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Commentary

Toward Precision Herbal Pharmacovigilance: How Multi-omics and Artificial Intelligence Are Reshaping Integrative Liver Health

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Herbal medicines are increasingly incorporated into healthcare systems worldwide, but their safety is difficult to evaluate. Unlike conventional pharmaceuticals developed around defined molecular targets, traditional Chinese medicine uses individualized prescriptions selected according to patient-specific clinical features. Traditional processing methods (Paozhi), including steaming, roasting, frying, and calcining, may alter the chemical composition, bioavailability, efficacy, and toxicity of herbal materials. Safety also varies with botanical identity, geographic origin, cultivation and harvesting conditions, storage, dose, treatment duration, and herb–drug interactions. Because the liver is the main organ of xenobiotic metabolism, herb-induced liver injury (HILI) is an important public health concern.[1,2]

Current pharmacovigilance and regulatory frameworks remain insufficient for the early detection and prevention of HILI. Existing strategies mainly depend on conventional liver injury biomarkers such as alanine aminotransferase and aspartate aminotransferase, which often increase only after clinically detectable liver damage has already occurred. Most herbal medicines are multi-component formulations that contain numerous bioactive constituents that may interact synergistically or antagonistically to produce emergent toxic effects that cannot be inferred from individual constituents alone, making toxicity assessment difficult because different constituents may affect multiple biological processes. Individual patient factors also contribute to idiosyncratic HILI, a rare form of liver injury that occurs unpredictably only in susceptible individuals.[3] Because these characteristics fundamentally distinguish herbal medicines from conventional drugs, their toxicological assessment requires different pharmacovigilance strategies (Table 1).[2,4-11]

These differences indicate that herbal hepatotoxicity should not be viewed simply as a variant of conventional chemical-drug toxicity; rather, it may reflect systems-level interactions among chemical complexity, processing-related changes, gut microbiota, immune status, host susceptibility, and concomitant medication.[2,3] These characteristics explain why conventional pharmacovigilance strategies often fail to capture the complexity of HILI. Rather than being driven by a single toxic compound, HILI may reflect interactions among multiple herbal constituents, host biology, gut microbiota, and environmental factors.[12] Multi-omics technologies, particularly when combined with artificial intelligence (AI), may help identify susceptible individuals, clarify toxicity mechanisms, and support earlier risk prediction.[13,14]

Singh described a framework integrating multi-omics and AI for herbal pharmacovigilance.[10] Genomics can authenticate herbal species and identify cytochrome P450 (CYP450)-related susceptibility; transcriptomics may reveal molecular perturbations before overt injury; proteomics and metabolomics can localize cellular damage and distinguish inherent toxicity from contaminants; and single-cell or spatial omics may map tissue-specific responses. AI can integrate these high-dimensional datasets to support hepatotoxicity prediction and individual risk assessment.

AI can model complex nonlinear interactions and extract meaningful patterns from high-dimensional multi-omics data.[15] Hepatic organoid studies have shown improved hepatotoxicity prediction,[16,17] suggesting that AI may support multi-omics integration. Such approaches could shift pharmacovigilance from retrospective adverse-event reporting toward earlier risk detection. Preemptive CYP450 genotyping has been estimated to provide population-level benefits in preventing serious adverse drug events,[18] and AI-based predictive models may also help identify and assess potential herb–drug interactions.[19] However, performance in experimental datasets may not translate directly to clinical utility when patient populations, herbal formulations, and healthcare settings differ.

Multi-omics has become vital for investigating herbal safety. HILI arises through multiple pathological pathways, including immune dysregulation, oxidative stress, mitochondrial damage, bile acid imbalance, and gut–liver axis dysfunction. *Polygonum multiflorum*, a traditional Chinese medicinal herb widely used to

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Table 1. Key differences between herbal medicines and conventional chemical drugs relevant to hepatotoxicity assessment

Feature	Conventional chemical drugs	Herbal medicines
Chemical composition	Usually contain one or a few well-defined active compounds[4]	Complex mixtures containing hundreds of bioactive constituents that may interact synergistically or antagonistically[2]
Sources of variability	Manufacturing processes are highly standardized with relatively consistent composition[5]	Composition varies according to botanical species, geographical origin, harvesting conditions, storage, and traditional processing (Paozhi)[2]
Mechanisms of hepatotoxicity	Often associated with defined molecular targets, reactive metabolites, or predictable dose-related toxicity[6]	Frequently involve multiple interacting mechanisms, including constituent interactions, immune-mediated responses, gut microbiota alterations, metabolic perturbations, and host susceptibility[8,9]
Risk prediction	Often evaluated using pharmacokinetic/pharmacodynamic models and dose-response relationships[7]	Requires systems-level integration of multi-omics data to characterize chemical complexity and host-specific biological variability[10,11]

tonify the liver and kidney, has been frequently implicated in idiosyncratic HILI. Its hepatotoxic risk is linked to Paozhi processing, dosage, host inflammation, and gut microbiota; TNF-α synergizes with its ingredients to damage the gut–liver axis and disrupt hepatic metabolism.[3] *Tripterygium wilfordii* has anti-inflammatory and immunosuppressive effects in autoimmune diseases but carries a risk of severe hepatotoxicity and has a narrow therapeutic window. Its core toxic component, triptolide, triggers liver damage via mitochondrial impairment, inflammatory responses, and gut microbiota-associated metabolic alterations,[9] showing that toxicity is strongly influenced by individual host conditions. These two examples illustrate that HILI stems from complex interactions among herbal components, host immunity, and gut microbiota instead of single toxic substances, which cannot be explained by traditional reductionist toxicology. Multi-omics integrates multi-layer molecular changes to deepen mechanistic research beyond simple risk prediction.[2,3]

With the increasing adoption of precision medicine, herbal safety assessment is gradually shifting toward a more individualized and data-informed framework, enabling refined stratification of patient-specific risk. A central objective of this transition is the ability to identify potential hepatotoxic risk before the onset of clinically apparent liver injury, thereby expanding the temporal window available for intervention. This evolution from reliance on isolated biochemical markers toward multidimensional risk evaluation highlights the importance of integrating longitudinal clinical indicators with multi-omics data and AI-based predictive models, allowing a more coherent interpretation of dynamic biological changes rather than static endpoint measurements.

However, the clinical implementation of precision herbal pharmacovigilance remains constrained by three major challenges: heterogeneous herbal and clinical datasets, limited interpretability of AI models, and insufficient prospective validation. Differences in omics platforms, sample processing, herbal sources, processing methods, and concomitant medications may compromise reproducibility and model generalizability. In addition, most AI toxicity models remain internally validated, with limited multicenter, cross-population, and real-world evaluation, while their black-box nature may hinder clinician acceptance.[11,20] Addressing these issues through standardized data frameworks, interpretable models, and multicenter prospective validation will be essential for translating technological advances into routine healthcare practice.

Overall, multi-omics and AI have the potential to shift herbal pharmacovigilance from retrospective adverse event reporting toward mechanism-based and predictive risk assessment. Realizing this potential will require robust clinical validation, interpretable AI models, and seamless integration into routine healthcare workflows.

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Conflict of interest

None.

Author contributions

Study concept and design (ML), funding acquisition (ML), drafting of the manuscript (ML, JQ), critical revision of the manuscript for important intellectual content (ML, JQ), and supervision (ML, JQ). Both authors contributed significantly to this work and approved the final manuscript.

References

[1] Halegoua-DeMarzio D, Navarro V. Challenges in herbal-induced liver injury identification and prevention. Liver Int 2025;45(3):e16071. DOI: 10.1111/liv.16071, PMID: 39136211.

[2] Fan Y, Guo X, Zhang C, Huang T, Huang HD, He Y. A comprehensive

review of herb-induced liver injury: Mechanisms, clinical management, and future perspectives in natural product safety. Phytomedicine 2026;150:157647. DOI: 10.1016/j.phymed.2025.157647, PMID: 41380411.

[3] Aimaier D, Bai W, Zhang Y, Li X, Ma C, Gu J, *et al*. Susceptibility Factor TNF-α Synergizes with Polygonum multiflorum to Drive Idiosyncratic Liver Injury in Mice by Disrupting Gut Microbiota Composition and Hepatic Metabolite Homeostasis. J Inflamm Res 2025;18:9477–9494. DOI: 10.2147/JIR.S528667, PMID: 40692546.

[4] Kullak-Ublick GA, Andrade RJ, Merz M, End P, Benesic A, Gerbes AL, *et al*. Drug-induced liver injury: recent advances in diagnosis and risk assessment. Gut 2017;66(6):1154–1164. DOI: 10.1136/gutjnl-2016-313369, PMID: 28341748.

[5] Duarte JG, Duarte MG, Piedade AP, Mascarenhas-Melo F. Rethinking Pharmaceutical Industry with Quality by Design: Application in Research, Development, Manufacturing, and Quality Assurance. AAPS J 2025;27(4):96. DOI: 10.1208/s12248-025-01079-w, PMID: 40389714.

[6] Skat-Rørdam J, Lykkesfeldt J, Gluud LL, Tveden-Nyborg P. Mechanisms of drug induced liver injury. Cell Mol Life Sci 2025;82(1):213. DOI: 10.1007/s00018-025-05744-3, PMID: 40418327.

[7] Varnekar S, Sohal M, Tikale N, Reddy RS, Bose A, Pawar S, *et al*. Physiologically based pharmacokinetic (PBPK) modeling and pharmacokinetic pharmacodynamic (PKPD) modelling. In: Rao GSK, Alavala RR, editors. Singapore: Springer Nature Singapore; 2025: 475-515. DOI: 10.1007/978-981-96-4154-3_14.

[8] Ma ZT, Shi Z, Xiao XH, Wang JB. New Insights into Herb-Induced Liver Injury. Antioxid Redox Signal 2023;38(16-18):1138–1149. DOI: 10.1089/ars.2022.0134, PMID: 36401515.

[9] Hu Y, Wu Q, Wang Y, Zhang H, Liu X, Zhou H, *et al*. The molecular pathogenesis of triptolide-induced hepatotoxicity. Front Pharmacol 2022;13:979307. DOI: 10.3389/fphar.2022.979307, PMID: 36091841.

[10] Singh A. Bridging Traditional Medicine with Modern Technology: "Omics"-guided Herbal Pharmacovigilance for Integrative Liver Health. Future Integr Med 2026;5(1):13–26. DOI: 10.14218/FIM.2025.00059.

[11] Kim TW, Park S, Kim M. Artificial Intelligence for Drug Safety Across the Lifecycle and Decision Type: A Scoping Review. Pharmaceuticals (Basel) 2026;19(2):334. DOI: 10.3390/ph19020334, PMID: 41754874.

[12] Fu L, Jia G, Liu Z, Pang X, Cui Y. The applications and advances of artificial intelligence in drug regulation: A global perspective. Acta Pharm Sin B 2025;15(1):1–14. DOI: 10.1016/j.apsb.2024.11.006, PMID: 40041903.

[13] Ramesh D, Manickavel P, Ghosh S, Bhat M. The Integration of Multi-omics With Artificial Intelligence in Hepatology: A Comprehensive Review of Personalized Medicine, Biomarker Identification, and Drug Discovery. J Clin Exp Hepatol 2025;15(6):102611. DOI: 10.1016/j.jceh.2025.102611, PMID: 40689362.

[14] Ghosh S, Zhao X, Alim M, Brudno M, Bhat M. Artificial intelligence applied to 'omics data in liver disease: towards a personalised approach for diagnosis, prognosis and treatment. Gut 2025;74(2):295–311. DOI: 10.1136/gutjnl-2023-331740, PMID: 39174307.

[15] Zack M, Stupichev DN, Moore AJ, Slobodchikov ID, Sokolov DG, Trifonov IF, *et al*. Artificial Intelligence and Multi-Omics in Pharmacogenomics: A New Era of Precision Medicine. Mayo Clin Proc Digit Health 2025;3(3):100246. DOI: 10.1016/j.mcpdig.2025.100246, PMID: 40881104.

[16] Kim H, Park HJ. Current hPSC-derived liver organoids for toxicity testing: Cytochrome P450 enzymes and drug metabolism. Toxicol Res 2025;41(2):105–121. DOI: 10.1007/s43188-024-00275-8, PMID: 40013078.

[17] Kim H, Kim SK, Oelgeschläger M, Park HJ. Prediction of Acute Hepatotoxicity With Human Pluripotent Stem Cell-Derived Hepatic Organoids. Curr Protoc 2024;4(4):e1015. DOI: 10.1002/cpz1.1015, PMID: 38597874.

[18] Huh KY, Hwang S, Na JY, Yu KS, Jang IJ, Chung JY, *et al*. Estimation of the benefit from pre-emptive genotyping based on the nationwide cohort data in South Korea. Clin Transl Sci 2024;17(3):e13772. DOI: 10.1111/cts.13772, PMID: 38501281.

[19] Spanakis M, Tzamali E, Tzedakis G, Koumpouzi C, Pediaditis M, Tsatsakis A, *et al*. Artificial Intelligence Models and Tools for the Assessment of Drug-Herb Interactions. Pharmaceuticals (Basel) 2025;18(3):282. DOI: 10.3390/ph18030282, PMID: 40143062.

[20] Mohsin Khan M, Shah N, Shaikh N, Thabet A, Alrabayah T, Belkhair S. Towards secure and trusted AI in healthcare: A systematic review of emerging innovations and ethical challenges. Int J Med Inform 2025;195:105780. DOI: 10.1016/j.ijmedinf.2024.105780, PMID: 39753062.