Advances in the Standardization of a Rapid Quality Evaluation System for TCM Based on the Fusion of Electronic Senses (E-eye, E-nose, E-tongue) and AI

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Abstract

The quality evaluation of traditional Chinese medicine is moving from traditional sensory identification to a data-driven intelligent stage. Electronic sensory systems such as electronic eyes, electronic noses and electronic tongues can simulate visual, olfactory and taste signals on an objective and quantifiable basis, but their individual discrimination capabilities remain limited within the complex compositional environment of medicinal materials. In recent years, deep learning, multimodal information fusion and standardized testing processes have provided new opportunities for a fast, accurate and traceable "full sensory-intelligent" evaluation system.This paper systematically reviews relevant research conducted both domestically and internationally between 2020 and 2025, proposes a joint framework of "electronic sensory+AI", deeply compares 8 representative technical solutions, connects with national and industry standards, evaluates the current status of industrialization, and analyzes future challenges and opportunities in database construction, interoperability protocols and regulatory coordination, in order to provide a reference for the digitalization and standardization upgrade of the traditional Chinese medicine industry.

Keywords Electronic Sensory System; Artificial Intelligence; Quality Control of Traditional Chinese Medicine; Rapid Evaluation; Standardization

1 Introduction

As an important part of China's traditional medicine system, the quality control of Chinese medicine has always been the core link to ensure efficacy and promote modernization. Traditional Chinese medicine identification methods are highly dependent on artificial sensory experience, such as "three checks and four observations", which are highly subjective and have poor repeatability, and are difficult to meet the stringent requirements of the modern pharmaceutical industry in terms of traceability and objective quantification. In recent years, the development of electronic sensory technology has provided new technical support for the quality evaluation of Chinese medicine. Electronic eye, electronic nose, and electronic tongue systems simulate human vision, smell, and taste, obtain the appearance, smell, and flavor information of medicinal materials through physical or chemical sensors, and can output them in a structured form, which is expected to realize the automation and standardized evaluation of the sensory quality of Chinese medicine. At the same time, the widespread application of artificial intelligence (AI) technology, especially deep learning and multimodal fusion algorithms, provides electronic sensory systems with the ability to extract discriminant features from high-dimensional data and make nonlinear decisions. Studies have shown that deep neural networks that integrate multimodal inputs such as vision, smell, and taste have significantly improved the accuracy of tasks such as Chinese medicine variety identification, origin tracing, and grade discrimination, and have gradually been verified in industrial practice. Since 2020, the integration of electronic sensory technologies and artificial intelligence has emerged as a significant interdisciplinary research hotspot in the field of TCM quality control.

It has made breakthroughs not only in hardware systems and algorithmic architectures but also in the rapid development of standardization frameworks and industrialization pathways.A number of national standards and group specifications have been introduced, marking the technology's move from the laboratory to practical application.

This paper aims to sort out the research results and development trends of "electronic sensory + AI" integration for rapid quality evaluation of traditional Chinese medicine at home and abroad during 2020-2025, focusing on the performance evolution of the three types of perception modules of electronic eyes, noses, and tongues, the deep integration strategy of AI algorithms, the comparative analysis of typical technical solutions, and the promotion of standardization. Through a systematic literature review, the advantages and disadvantages of current research are revealed, the practical application prospects are evaluated, and the theoretical and reference basis for the construction of sensory intelligent detection systems in the future is provided.

2 Technical Basis for the Integration of Electronic Senses and AI

In recent years, with the in-depth application of artificial intelligence in the quality control of traditional Chinese medicine, the hardware performance and algorithm models of electronic sensory systems have shown a trend of coordinated upgrading, and a fusion system with "electronic eye-electronic nose-electronic tongue" as the perception core and AI model as the decision engine has been constructed. This article sorts out the development of relevant key technologies from 2020 to 2025, covering the sensing mechanisms of vision, smell, and taste and their adaptation relationship with deep learning methods.

visual perception (electronic eye) , research generally uses multispectral or high-resolution image acquisition systems to extract morphological information through color space conversion and texture analysis algorithms such as Lab and HSV. Since 2020, Vision Transformer (ViT) has replaced traditional CNN as the mainstream structure, realizing feature extraction and grade recognition of the appearance of Chinese herbal medicine pieces in the range of 300–1000 nm. Its Top - 1 accuracy is about 7 percentage points higher than that of traditional methods [3] .

Olfactory perception (electronic nose) is based on MOX (metal oxide semiconductor) or QCM (quartz crystal microbalance) arrays and can collect volatile organic compounds (VOCs) emitted by Chinese medicinal materials. In order to cope with the response drift of sensors in long-term use, Chen et al. proposed a two-stage drift compensation model in 2024, which increased the F1 value of the odor classification model to 0.93, enhancing the stability and reusability of the model [4] .

Taste perception (electronic tongue) detects soluble bitter substances and flavor ions through optical fiber electrochemical, capacitance/conductivity and other sensors. The mixed signal electronic tongue system developed by Kim et al. (2025) has the ability to resolve 1 μM bitter substances and achieves sub-second response in actual measurements [5].

Multimodal fusion mechanisms have developed rapidly in the past five years. The traditional serial feature concatenation method has been gradually replaced by the multimodal Transformer that integrates the attention mechanism. For example, the AM-DMFN network proposed by Zhang et al. can realize information enhancement interaction between heterogeneous modalities, improve the accuracy of traditional Chinese medicine sample discrimination to 96.1%, and maintain an average inference time of < 0.6 seconds [6].

In addition, the AI model architecture has evolved from early shallow learning algorithms such as support vector machines (SVM) and PCA to lightweight CNN, MobileViT , GNN and interpretable Transformer, taking into account both model accuracy and industrial deployment efficiency. The key feature of this stage is the coordinated advancement of the three aspects of "sensor performance-data fusion strategy-deep model framework", which has laid the technical foundation for the "electronic sensory + AI" joint system in the quality identification of traditional Chinese medicine.

3 Overview of Domestic and Foreign Research Results and Technical Solutions

3.1 List of Representative Technical Solutions

In order to summarize the representative achievements of the integration of electronic sensory and AI in the quality evaluation of traditional Chinese medicine in the past five years, this paper summarizes eight typical technical solutions published in 2020-2025, covering different sensor combinations and algorithm frameworks, with diverse representative medicinal materials, reflecting the current research trend from single modality to multimodality, and from shallow recognition to deep fusion. These solutions have a high frequency of citation and industry representativeness, and can provide a reference for future standardized modeling and industrial application, see Table 1.

Table 1. Representative technical solutions

Serial number	literature	Hardware combination	Core Algorithm	Main medicinal materials	Overall accuracy (%)
1	Zhou 2023	RGB + VIS/NIR Eye	ResNet - 50	Scutellaria baicalensis	95.4
2	Wu 2022	VIS/NIR Eyes + MOX Nose	ViT + PCA	Salvia miltiorrhiza	93.8
3	Chen 2024	10 - MOX Nose	SVM + Drift Compensation	Tangerine peel	90.5
4	Kim 2025	Fiber - optic E - Tongue	Dual-channel CNN	Bitter almonds	92.1
5	Zhang 2025	RGB eyes + MOX nose	AM - DMFN	Chuanxiong	96.1
6	Li 2025	Mobile RGB Eye	MobileViT - Tiny	Angelica	92.4
7	Liu 2025	RGB/VIS Eye + QCM Nose	Explainable GNN	Compound Herbal Pieces	94.2
8	Gobel 2024	VIS Eye + MOX/QCM Nose + E - Tongue	Multimodal Transformer	Saffron	95.3

3.2 Topic Evolution and Research Hotspots

Bibliometrics show that between 2020 and 2025, a total of 986 core papers were published in the field of electronic sensory and artificial intelligence integration, and the research hotspots were mainly concentrated in three key technical directions: "multimodal learning", "sensor drift compensation" and "Explainable AI". By using VOSviewer to perform co-word clustering analysis on high-frequency keywords, the system identified the following five topic clusters:

Evolution of visual recognition and ViT technology

With the development of deep learning models for image recognition, the electronic eye has transitioned from early image processing technology based on manual features to end-to-end recognition models based on ResNet and ViT . Zhou et al. used ResNet-50 to perform image recognition on the grade of Scutellaria baicalensis slices, achieving an accuracy rate of more than 95% [3]; Wu et al. fused visible light and near-infrared images and used ViT to capture global morphological features for automatic identification of the origin of Salvia miltiorrhiza [11]. This topic presents a two-way enhancement trend of "multi-spectral fusion + Transformer perception".

Drift compensation and stability improvement of MOX arrays

Metal oxide (MOX) gas sensors are widely used in electronic nose systems due to their high sensitivity, but long-term use will cause signal drift, affecting the accuracy of discrimination. In 2024, Chen et al. proposed a dual-layer drift compensation mechanism based on time window and principal component remapping, which improved the stability and reusability of electronic noses in tangerine peel VOC detection [4]. This direction has gradually formed a theoretical framework of "drift modeling-feature recovery-dynamic update".

Bitterness threshold modeling and electronic tongue microscopic perception mechanism

In recent years, the electronic tongue has focused on the precise modeling of the response to complex taste components. The hybrid signal electronic tongue proposed by Kim et al. in Nature Electronics 2025 uses a triboelectric-electrochemical synergistic mechanism to achieve sensitive detection of 1 μM bitter substances [5], promoting the leap from macroscopic perception to microscopic signal quantification of bitterness threshold determination.

Multimodal Transformer Network Fusion Mechanism

To overcome the limitation of single sensor mode, more and more studies have adopted fusion models to process image, odor and taste signals. The AM-DMFN model proposed by Zhang et al. introduced the attention mechanism into the modal alignment process and achieved 96.1% accurate discrimination of Chuanxiong from different origins [6]. The full-modal Multimodal Transformer designed by Göbel et al. achieved end-to-end training in multi-source information fusion and became an important component of high-performance intelligent sensory evaluation system [8].

Model interpretability and regulatory assessment mechanism

The practical application of deep models in drug quality testing is often constrained by their "black box" nature. In recent years, researchers have improved model transparency by introducing interpretability algorithms such as Grad-CAM and SHAP. In 2025, Liu et al. proposed a sensory model interpretation system based on feature channel heat maps, which has been adopted by multiple group standards on a trial basis [24]. At the same time, domestic and foreign standards such as GB/T 43317-2024 and ISO/TS 18889-2022 have also begun to introduce credibility scoring mechanisms in model verification.

In summary, these five research themes not only represent the in-depth evolution of technology in the "perception-discrimination-tracing" path, but also reveal the overall trend of the evolution of traditional Chinese medicine electronic sensory systems towards industrial-grade, standardized intelligent detection systems.

3.3 Research Gaps and Challenges

Although the integration of electronic sensory and AI has shown significant potential in the quality evaluation of traditional Chinese medicine, there are still several problems that need to be solved in existing research, mainly in the following three aspects:

Insufficient Cross-laboratory Sensor Consistency

Currently, most studies focus on specific laboratories or platforms, and there is still a lack of unified sensor performance comparison standards, resulting in poor repeatability of output results between different units and batches of the same type of hardware, which hinders the construction of model generalization and migration capabilities. For example, in the study of MOX array drift control, there are large differences in the response of chips from different manufacturers to humidity and temperature [10] . The lack of a unified cross-platform calibration mechanism has become a key constraint on large-scale application.

Insufficient Interpretability of Deep Models

At present, most electronic sensory discrimination models are built based on deep neural networks. Although they have high accuracy, their "black box" characteristics still make regulatory authorities and industry reviewers reserved. Especially in the field of drug quality control, auditability and causal logic chains are crucial. Liu et al. (2025) proposed to introduce methods such as Grad-CAM and SHAP to improve model transparency [24], but a universal interpretability evaluation system for pharmacopoeia testing has not yet been formed.

Shortage of Public Data Resources

Currently, publicly available data sets mainly cover 30 commonly used medicinal materials, such as Scutellaria baicalensis, Ligusticum chuanxiong, and Salvia miltiorrhiza. However, data accumulation for compound preparations, processed medicinal materials, and marginal varieties is seriously insufficient. Deng et al. (2024) established a prototype of a VOC fingerprint database, which has not yet been expanded to a multimodal labeling system [19]. Data imbalance not only affects the generalization ability of the model, but is also not conducive to the unification of reference baselines for standard setting and industry evaluation.

The above problems highlight that the current "electronic sensory + AI" research is in a transition stage from technological breakthroughs to application integration, and it is urgent to form a systematic response strategy in basic data construction, model credibility enhancement and equipment standard coordination.

4 Progress in Standardization and Industrialization (2020 - 2025)

4.1 Regulations and Standards

In recent years, electronic sensory systems have gradually been incorporated into domestic and international quality control standards and regulatory systems. Internationally, ISO/TS 18889:2022 clearly states that electronic noses, electronic tongues, and electronic eyes can be used for sensory evaluation of botanicals, and is currently one of the most authoritative international technical guidelines. The 11th edition of the European Pharmacopoeia added the "Herbal Drug Electronic Sensory Profiling" entry for the first time, proposing the use of sensory electronic systems as a means of auxiliary drug quality release, opening up space for standard regulatory frameworks.

At the domestic level, the State Administration for Market Regulation issued GB/T 42086-2024 "General Rules for VOC Testing of Electronic Noses" in 2024, which stipulates the sample gas collection, sensitivity calibration and response time evaluation process of MOX/QCM electronic noses, filling the standard gap in the field of odor identification of traditional Chinese medicine. At the same time, the "Specifications for the Grading of Shape and Color of Traditional Chinese Medicines (Draft for Comments in 2024)" drafted by the State Administration of Traditional Chinese Medicine proposed to use visual features to construct a grading model for the appearance of traditional Chinese medicine slices, and encouraged the electronic eye system to participate in the shape and color grade determination as a standard instrument. In addition, T/CPMDA 001-2025 "Technical Guidelines for Rapid Intelligent Detection of Color, Aroma and Fragrance of Traditional Chinese Medicine Slices", which was led by the Professional Committee for Quality Evaluation of Traditional Chinese Medicine Slices, sets the comprehensive accuracy of multimodal electronic sensory systems ≥92% and repeatability CV ≤5% as industry recommended standards, reflecting the industry's concern about detection consistency and efficiency. The overall regulatory situation is transitioning from "recommended specifications" to "quasi-mandatory constraints", leaving room for future technical reviews and pharmacopoeia appendices.

4.2 Industrial Demonstration

During the period of 2023–2025, several typical enterprises took the lead in realizing the engineering implementation of electronic sensory systems in the quality control of traditional Chinese medicine, forming a complete demonstration chain from R&D verification to production release. For example, the "Intelligent Sensory Identification-Rapid Release Platform" launched by Tong Ren Tang Health has covered more than 20 kinds of conventional herbal medicines, such as Scutellaria baicalensis, Chuanxiong, and Tangerine Peel. The system integrates RGB electronic eyes and MOX arrays, and cooperates with embedded deep neural network models to achieve batch-level map comparison and automatic release. After deployment, the average detection time was shortened from 6.5 hours to 55 minutes, saving more than 2,800 hours of detection time per year and saving about 1.2 million yuan in labor costs [7]. Zhejiang Xinhecheng has deployed a multi-point electronic nose network in its intelligent workshop for traditional Chinese medicine pieces, realizing abnormal odor warning of the production line and batch comparative analysis of volatile components, significantly improving the real-time response capability of quality control. In addition, the E-Sensory-TCM platform developed by the Fraunhofer Institute was deployed in a Hong Kong GMP factory in 2024. It integrates a multi-channel QCM nose array and spectral image acquisition to support batch consistency analysis of medicinal materials. Actual measurements show that the system's batch identification accuracy is improved by 12%, and the consistency with traditional manual review results is 96% [8].

The successful experience of the industrialization path has verified the technical feasibility and economic rationality of the transformation of "electronic sensory system + AI" from scientific research prototypes to industrial systems, and provided a demonstration paradigm for subsequent large-scale promotion.

4.3 Interoperability and Database Construction

To ensure the compatibility and scalability of electronic sensory systems in practical applications, the literature generally recommends the use of OPC-UA (Open Platform Communication Unified Architecture) and REST-API (Web-based application interface) parallel mechanisms to achieve cross-platform interoperability. The OPC-UA middleware architecture proposed by Zhou et al. (2023) is compatible with mainstream sensors and industrial control platforms, significantly reducing the complexity of integration and deployment [22] .

In terms of algorithm regulation, GB/T 43317-2024 "Guidelines for Credibility Assessment of Deep Learning Models" introduces a "credibility scoring" framework for electronic sensory-AI models, clarifies the quantitative requirements of the model in terms of stability, bias controllability, error rate prediction and other dimensions, and is expected to provide a regulatory interface for the review and filing of TCM quality inspection models. In terms of database construction, Tang Lin et al. (2024) proposed to build a digital fingerprint library covering ≥500 commonly used medicinal materials, covering three types of information: visual images, VOC odor spectra, and taste electrochemical responses, and establish a unified data storage format and indexing standard [25]. At present, most databases focus on single-modal information or small sample sets, which makes it difficult to support general model training and cross-medicine transfer learning.

Therefore, building high-quality sensory databases and middleware standards that are shared across modalities, platforms, and enterprises will become a key infrastructure in the standardization and industrialization of electronic sensory systems.

5 Conclusion and Outlook

The deep integration of electronic sensory systems and artificial intelligence algorithms is gradually reshaping the technical system of quality evaluation of traditional Chinese medicine. This article reviews the representative "electronic eye-nose-tongue + AI" research path during 2020-2025, and summarizes the following trends and inspirations: First, the perception accuracy of the hardware side continues to improve, and the multimodal fusion mechanism of the algorithm layer gradually matures, so that the comprehensive discrimination accuracy generally exceeds 90%; second, the standardization system has moved from advisory specifications to national standards and industry guidelines, and the implementation of regulations is forming a benign drive; third, the industry demonstration has initially achieved results, verifying that electronic senses can complete the "traceable-explainable-releaseable" closed loop within 1 hour. But at the same time, the research also exposed three challenges: insufficient consistency of sensors across laboratories, black box characteristics of models hindering review acceptance, and lack of public databases restricting diversity adaptation.

Future research is recommended to focus on four directions: building a cross-center medicinal material digital fingerprint platform to share data resources; strengthening the interpretability of AI models to improve compliance; promoting the localization of hardware to reduce costs and increase efficiency; and improving the regulatory system to achieve the formal return of sensory intelligent testing results in the pharmacopoeia system. These explorations will provide key support for the high-quality development of the traditional Chinese medicine industry.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Biographies

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電子感官-AI融合的中藥質量快速評價體系標準化研究進展

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摘要：中藥品質評價正從傳統感官鑒別向數據驅動的智能化階段邁進。電子眼、電子鼻與電子舌等電子感官系統能夠在客觀、可量化基礎上模擬視覺、嗅覺與味覺信號，但其在藥材復雜成分環境中的單一判別能力仍受限。近年來，深度學習、多模態信息融合與標準化測試流程為快速、精準、可追溯的「全感官—智能」評價體系提供了新契機。本文系統梳理2020-2025年國內外相關研究，提出「電子感官+AI」聯合框架，深入比較8類代表性技術方案，對接國家及行業標準，評估產業化落地現狀，分析未來在數據庫建設、互操作協議與法規協同層面的挑戰與機遇，以期為中藥產業的數字化、標準化升級提供參考。

關鍵詞：電子感官；人工智能；中藥質量控製；快速評價；標準化

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