). A cognitive onomastics study of traditional chinese herb names. *Sage Open,* 15(1). https://doi.org/10.1177/21582440251323662

Jin, X., Zhou, Z., Zhuo, L., Li, K., & Yuan, S. (2025). Enhancing Herbal Medicine-Drug Interaction Prediction Using Large Language Models. *IEEE journal of biomedical and health informatics*, https://doi.org/10.1109/JBHI.2025.3558667.

Kumbhar, P., Pandey, N., Kumar, B., & Vinchurkar, K. (2024). Artificial intelligence in herbal medicine formulations. 147-162. https://doi.org/10.2174/9789815305753124010010

Leung, E., Chang, H., Wang, X., Wu, C., & Chen, J. (2022). Editorial: Artificial Intelligence in Traditional Medicine. *Frontiers in Pharmacology,* 13. https://doi.org/10.3389/fphar.2022.933133.

Li, C., Zhao, W., Fan, H., Li, Z., Lin, X., Zhou, C., Yang, Z., & Lu, W. (2022). TCM herbal prescription recommendation model based on multi-graph convolutional network. *Journal of ethnopharmacology,* 115109 . https://doi.org/10.1016/j.jep.2022.115109.

Man, K. F., Tang, K. S., & Kwong, S. (2001). Genetic algorithms: concepts and designs. Springer Science & Business Media.

Mwogosi, A. (2025). ethical and privacy challenges of integrating generative ai into ehr systems in tanzania: a scoping review with a policy perspective. *Digital Health,* 11. https://doi.org/10.1177/20552076251344385

Navya, K., Kamaraj, R., & Bharathi, M. (2022). The Trending Role of Artificial Intelligence and Its Applications in Formulation of Solid Dosage Forms: A Review. *ECS Transactions,* 107(1), 20049.

Nguyen, M. and Truong, H. (2024). On optimizing resources for real-time end-to-end machine learning in heterogeneous edges. *Software Practice and Experience,* 55(3), 541-558. https://doi.org/10.1002/spe.3383

Noorain, Srivastava, V., Parveen, B., & Parveen, R. (2023). Artificial intelligence in drug formulation and development: applications and future prospects. *Current drug metabolism,* 24(9), 622-634.

Rahmani, A. M., Yousefpoor, E., Yousefpoor, M. S., Mehmood, Z., Haider, A., Hosseinzadeh, M., & Naqvi, R. A. (2021). Machine Learning (ML) in Medicine: review, applications, and challenges. *Mathematics,* 9(22), 2970. https://doi.org/10.3390/math9222970

Rane, J., Kaya, Ö., Mallick, S., & Rane, N. (2024). Enhancing black-box models: advances in explainable artificial intelligence for ethical decision-making. https://doi.org/10.70593/978-81-981271-0-5_4

Sakkalis, V., Tsatsakis, A., Pediaditis, M., Tzamali, E., Tzedakis, G., Koumpouzi, C., & Spanakis, M. (2025). Artificial Intelligence Models and Tools for the Assessment of Drug–Herb Interactions. *Pharmaceuticals,* 18. https://doi.org/10.3390/ph18030282.

Sethuraman, N. (2020). Artificial intelligence: a new paradigm for pharmaceutical applications in formulations development. *Indian J Pharm Educ Res,* 54(4), 843-846.

Sharma, S., Naman, S., & Baldi, A. (2025). Recognition and quality mapping of traditional herbal drugs: way forward towards artificial intelligence.

Soni, P., Yenishetti, S., Panat, L., Karajkhede, G., & Dhavale, S. (2023). Medicinal Plant Species Identification Using AI. 2023 IEEE 11th Region 10 Humanitarian Technology Conference (R10-HTC), 662-668. https://doi.org/10.1109/R10-HTC57504.2023.10461734.

Spanakis, M. (2023). InSilico Pharmacology for Evidence-Based and Precision Medicine. Pharmaceutics, 15(3), 1014.

Syzdykova, S., Kulbayeva, M., Turekhanova, A., Ibragimova, A., & Toksanbaeva, Z. (2025). Possibilities of artificial intelligence in the development of antihypertensive herbal preparations. *Medicine and ecology.* https://doi.org/10.59598/me-2305-6053-2025-114-1-137-140.

Tong, L., Tian, S., Li, B., Wang, J., Wang, Z., Zong, W., Zhang, S., Liu, S., Zhang, H., Niu, Q., Li, H., & Liu, J. (2023). TCMFP: a novel herbal formula prediction method based on network target's score integrated with semi-supervised learning genetic algorithms. Briefings in bioinformatics. https://doi.org/10.1093/bib/bbad102.

Yang, J., Ahn, J., Yoon, H., Kim, M., Park, S., Lee, H., Jung, D., & Park, S. (2024). Evaluating the Accuracy of Machine Learning Classification Models for Similar Herbal Medicine Using Hyperspectral Imaging. *Journal of Biosystems Engineering.* https://doi.org/10.1007/s42853-024-00224-1.

Yang, K., Wen, T., Zhang, F., Yu, Z., He, X., Wang, N., Su, X., Yu, F., Zhou, X., & Zheng, Q. (2024). PrescDRL: deep reinforcement learning for herbal prescription planning in treatment of chronic diseases. *Chinese Medicine,* 19. https://doi.org/10.1186/s13020-024-01005-w.

Yang, K., Yu, Z., Su, X., He, X., Wang, N., Zheng, Q., Yu, F., Liu, Z., Wen, T. and Zhou, X., (2023). A optimization framework for herbal prescription planning based on deep reinforcement learning. arXiv preprint arXiv:2304.12828.

Zeng, J., & Jia, X. (2024). Graph artificial intelligence for quantifying compatibility mechanisms in traditional Chinese medicine.

arXiv (Cornell University). https://doi.org/10.48550/arxiv.2411.11474

Zhou, X., Li, S., Wang, X., Liu, B., Zhan, J., Zeng, D., Jiang, B., Chai, X., Gong, Z., Liu, M., Xiao, X., Liu, C., Zhu, Q., He, L., Huang, T., & Zhang, X. (2024). Rapid Targeted Screening and Identification of Active Ingredients in Herbal Extracts through Ligand-Detected NMR and Database Matching. *Analytical chemistry.* https://doi.org/10.1021/acs.analchem.4c02255.

Zhu, A., Han, J., Lou, Y., Zhang, Y., Wang, X., Sun, X., Qian, Y., Zhang, B., Cai, L., Wang, Y., & Huang, Z. (2023). Model informed precision medicine of Chinese herbal medicines formulas–A multi-scale mechanistic intelligent model. *Journal of Pharmaceutical Analysis,* 14. https://doi.org/10.1016/j.jpha.2023.12.004.

Zuo, Z., Ip, C., Lai, Y., & Zhang, Y. (2021). Overview of Current Herb–Drug Interaction Databases. *Drug Metabolism and Disposition,* 50, 86 - 94. https://doi.org/10.1124/dmd.121.000420.