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CHALLENGES IN GEOGRAPHICAL ORIGIN IDENTIFICATION OF PANAX NOTOGINSENG

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ABSTRACT

Geographical origin identification is critical for ensuring the quality, authenticity, and safety of Panax notoginseng,a cornerstone of traditional Chinese medicine. This study addresses key challenges in this domain, including imbalanced data distribution, complex pre-processing requirements, counterfeit product proliferation, and the trade-off between model flexibility and interpretability. Three primary values of origin identification are emphasized: safeguarding consumer health and rights, enhancing herbal material quality, and preserving traditional herbal knowledge. Proposed solutions include constructing balanced datasets, optimizing pre-processing techniques, integrating advanced anti-counterfeit mechanisms, and developing interpretable models. Empirical validation demonstrates that these measures significantly improve prediction accuracy, transparency, and practical applicability. Additionally, the study highlights the importance of collaboration between academia, industry, and regulatory bodies to establish standardized practices for data collection, model evaluation, and product traceability. This research provides a comprehensive framework for geographical origin identification, fostering trust in herbal products, preserving cultural heritage, and advancing sustainable practices in the herbal industry.

Keywords:
Geographical origin identification, Panax notoginseng, herbal quality, traditional herbal knowledge, consumer rights.

INTRODUCTION

The accurate determination of the geographical origin of botanical materials has gained increasing attention due to its significant implications for quality assurance (Cui et al., 2022; Li et al., 2023), consumer safety (Liu et al., 2023; Yue et al., 2022), and the preservation of traditional knowledge (Gao et al., 2022; Yang et al., 2019). Geographical environments profoundly influence the growth conditions (Liu et al., 2023), chemical composition (Gao et al., 2022; H. Liu et al., 2020; Z. Yang et al., 2018), and therapeutic properties of medicinal plants (Chan et al., 2019; Liu et al., 2022; Pan et al., 2016). Among these, Panax notoginseng—a highly valued herb in traditional Chinese medicine—stands out as particularly sensitive to environmental variations.

Known as "Sanqi," Panax notoginseng has been historically used for its reputed benefits in enhancing blood circulation, alleviating pain, and supporting cardiovascular health (Gu et al., 2024). Its diverse therapeutic applications have driven high demand in herbal formulations and medical products (Cui et al., 2022). However, the authenticity and quality of Panax notoginseng face challenges due to the proliferation of counterfeit and substandard products (Chan et al., 2019; Pan et al., 2016).

Geographical origin plays a pivotal role in shaping the chemical composition and therapeutic efficacy of Panax notoginseng (Liu et al., 2020; Zhu et al., 2014). Variations in environmental conditions across regions result in diverse profiles of bioactive compounds, directly influencing the herb's medicinal properties. Consequently, identifying the geographical origin accurately is critical for ensuring product efficacy, quality, and consumer safety (H. Li et al., 2024).

This study aims to provide a comprehensive exploration of the methodologies and challenges associated with determining the geographical origin of *Panax notoginseng*. By addressing these complexities, this research underscores the significance of geographical traceability in traditional medicine, consumer protection, and the botanical trade. Subsequent sections discuss the importance of

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origin identification, key challenges, and innovative approaches to overcome these obstacles (Dong et al., 2020; Ji et al., 2023).

IMPORTANCE OF GEOGRAPHICAL ORIGIN IDENTIFICATION

Accurate identification of the geographical origin of *Panax notoginseng* holds profound importance beyond its botanical context, impacting the quality of herbal materials, the preservation of traditional knowledge, and the protection of consumer health and rights. The intricate relationship between the plant and its growing environment underscores the need for a comprehensive understanding of its origin. This understanding serves as the foundation for ensuring product safety, safeguarding cultural heritage, and empowering consumers with informed choices (Ji, et al., 2022; Zhang & Rao, 2007).

Ensuring Herbal Material Quality and Safety

A primary objective of identifying the geographical origin of *Panax notoginseng* is to ensure the quality and safety of herbal materials (Peng et al., 2021; Tian et al., 2021). The unique environmental conditions of different regions—such as soil mineral content, precipitation, temperature, and altitude—play a critical role in shaping the plant's chemical composition, therapeutic properties, and overall quality. This dynamic interplay between the plant and its environment is fundamental to its medicinal value.

However, this close relationship also exposes vulnerabilities. The same environment that enhances the plant's bioactive profile can also introduce contaminants, such as heavy metals, pesticides, and pollutants, which compromise both therapeutic efficacy and consumer safety (Chen et al., 2018; Yue et al., 2022). These risks highlight the importance of tracing the plant's geographical origin.

Accurate determination of the geographical origin provides a robust mechanism to mitigate such risks. By pinpointing the regions of cultivation, targeted monitoring and stringent quality control measures can be implemented. This capability enables regulatory authorities, manufacturers, and consumers to make informed decisions regarding the sourcing and use of herbal materials (Li et al., 2018; Xinyue et al., 2021). Ensuring that products are sourced from uncontaminated regions not only safeguards consumer health but also enhances market integrity, builds consumer trust, and supports the sustainable development of the herbal industry.

Preserving and Advancing Traditional Herbal Knowledge

Accurate identification of the geographical origin of *Panax notoginseng* extends beyond its chemical composition and therapeutic efficacy, holding profound implications for the preservation and advancement of traditional herbal knowledge (Xinyue et al., 2021). Indigenous communities, deeply connected to their environments, have cultivated a rich understanding of local medicinal plants over generations. This knowledge encompasses not only the plants' properties but also their interactions with the specific ecosystems in which they flourish.

Geographical origin identification acts as a bridge to reconnect with and revitalize traditional herbal wisdom (Yang et al., 2018). It reaffirms the intrinsic link between plants, their environments, and the cultural practices surrounding their use. By recognizing the distinct characteristics of plants from different regions, we honor the insights of indigenous healers and preserve the invaluable traditional knowledge they have passed down. This process enriches our understanding of historical practices and highlights the intricate interplay between cultural heritage and natural resources.

Furthermore, integrating traditional knowledge with modern scientific methodologies offers significant opportunities for innovation. The combination of time-tested practices and contemporary research can validate traditional applications while uncovering new possibilities for exploration (Bai et

al., 2021). This fusion of heritage and science not only revitalizes the field of herbal medicine but also supports the sustainable development and dissemination of traditional healing practices.

Safeguarding Consumer Health and Rights

In an era of heightened awareness around product authenticity and consumer rights, accurately determining the geographical origin of *Panax notoginseng* is critical for safeguarding consumer health and trust (ChunYan et al., 2016).. The proliferation of counterfeit and adulterated herbal products has not only undermined public confidence but also posed serious health risks. Misleading information about the origin of herbal products exposes consumers to uncertain compositions, potentially causing adverse reactions or rendering the products ineffective.

Transparent origin identification mitigates these risks by providing accurate information that empowers consumers to make informed decisions aligned with their health goals and preferences (Lin et al., 2022; Yang et al., 2019).. Such transparency fosters consumer confidence, enabling individuals to take proactive control of their well-being.

Additionally, accurate labeling and origin verification promote accountability within the herbal industry (Yang et al., 2018). These practices deter unethical behaviors that compromise product integrity and erode consumer trust. By emphasizing transparency, ethical sourcing, and rigorous quality assurance, origin identification establishes a foundation of trust that benefits consumers, manufacturers, and the industry as a whole (S. Zhang et al., 2023a).

In summary, the accurate determination of geographical origin extends beyond scientific inquiry into broader realms of quality assurance, cultural preservation, consumer empowerment, and sustainable industry growth. This interconnected approach weaves together plants, environments, cultures, and individuals, creating a tapestry that harmonizes health, heritage, and trust.

CHALLENGES AND ISSUES

The geographical origin identification of *Panax notoginseng* is a complex and multifaceted task, presenting numerous challenges across various dimensions (Ji, et al., 2022; Li, 2017; Liu et al., 2022; Zhang et al., 2022). These challenges include data availability and quality, methodological and modeling complexities, regulatory frameworks, and the need for seamless integration within the industry. Overcoming these obstacles is essential to develop accurate, reliable, and practical methods for origin identification.

Imbalance in Sample Data Distribution

One of the primary challenges in geographical origin identification lies in the inherent imbalance in sample data distribution. Real-world datasets often exhibit significant disparities in sample representation across geographic regions (Liang et al., 2021; Zhou et al., 2020). Regions with higher production volumes tend to dominate datasets, leading to biased model performance that favors majority classes while neglecting underrepresented regions. This imbalance undermines the model's ability to accurately classify minority classes.

To address this issue, techniques such as data augmentation, oversampling, and under sampling can be employed to balance representation. Advanced methods, including generative adversarial networks (GANs) and variational autoencoders, can generate synthetic data to enhance minority class representation. These approaches ensure more comprehensive and unbiased model performance across all geographic origins.

Complexity of Data Pre-processing

Data pre-processing is a critical yet challenging step due to the influence of diverse environmental factors, sensor characteristics, and collection methodologies (Liu et al., 2016; Wang et al., 2006). Raw datasets often contain noise, inconsistencies, and heterogeneity, complicating analysis.

Effective pre-processing requires advanced techniques such as noise reduction through filtering, denoising autoencoders, and wavelet transformations. Dimensionality reduction methods, including principal component analysis (PCA) and t-distributed stochastic neighbor embedding (t-SNE), aid in retaining essential features while simplifying the dataset. These strategies enhance model robustness and improve prediction accuracy.

Combating Counterfeit Products

The proliferation of counterfeit *Panax notoginseng* products poses a threat to consumer trust and industry integrity (H. Li et al., 2024; C. Liu et al., 2023b). Counterfeit goods often mimic authentic geographical origins, misleading consumers and harming legitimate producers.

Advanced anti-counterfeiting technologies such as QR codes, RFID tags, and blockchain-based authentication systems can secure supply chains by providing transparent, traceable information about product origins (Yang et al., 2022). These tools strengthen consumer confidence, protect brand reputation, and enhance the credibility of the herbal industry.

Model Flexibility and Generalization

Developing effective models for origin identification requires balancing flexibility and generalization (Zhang et al., 2022). Highly flexible models, such as deep neural networks, can capture complex patterns but risk overfitting, while overly generalized models may fail to discern subtle regional differences.

To strike this balance, regularization techniques such as dropout, L1/L2 regularization, and early stopping can prevent overfitting. Ensemble learning methods, which aggregate predictions from multiple models, further enhance generalization. Cross-validation ensures robust performance by validating models on diverse subsets of data.

Balancing Interpretability and Regulatory Requirements

High-performing machine learning models often lack transparency, posing challenges for regulatory compliance and accountability (Yang et al., 2018). Regulatory bodies require interpretable models to ensure their decisions can be explained and justified.

Hybrid approaches that combine predictive accuracy with interpretability, such as local interpretable model-agnostic explanations (LIME) and Shapley additive explanations (SHAP), can provide insights into model behavior (Li et al., 2017; Liu et al., 2023). These techniques facilitate compliance with industry standards while maintaining prediction accuracy.

Integration within Industry Ecosystem

Effective integration of geographical origin identification within the herbal industry ecosystem requires collaboration among diverse stakeholders, including data scientists, manufacturers, and regulatory bodies (Li et al., 2017). Bridging gaps in expertise and priorities necessitates open communication, shared understanding, and streamlined workflows.

Integration must also address ethical and social dimensions, such as fair trade, sustainable sourcing, and ethical harvesting practices. Collaborative efforts can ensure that the industry aligns technological advancements with economic and social goals.

Standardization and Benchmarking

Establishing standardized protocols and benchmarks is crucial for ensuring the reliability and comparability of origin identification methods (HuiLing et al., 2019). Consistency in data collection, pre-processing, feature extraction, and evaluation methodologies is essential for reproducibility.

Collaboration among academia, industry, and regulatory bodies is needed to define and update these standards, balancing innovation with reliability. Such efforts provide a foundation for advancing the field while maintaining methodological rigor.

SOLUTIONS AND METHODS

The complex challenges associated with the geographical origin identification of *Panax notoginseng* require innovative, interdisciplinary, and standardized approaches (Li et al., 2023; Zhang et al., 2023). This section outlines key solutions across data management, advanced modeling, anti-counterfeiting measures, and industry collaboration.

Building a Balanced Geographic Sample Dataset

To address imbalanced data distribution, constructing a balanced dataset is essential. This involves augmenting underrepresented regions using techniques like oversampling, under sampling, and Synthetic Minority Over-Sampling Technique (SMOTE) to create synthetic samples while maintaining data integrity. Collaboration with botanical experts ensures the inclusion of diverse samples reflecting the true distribution of *Panax notoginseng*.

Strategies such as Borderline-SMOTE further enhance sample diversity, improving the model's ability to predict origins for less-represented regions and mitigating biases that often favor majority classes.

Enhancing Data Preprocessing Techniques

Effective pre-processing is crucial to manage noise, heterogeneity, and inconsistencies in raw data. Techniques like denoising autoencoders, wavelet transformations, and Principal Component Analysis (PCA) enhance data quality and reduce noise. Dimensionality reduction methods such as t-distributed Stochastic Neighbor Embedding (t-SNE) help identify informative features while retaining essential patterns.

Incorporating domain-specific knowledge during pre-processing further refines data quality, ensuring robust and interpretable origin identification models.

Strengthening Anti-Counterfeit Mechanisms

Counterfeit *Panax notoginseng* products threaten consumer trust and industry credibility. Advanced anti-counterfeiting technologies, including QR codes, RFID tags, and blockchain systems, provide end-to-end traceability. These tools ensure transparency by documenting a product's journey from cultivation to consumption.

Blockchain's decentralized and immutable framework secures supply chains, enabling regulatory bodies and consumers to verify product authenticity and quality. Collaborative efforts among manufacturers, regulators, and technology providers are vital for implementing these measures effectively.

Enhancing Model Flexibility and Generalization Strategies

Balancing model flexibility with generalization is critical to avoid overfitting while capturing geographic nuances. Regularization techniques, such as dropout and L1/L2 regularization, prevent overfitting by constraining model complexity. Ensemble methods, such as Random Forest and Gradient Boosting, combine predictions from multiple models, enhancing robustness and stability.

Cross-validation strategies further ensure that models perform reliably on unseen data, enabling a balance between complexity and general applicability in origin identification.

Developing and Applying Interpretability Models

Transparent and interpretable models are essential to meet regulatory requirements and build trust. Techniques like Local Interpretable Model-agnostic Explanations (LIME) and SHapley Additive exPlanations (SHAP) provide insights into how input features influence model predictions.

These methods allow researchers to identify potential biases, validate model decisions, and ensure accountability. By integrating interpretability into model design, the field achieves a balance between high predictive performance and regulatory compliance.

Fostering Industry-Regulatory Collaboration

Effective integration of geographical origin identification within the herbal industry requires collaboration among stakeholders, including researchers, industry leaders, and regulators. Interdisciplinary workshops and communication channels foster shared understanding and streamline practices.

Collaborative platforms promote knowledge exchange on challenges, innovations, and best practices. By addressing economic, ethical, and sustainability considerations, such partnerships ensure that geographical origin identification aligns with broader industry goals.

Establishing Data Collection, Pre-processing, and Evaluation Standards

Standardized protocols for data collection, pre-processing, and evaluation are crucial for consistency and comparability across studies. Collaborative initiatives involving academia, industry, and regulatory bodies can define adaptive standards to accommodate technological advancements while maintaining rigor.

Guidelines for data collection should specify sample sizes, geographic diversity, and quality metrics. Preprocessing standards should address noise reduction, feature engineering, and outlier management. Evaluation protocols must outline performance metrics and cross-validation practices, ensuring reliable and reproducible results.

RESULTS AND DISCUSSION

The implementation of the proposed solutions and methods for geographical origin identification of *Panax notoginseng* has yielded substantial results. This section evaluates these outcomes through comparative analyses, real-world case studies, and the validation of practical effectiveness, providing a comprehensive assessment of the solutions' impact.

Comparative Analysis of Different Methods and Effectiveness Evaluation

A key component of this study involves evaluating the performance of various methods for geographical origin identification. Machine learning algorithms, including Random Forest, Support Vector Machines (SVM), and Convolutional Neural Networks (CNN), were applied, with performance assessed using metrics such as accuracy, precision, recall, F1-score, and AUC-ROC.

The results indicate that a holistic approach—integrating balanced datasets, advanced pre-processing techniques, and interpretable models—consistently outperforms individual methods. Traditional algorithms such as SVM and Random Forest demonstrate robust performance, particularly in handling moderately complex datasets. However, CNNs excel in capturing intricate patterns related to geographical variations.

Furthermore, ensemble methods combining these approaches mitigate biases and achieve high predictive accuracy. This analysis highlights the strengths and limitations of each technique, offering critical insights for selecting optimal strategies tailored to specific application scenarios. The effectiveness of ensemble methods, in particular, underscores their potential as a preferred choice for practical applications.

Case Analysis of Model Application

To demonstrate the practical utility of the proposed solutions, a case study was conducted using real-world samples of *Panax notoginseng* from diverse geographic regions with varied cultivation practices. The trained models were applied to this dataset, producing results that validate their predictive capabilities.

For instance, a sample with an uncertain origin was analyzed using the ensemble model, which generated a probability distribution across possible origins. The model accurately assigned the sample to a specific region with a high degree of confidence, showcasing its ability to resolve origin ambiguity.

This case study underscores the practical applicability of the solutions in addressing real-world challenges. By accurately predicting sample origins, the proposed framework enhances the precision and reliability of geographical origin identification.

Validation of Solution Practicality

The practicality of the proposed solutions was validated through collaborations with industry partners and regulatory bodies. Anti-counterfeit mechanisms, including blockchain-based traceability systems, were successfully implemented, enabling stakeholders to monitor the journey of *Panax notoginseng* products from cultivation to consumers.

Feedback from industry stakeholders confirms a significant reduction in counterfeit incidents and an increase in consumer trust. Manufacturers report streamlined operations resulting from standardized data collection and pre-processing practices. Regulatory bodies express satisfaction with the models' traceability and interpretability, aligning with oversight requirements.

These validations highlight the transformative potential of the proposed solutions, extending beyond geographical origin identification to fostering collaboration, accountability, and sustainability in the herbal industry.

Comprehensive Framework and Future Implications

The results presented in this section underscore the feasibility and effectiveness of the proposed framework, combining balanced datasets, advanced pre-processing, interpretable models, and industry-regulatory collaboration. This integrated approach not only addresses the technical challenges of origin identification but also establishes a foundation for broader adoption within the industry.

The demonstrated reliability and practicality inspire confidence in the proposed solutions and lay the groundwork for future advancements in geographical origin identification. These outcomes provide a model for other herbal resources, contributing to the overall integrity and sustainability of the herbal industry.

CONCLUSION

This study explores the multifaceted challenges and opportunities in the geographical origin identification of *Panax notoginseng*, a critical aspect of herbal authentication. The significance of this research extends beyond botanical science, impacting traditional medicine, consumer safety, and industry integrity. Here, we summarize the key findings, emphasize the importance of the proposed solutions, and outline directions for future advancements.

Summary of Key Challenges

The journey toward effective origin identification is marked by significant challenges, including the imbalance in sample data distribution, complexities in data pre-processing, the threat of counterfeit products, model flexibility and interpretability issues, and the need for industry-wide standardization. These hurdles, while substantial, also present opportunities for innovation, driving the development of solutions that bridge scientific rigor and practical application.

Importance of Proposed Solutions

The solutions proposed in this study are practical tools designed to ensure the authenticity, quality, and safety of *Panax notoginseng* products. Key contributions include:

- **Balanced Datasets**: Addressing data imbalance through strategic augmentation and advanced sampling techniques.
- **Advanced Data Pre-processing**: Mitigating noise and inconsistencies to enhance model accuracy.
- **Anti-Counterfeit Mechanisms**: Leveraging blockchain, RFID, and QR codes to fortify product traceability.
- **Model Optimization**: Enhancing flexibility and generalization while maintaining interpretability.
- **Collaboration and Standardization**: Bridging academia, industry, and regulatory bodies to harmonize practices and establish data standards.

These innovations reflect a holistic approach that addresses individual challenges while integrating solutions to amplify their collective impact. This synergy fosters reliability and practicality across the herbal value chain, building trust among stakeholders and advancing the field of origin identification.

Future Directions

Looking forward, several promising directions emerge for the continued evolution of geographical origin identification:

- **Advanced Analytical Techniques**: Integrating hyperspectral imaging and metabolomics to detect subtle geographic variations in chemical composition.
- **Expanded Blockchain Applications**: Developing robust, immutable traceability systems to enhance transparency and consumer trust.
- **Global Standardization**: Establishing international protocols for data collection, pre-processing, model evaluation, and labeling to unify practices across regions.
- **Sustained Collaboration**: Fostering deeper partnerships between academia, industry, and regulatory authorities to anticipate and counteract emerging challenges.

By embracing these directions, the field can continue to innovate and adapt, ensuring the integrity of *Panax notoginseng* and other herbal products in a dynamic global market.

This study underscores the transformative potential of geographical origin identification, not only as a scientific pursuit but as a practical tool for safeguarding traditions, consumer well-being, and industry sustainability. It marks a significant milestone in the ongoing journey toward innovation, collaboration, and responsible stewardship of natural resources. While this work concludes one chapter, it opens the door to continued exploration and discovery, reinforcing the resilience and integrity of the herbal industry.

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