Specialty Journal of Pharmacognosy, Phytochemistry, and Biotechnology
ISSN: 3062-441X
2026, Volume 6, Issue 1, Page No: 71-79

Available online at: www.galaxypub.co/page/journals

Galaxy Publication

Medicinal-Plant Chemistry Under Climate Instability Requires Dynamic Provenance: A Risk Model Linking Environment, Developmental Stage, Harvest Timing, and Therapeutic-Quality Specifications

Mateo Alvarez[1]*, Sofia Herrera[2], Diego Cruz[1], Andres Castro[3]

[1] Department of Climate-Responsive Medicinal-Plant Chemistry, Faculty of Pharmacy, National University of Colombia, Bogota, Colombia.
[2] Department of Developmental Stage and Harvest Timing, Faculty of Pharmacy, University of Chile, Santiago, Chile.
[3] Department of Therapeutic-Quality Risk Modeling, Faculty of Pharmacy, University of Antioquia, Medellin, Colombia.

***E-mail** ✉ mateo.alvarez@unal.edu.co
Received: 15 December 2025; **Revised:** 11 March 2026; **Accepted:** 14 March 2026

ABSTRACT

Medicinal-plant provenance is commonly recorded as a geographic property, yet climate instability increasingly challenges the assumption that material collected from the same named region will retain a chemically comparable state across years, seasons, developmental stages, and harvest conditions. This article develops an original provenance-risk model for medicinal plants that treats provenance as a dynamic combination of botanical identity, environmental exposure, developmental state, harvest timing, early post-harvest history, and analytical confidence. The supporting literature shows that climatic and edaphic variables can influence specialized-metabolite profiles, that different metabolite classes may respond differently to the same environmental stress, and that developmental and harvest transitions can substantially alter medicinal-material chemistry. These observations do not establish a universal direction of chemical change or demonstrate that chemical drift necessarily changes therapeutic efficacy. The proposed model therefore separates observed chemical variation from specification-relevant drift and, further, from any inference concerning therapeutic-quality consequences. It also preserves geographic origin as an essential baseline while rejecting its use as a sufficient proxy for the environmental and temporal conditions that generate the measured chemical state. The resulting framework is intended to support risk-informed sourcing, longitudinal chemical surveillance, and evidence-linked quality specifications rather than provide a validated predictive score. Prospective multi-year, multi-site, genotype-aware, analytically harmonized, and functionally qualified studies will be required before dynamic provenance can be translated into generalizable decision thresholds or regulatory practice.

Keywords: Medicinal plants, Dynamic provenance, Climate instability, Phytochemical variation, Harvest timing, Quality specifications

How to Cite This Article: Alvarez M, Herrera S, Cruz D, Castro A. Medicinal-Plant Chemistry Under Climate Instability Requires Dynamic Provenance: A Risk Model Linking Environment, Developmental Stage, Harvest Timing, and Therapeutic-Quality Specifications. Spec J Pharmacogn Phytochem Biotechnol. 2026;6(1):71-9. https://doi.org/10.51847/xWI6dwzZZC

Introduction

Medicinal plants are biological raw materials whose chemical composition is produced under environmental conditions that are neither spatially nor temporally fixed. Climate change is already recognized as relevant to medicinal-plant distribution, availability, cultivation, and the production of bioactive metabolites, creating a quality problem that extends beyond conservation or agricultural yield [1]. The analytical implication is important: a botanical material may remain taxonomically identical while entering a different chemical state because the conditions under which it developed have changed. For pharmaceutical-quality interpretation, provenance

therefore cannot be reduced to where a plant was collected if the relevant chemistry depends on what the plant experienced before collection.

Environmental stress does not act as a single undifferentiated exposure. Heat, cold, drought, altered carbon dioxide, ultraviolet radiation, ozone, salinity, and nutrient conditions can influence specialized-metabolite pathways through distinct physiological and regulatory responses [2]. These responses are also contingent on stress magnitude, duration, genotype, tissue, and developmental stage. Consequently, even when environmental stress increases a particular constituent in one system, that observation cannot be generalized into a rule that climatic stress improves medicinal quality. Climate instability instead increases the probability that previously stable relationships among place, season, developmental state, and chemical composition will become less reliable.

Medicinal-material quality is already known to depend on more than geography. Germplasm, cultivation practices, soil and nutrient conditions, harvest timing, processing, and storage may each contribute to the eventual chemical characteristics of plant-derived medicines [3]. The unresolved problem is how these variables should be organized when environmental conditions themselves are becoming more variable. Conventional provenance documentation remains indispensable, but it is principally descriptive: it records source identity and location. It does not necessarily encode the dynamic exposures that generated the harvested material's chemical state.

This article therefore proposes dynamic provenance as a risk-oriented extension of conventional provenance. The model does not replace botanical authentication, geographic traceability, pharmacopoeial specifications, or validated analytical methods. Instead, it proposes that the interpretive unit for climate-sensitive medicinal plants should combine source identity with temporally varying environmental exposure, developmental stage, harvest state, and early post-harvest history. The central distinction is between where material came from and the biological–environmental state in which it was produced. A second distinction separates measured chemical drift from therapeutic-quality consequences: altered chemistry can justify additional quality scrutiny, but does not by itself establish altered efficacy, safety, or clinical performance. These boundaries are essential if dynamic provenance is to function as an evidence-bounded pharmaceutical risk model rather than as a new geographic label.

Why geographic provenance alone is becoming insufficient

Geographic origin remains analytically valuable. In *Peucedanum praeruptorum*, integration of inorganic-element and organic-metabolite profiles improved discrimination among production areas, demonstrating that source location can be represented by chemically informative multivariate signatures [4]. Yet this finding also exposes the limitation of a place name: the detectable signature is generated by biological and environmental processes associated with the site, not by latitude or administrative region as an isolated causal variable. Geographic provenance is therefore best viewed as a container for potentially relevant exposures rather than as their substitute.

The same limitation appears when medicinal materials are stratified by variables other than production area. Metabolomics combined with machine learning distinguished Astragali Radix according to production area, growth mode, species, and grade, indicating that several material attributes can coexist within the chemical information carried by a sample [5]. A regional designation therefore cannot safely be assumed to capture cultivation mode, biological identity, or quality state. These dimensions may correlate in one dataset while separating in another.

Regional chemical differences can also coincide with measured functional differences. In *Thesium chinense*, geographical variation was accompanied by metabolomic differentiation and variation in measured bioactivities [6]. Such findings make provenance relevant to pharmaceutical interpretation, but they do not prove that geography itself caused the functional difference. Genotype, soil composition, weather, harvest state, and local management can all co-vary with location.

More direct environmental analyses reinforce this distinction. In *Rubia cordifolia*, the two marker metabolites purpurin and mollugin showed different relationships with climatic and soil variables, including precipitation-related factors [7]. Thus, even within one medicinal species, “favorable provenance” cannot be represented reliably as a single geographic gradient. Dynamic provenance should preserve geography as a stable traceability layer while separately representing the environmental and temporal variables that may explain the observed chemical state.

Environmental drivers of phytochemical variation

Environmental provenance should be decomposed into interpretable exposure dimensions rather than compressed into a general "climate" variable. In ginseng, temperature seasonality and soil phosphorus availability were associated with differences in ginsenoside composition across cultivation locations [8]. These data are observational and do not establish that either variable alone caused the measured profile, but they demonstrate why climatic and edaphic information should remain analytically distinct. A location can be unchanged while its seasonal temperature pattern, nutrient availability, or water regime shifts enough to alter the chemical context in which a crop develops.

Controlled stress studies provide stronger evidence that environmental perturbation can modify medicinal-plant chemistry. In *Salvia miltiorrhiza*, drought treatments produced coordinated transcriptomic and metabolomic responses and altered tanshinone accumulation, with effects depending on drought intensity [9]. In *Sophora alopecuroides*, integrated transcriptome and metabolome analyses similarly showed drought-associated changes in alkaloid accumulation and related biosynthetic pathways [10]. These findings support stress-responsive chemistry, but not a universal rule that drought enhances or degrades medicinal quality.

Independent multi-omics evidence from *Glycyrrhiza uralensis* further demonstrates coordinated metabolic and transcriptional adaptation to water deficit [11]. Importantly, the value of these studies lies less in finding a common direction than in showing that medicinal chemistry is environmentally responsive across chemically different systems. Evidence spanning climatic, edaphic, and drought contexts therefore supports treating environmental provenance as a set of distinct exposures rather than one categorical attribute [8, 11].

The proposed risk model consequently treats environmental variables as state descriptors, not as universal quality predictors. Temperature history, water status, soil nutrient conditions, and other relevant exposures should enter the provenance record only when they are plausibly connected to the medicinal material and can be measured with adequate reliability. Their meaning must remain constituent-, species-, organ-, and context-dependent. No exposure should be assigned a positive or negative pharmaceutical interpretation merely because it has previously been associated with increased concentrations of a desired metabolite.

The distinctions established in these sections are organized in **Table 1** to show why static geographic origin, environmental exposure, and measured chemical response should remain analytically separable.

Table 1. Concept-and-evidence classification of provenance dimensions relevant to climate-sensitive medicinal-plant chemistry

Provenance dimension	What it represents	Evidence-supported analytical role	Main interpretation risk	Proposed role in dynamic provenance
Botanical and source identity	Taxon, material identity, documented production source	Establishes traceability and constrains comparison	Correct identity may be mistaken for chemical equivalence	Fixed baseline required before dynamic variables are interpreted
Geographic origin	Named region or production location	Can support authentication and multivariate source discrimination	Place may be treated as the causal explanation for chemistry	Stable location layer retained, but not used as a sufficient quality proxy
Climatic exposure	Temperature pattern, precipitation, drought or related weather history	Can associate with or experimentally alter specialized-metabolite profiles	Different stress intensities or metabolite classes may respond differently	Time-varying exposure layer interpreted in material-specific context
Edaphic environment	Soil nutrients and other locally relevant soil conditions	May explain variation not captured by geography alone	Confounding with climate, management, or genotype	Separate environmental layer rather than component of a single location score
Chemical state	Measured constituent or metabolomic profile at sampling	Directly reveals whether materials are chemically comparable	Analytical drift or uncertain annotation may mimic biological change	Primary observation layer for detecting provenance-relevant drift
Functional relevance	Experimentally measured activity linked to differing chemical states	Can strengthen concern that chemical variation matters to quality	Preclinical activity may be mistaken for therapeutic equivalence	Escalation criterion requiring evidence beyond compositional difference

Note: The final column represents the proposed synthesis of this article. No universal direction, magnitude, or numerical risk threshold is assigned to any provenance dimension.

Development and harvest as dynamic provenance variables

Environmental exposure alone cannot define the chemical state of a medicinal plant because the plant itself changes while that exposure is occurring. Harvest optimization literature shows that secondary-metabolite abundance may vary with plant age, season, time of day, and developmental stage [12]. Accordingly, two samples harvested under similar weather conditions may still be chemically non-equivalent if they were collected at different biological stages. Dynamic provenance therefore requires a temporal descriptor that is biologically meaningful rather than relying only on a calendar date.

Longitudinal evidence from *Astragalus membranaceus* var. *mongholicus* demonstrates the problem directly: phenotypic development, transcriptomic state, and metabolite accumulation changed across harvest periods, and the balance between growth and medicinal-material chemistry was not static [13]. An "October harvest" or "autumn material" is therefore an incomplete descriptor unless the underlying developmental state is also known. Exact optimal dates reported in one cultivation setting should not be exported as universal thresholds.

The pharmaceutical relevance of harvest timing becomes stronger when chemical evidence is supplemented by orthogonal quality information. In cultivated *Chrysanthemum indicum* flowers, untargeted and targeted metabolomics, chemometric analyses, and in vivo evidence were integrated to evaluate harvest period and candidate quality-control markers [14]. This does not establish clinical superiority of a harvest stage, but it illustrates how chemical timing can be evaluated against additional evidence rather than judged from abundance alone.

Developmental dependence is also observed across different medicinal materials. Stage-dependent metabolomic variation has been characterized during *Albizia julibrissin* flower development [15], supporting the broader conclusion that medicinal roots and flowers can occupy chemically distinct developmental states [13–15]. In *Akebia trifoliata* flowers, different classes of potentially useful constituents also showed stage-specific patterns, emphasizing that the preferred harvest state can depend on which quality attribute is being prioritized [16].

Harvest does not necessarily terminate the dynamic provenance process. Untargeted metabolomics of *Rosa rugosa* demonstrated that both development and subsequent processing alter the nonvolatile chemical profile [17]. Likewise, temporal profiling of *Pogostemon cablin* leaves showed continued changes in metabolites and phytohormones under post-harvest processing stress [18]. Dynamic provenance should therefore distinguish developmental state at cutting, harvest timing, and early post-harvest history. These variables are related but not interchangeable, and their pharmaceutical interpretation must remain specific to the plant material, processing system, target constituents, and intended quality attributes.

Therapeutic-quality consequences of chemical drift

Chemical drift becomes pharmaceutically important when variation affects constituents, chemical patterns, or functional properties that contribute to material quality. In *Echinacea purpurea*, geographical and environmental variation was associated not only with metabolomic differences but also with differences in measured immune-related activity [19]. This type of evidence strengthens the proposition that provenance-linked chemistry can matter functionally. It does not, however, establish that an environmentally induced metabolomic shift necessarily changes clinical efficacy. Dynamic provenance must therefore distinguish observed chemical drift, quality-relevant chemical drift, and demonstrated functional consequence rather than treating these states as equivalent.

That distinction also depends on analytical confidence. Plant metabolite profiles can be distorted by inadequate material characterization, sample handling, spectral interpretation, compound annotation, and reporting practices [20]. Apparent temporal or geographic differences therefore require an analytical explanation to be excluded before they are interpreted biologically. A poorly identified feature or an instrument-dependent signal cannot acquire pharmaceutical significance merely because it separates two provenance groups.

Classical source documentation remains essential to this process. Botanical identity, voucher information, collection location, and source-material characterization are prerequisites for reproducible phytochemical and phytopharmacological interpretation [21]. Dynamic provenance is proposed here as an extension of those requirements, not a replacement. It adds time-dependent biological and environmental state to the static source record.

Table 2 separates the evidential transitions that are easily conflated when chemical variation is translated into therapeutic-quality interpretation.

Table 2. Analytical distinctions governing interpretation of provenance-associated chemical drift

Observed state	What may be concluded	What remains unresolved	Appropriate next analytical step
Reproducible compositional difference	Materials occupy different measured chemical states	Cause and pharmaceutical importance	Confirm identity, sampling comparability, and analytical reproducibility
Difference associated with environment or harvest state	A provenance variable may help explain chemical variation	Causality and transferability	Replicate across seasons, sites, or controlled conditions
Drift involving recognized quality-related constituents	Specification relevance may be plausible	Functional consequence	Targeted quantitative confirmation and stability assessment
Chemical change accompanied by functional-assay change	Functional relevance is strengthened	Therapeutic equivalence or clinical consequence	Orthogonal biological validation
Proposed specification-relevant drift	Additional quality scrutiny may be justified	Valid acceptance limits and predictive performance	Prospective qualification before operational use

Note: The final row is a proposed decision state. None of these transitions alone demonstrates altered clinical effectiveness.

A dynamic provenance risk model

Medicinal-plant metabolomics provides a practical analytical basis for following changing chemical states, but longitudinal interpretation depends on controlled sampling, preparation, data acquisition, normalization, annotation, and quality assurance [22]. The proposed model therefore begins with an authenticated material identity and treats each subsequent observation as a time-indexed provenance state rather than as another sample from a permanently defined geographic source.

The model contains four interacting information layers. The first is stable source identity, including taxon and documented production origin. The second is dynamic production state, comprising environmentally relevant exposure history, developmental stage, harvest timing, and early post-harvest conditions. The third is the measured chemical state, including qualified marker concentrations or broader metabolomic patterns with explicit analytical confidence. The fourth is a quality-interpretation layer that asks whether observed drift involves constituents or patterns justified as quality relevant. Multimodal strategies for identifying quality markers support the principle that quality interpretation should integrate several evidence types rather than elevate every discriminating metabolite to marker status [23].

Risk arises in the proposed architecture when previously characterized relationships among these layers become unstable. A changed climate exposure without detectable chemical drift need not trigger the same response as reproducible chemical drift involving a specification-relevant constituent. Similarly, metabolomic separation without adequate annotation or batch control remains an analytical warning rather than a pharmaceutical failure. No numerical risk score is proposed because the selected evidence does not establish transferable thresholds.

Figure 1 integrates the mature model, including the longitudinal surveillance and boundary conditions required for its interpretation.

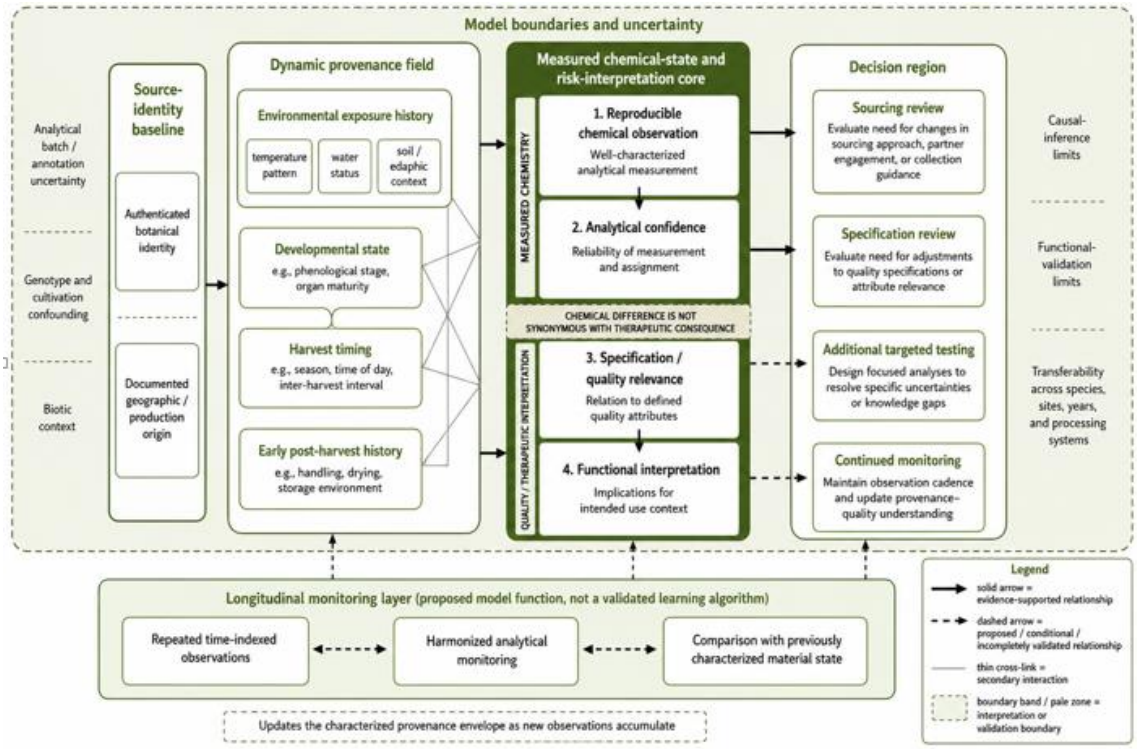

Figure 1. Proposed dynamic provenance-risk architecture for climate-sensitive medicinal-plant quality

Applications to sourcing and quality specifications

Dynamic provenance is intended to modify when and why additional quality evidence is requested, not to replace established specifications. Quality-marker frameworks already emphasize that measurable constituents should be selected because of defensible relationships to identity and quality rather than because they are analytically convenient or abundant [24]. Under climate instability, that principle can be extended by asking whether a specification remains sufficiently sensitive to the kinds of chemical variation that the production environment and harvest state can plausibly generate.

Multivariate metabolomics also demonstrates that complex chemical information can support practical material classification. Mass-spectrometry-based metabolomics and machine learning have been used to predict grades of Astragali Radix [25]. Such classification illustrates analytical feasibility but should not be interpreted as causal validation of provenance or therapeutic equivalence. Quality-marker frameworks and multivariate classification consequently provide complementary—but limited—routes for converting complex chemistry into quality-oriented decisions [23–25].

The proposed application is therefore selective escalation. A source with an established history and chemically stable longitudinal profile may continue under routine controls, whereas a material produced under substantially altered environmental or harvest conditions could receive additional targeted or metabolomic assessment. If reproducible drift affects a qualified quality marker, sourcing review or specification reassessment may become appropriate. **Table 3** summarizes these proposed decision states without assigning unsupported thresholds.

Table 3. Proposed decision workflow for applying dynamic provenance to sourcing and quality control

Decision state	Evidence available	Proposed response	Key boundary
Characterized and chemically stable	Traceable source plus comparable longitudinal chemistry	Continue established controls	Stability is specific to the monitored context
Provenance conditions changed, chemistry not yet changed	Meaningful exposure or harvest-state departure	Increase surveillance where scientifically justified	Exposure change alone is not quality failure
Reproducible chemical drift detected	Comparable analytical data confirm change	Determine constituent identity and specification relevance	Analytical and biological causes must be separated

Quality-relevant drift suspected	Qualified marker or validated quality pattern affected	Confirm quantitatively and consider sourcing/specification review	No universal acceptance threshold is established
Functional consequence suspected	Chemistry plus orthogonal functional evidence	Escalate validation before therapeutic interpretation	Preclinical evidence does not establish clinical equivalence

Note: All workflow responses are proposed and require product-, species-, method-, and context-specific qualification.

Longitudinal monitoring needs

Dynamic provenance cannot be implemented from isolated snapshots. Repeated measurements should be designed so that biological change can be distinguished from analytical drift. Consistent material characterization, reference standards, quality-control samples, annotation confidence, and transparent reporting are therefore central to longitudinal interpretation [20]. A temporal difference that disappears after batch correction or targeted confirmation should not be converted into a provenance-risk signal.

Botanical and collection metadata must also remain linked to each chemical observation. Classical source documentation provides the stable identity framework on which dynamic information can be added [21]. The proposed extension includes phenological stage, harvest status, relevant exposure history, and early processing state when these variables can be recorded reliably.

Metabolomics is particularly suitable for detecting broad compositional change, but differences in extraction, instrumentation, preprocessing, and annotation can compromise cross-time comparability [22]. Longitudinal programs should therefore favor harmonized analytical workflows or validated bridging procedures. Where platforms or methods change, the transition itself should be treated as a potential source of uncertainty. The purpose of monitoring is not to create an indefinitely expanding chemical fingerprint, but to determine whether a material remains within a characterized and pharmaceutically interpretable chemical state.

Model boundaries

The proposed architecture is intentionally broader than climate, because residual variation should not automatically be attributed to weather or geography. Biological interactions can modify medicinal-material chemistry independently of—or interactively with—abiotic conditions. In *Peucedanum praeruptorum*, fungal isolates were shown to influence quality-related chemical characteristics, illustrating that biotic context can become a meaningful alternative explanation for observed provenance-associated variation [26]. Soil microbiota, pathogens, symbionts, genotype, cultivation practice, and plant organ may therefore confound simple environment-to-chemistry interpretations.

The model also cannot distinguish causality from association without appropriate experimental design. Multisite field observations are valuable for detecting covariation but cannot isolate every co-varying environmental factor. Controlled stress studies improve causal inference for a defined perturbation, yet their magnitude and timing may not reproduce field climate trajectories. Likewise, developmental and harvest studies may identify chemically favorable stages without demonstrating that those stages remain optimal across years, genotypes, or production systems.

Analytical and therapeutic boundaries are equally important. Feature-level metabolomic differences can reflect uncertain structural annotation or methodological variation [20]. Even well-reproduced chemical drift should not be equated with changed therapeutic performance unless relevant constituents or functional pathways are independently qualified. Quality-marker frameworks can help prioritize such chemistry [23], but they do not establish universal regulatory specifications. Predictive grading models likewise demonstrate classification capability within defined datasets rather than external therapeutic validity [25].

Accordingly, dynamic provenance is not presented as a validated scoring system. Its principal use is conceptual: to identify when static source labels conceal biologically meaningful temporal variation and to organize the evidence needed before that variation influences sourcing or specification decisions. Multi-year, multi-site, genotype-aware replication, controlled perturbation, longitudinal harvest designs, analytical harmonization, external validation, and orthogonal functional testing are required before numerical risk thresholds or transferable decision rules could be justified.

Conclusion

Medicinal-plant provenance remains indispensable, but climate instability makes a static geographic interpretation increasingly incomplete. The central contribution of this article is a proposed dynamic provenance-risk model in which authenticated source identity is retained as the baseline while environmental exposure, developmental stage, harvest timing, early post-harvest history, measured chemical state, and analytical confidence are treated as separable but interacting dimensions.

The model changes the question from whether two medicinal materials came from the same place to whether they were produced under sufficiently comparable biological and environmental states to support the same chemical-quality interpretation. It further separates chemical drift from specification-relevant drift and from demonstrated functional consequence. That distinction prevents metabolomic variation from being promoted prematurely into claims of altered therapeutic performance.

Dynamic provenance may provide a useful architecture for longitudinal surveillance, risk-informed sourcing, and reconsideration of quality specifications when established source–chemistry relationships become unstable. Its value, however, depends on preserving rather than erasing uncertainty. Geography remains necessary; environmental associations are not automatically causal; harvest optima are not universally transferable; analytical differences can mimic biological change; and functional or clinical consequences require evidence beyond composition. The proposed model should therefore be understood as an evidence-organizing framework requiring prospective qualification, not as a validated predictive instrument or implementation standard.

Acknowledgments: None

Conflict of Interest: None

Financial Support: None

Ethics Statement: None

References

1. Takubessi MI, Jalil B, Heinrich M. The impact of climate change on medicinal plants and natural products: A scoping review. Front Pharmacol. 2025;16:1697581. doi:10.3389/fphar.2025.1697581
2. Jangpangi D, Patni B, Chandola V, Chandra S. Medicinal plants in a changing climate: Understanding the links between environmental stress and secondary metabolite synthesis. Front Plant Sci. 2025;16:1587337. doi:10.3389/fpls.2025.1587337
3. Zhang C, Zhong X, Bao S, Urtnasan M, Li M. Main factors affecting the efficacy of medicinal plants during the cultivation process. Front Plant Sci. 2025;16:1634926. doi:10.3389/fpls.2025.1634926
4. Li Y, Wu H, Fan J, Huang J, Jin H, Wei F. Innovative perspective on the geographical origin and quality of Peucedanum praeruptorum Dunn through the integration of inorganic and organic substance profiles. J Pharm Anal. 2026;16(4):101405. doi:10.1016/j.jpha.2025.101405
5. Wu J, Deng S, Yu X, Wu Y, Hua X, Zhang Z, et al. Identify production area, growth mode, species, and grade of Astragali Radix using metabolomics “big data” and machine learning. Phytomedicine. 2024;123:155201. doi:10.1016/j.phymed.2023.155201
6. Zhang F, Zhang G, Wang C, Xu H, Che K, Sun T, et al. Geographical variation in metabolite profiles and bioactivity of Thesium chinense Turcz. revealed by UPLC-Q-TOF-MS-based metabolomics. Front Plant Sci. 2025;15:1471729. doi:10.3389/fpls.2024.1471729
7. Wang Y, Liu H, Yu S, Zhang Y, Huang Y, He X, et al. Effects of geographical, soil and climatic factors on the two marker secondary metabolites contents in the roots of Rubia cordifolia L. Front Plant Sci. 2024;15:1419392. doi:10.3389/fpls.2024.1419392
8. Wu D, Xiong F, Wang H, Liu S, Zhu J, Zhao D, et al. Temperature seasonality and soil phosphorus availability shape ginseng quality via regulating ginsenoside contents. BMC Plant Biol. 2024;24(1):824. doi:10.1186/s12870-024-05518-2
9. Zhou Y, Bai YH, Han FX, Chen X, Wu FS, Liu Q, et al. Transcriptome sequencing and metabolome analysis reveal the molecular mechanism of Salvia miltiorrhiza in response to drought stress. BMC Plant Biol. 2024;24(1):446. doi:10.1186/s12870-024-05006-7

10. Huang X, Rong W, Zhang X, Gao Y, Zhou Y, Su J, et al. Transcriptome and metabolome analysis reveal the dynamic changes and biosynthesis pathways of alkaloids in Sophora alopecuroides L. under drought stress. Ind Crops Prod. 2024;212:118365. doi:10.1016/j.indcrop.2024.118365
11. Li Y, Jiang D, Liu XY, Li M, Tang YF, Mi J, et al. Multi-omics analysis provides crucial insights into the drought adaptation of Glycyrrhiza uralensis Fisch. J Agric Food Chem. 2023;71(13):5391-402. doi:10.1021/acs.jafc.2c07163
12. Hazrati S, Mousavi Z, Nicola S. Harvest time optimization for medicinal and aromatic plant secondary metabolites. Plant Physiol Biochem. 2024;212:108735. doi:10.1016/j.plaphy.2024.108735
13. Li X, Mu Y, Hua M, Wang J, Zhang X. Integrated phenotypic, transcriptomics and metabolomics: Growth status and metabolite accumulation pattern of medicinal materials at different harvest periods of Astragalus membranaceus mongholicus. BMC Plant Biol. 2024;24(1):358. doi:10.1186/s12870-024-05030-7
14. Yang P, Tian D, Han XY, Zou QJ, Ma LJ, Wei M, et al. Optimal harvest period and quality control markers of cultivated Flos Chrysanthemi Indici using untargeted/targeted metabolomics, chemometric analysis and in vivo study. J Ethnopharmacol. 2024;334:118533. doi:10.1016/j.jep.2024.118533
15. Cheng Y, Chen R, Chen F, Wu C, Zhou Y, Tian X, et al. Metabolomics reveals stage-dependent metabolic dynamics associated with quality variation during the development of Albizia julibrissin flower. Ind Crops Prod. 2026;240:122657. doi:10.1016/j.indcrop.2026.122657
16. Jia T, Nazir MF, Bovio-Zenteno EM, Feng C, Zhang Y, Lou J, et al. Stage-specific harvest of Akebia trifoliata flowers: An integrated multi-omics strategy for optimizing natural colorants, antioxidants and bioactive ingredients. Ind Crops Prod. 2026;241:122795. doi:10.1016/j.indcrop.2026.122795
17. Cheng X, Li X, Chen D, Wang Q, Wang H, Gao K, et al. Untargeted metabolomics analysis revealed metabolite dynamics during the development and processing of Rosa rugosa flowers. Ind Crops Prod. 2024;222:119954. doi:10.1016/j.indcrop.2024.119954
18. Ge X, Fang S, Chen L, Zhang D, Xu P, Luo H, et al. Profiling the dynamic alterations of metabolites and phytohormones in response to stress during the post-harvest processing of Pogostemon cablin leaves. Ind Crops Prod. 2025;230:121125. doi:10.1016/j.indcrop.2025.121125
19. Xu W, Cheng Y, Guo Y, Yao W, Qian H. Effects of geographical location and environmental factors on metabolite content and immune activity of Echinacea purpurea in China based on metabolomics analysis. Ind Crops Prod. 2022;189:115782. doi:10.1016/j.indcrop.2022.115782
20. Çiçek SS, Mangoni A, Hanschen FS, Agerbirk N, Zidorn C. Essentials in the acquisition, interpretation, and reporting of plant metabolite profiles. Phytochemistry. 2024;220:114004. doi:10.1016/j.phytochem.2024.114004
21. Zidorn C. Guidelines for consistent characterisation and documentation of plant source materials for studies in phytochemistry and phytopharmacology. Phytochemistry. 2017;139:56-9. doi:10.1016/j.phytochem.2017.04.004
22. Waris M, Koçak E, Gonulalan EM, Demirezer LO, Kır S, Nemutlu E. Metabolomics analysis insight into medicinal plant science. Trends Analyt Chem. 2022;157:116795. doi:10.1016/j.trac.2022.116795
23. Lu X, Jin Y, Wang Y, Chen Y, Fan X. Multimodal integrated strategy for the discovery and identification of quality markers in traditional Chinese medicine. J Pharm Anal. 2022;12(5):701-10. doi:10.1016/j.jpha.2022.05.001
24. Yang W, Zhang Y, Wu W, Huang L, Guo D, Liu C. Approaches to establish Q-markers for the quality standards of traditional Chinese medicines. Acta Pharm Sin B. 2017;7(4):439-46. doi:10.1016/j.apsb.2017.04.012
25. Yu X, Nai J, Guo H, Yang X, Deng X, Yuan X, et al. Predicting the grades of Astragali radix using mass spectrometry-based metabolomics and machine learning. J Pharm Anal. 2021;11(5):611-6. doi:10.1016/j.jpha.2020.07.008
26. Liu L, Wang X, Chen S, Liu D, Song C, Yi S, et al. Fungal isolates influence the quality of Peucedanum praeruptorum Dunn. Front Plant Sci. 2022;13:1011001. doi:10.3389/fpls.2022.1011001