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Quantifying Nature's Novelty: Trends in HPLC and HPTLC Fingerprinting for Herbal Drug Analysis

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Abstract:

The efficacy of herbal medicines in therapy, their cultural suitability, and relatively low degree of side effects have made them an inherent aspect of health care globally, yet the variability and complexity of phytochemical compositions are important concerns in quality, safety and reproducibility. Precisely, chromatographic fingerprinting techniques have emerged as an effective way of full characterization of herbal drugs particularly the High-Performance Liquid Chromatography (HPLC) and the High-Performance Thin Layer Chromatography (HPTLC). This review discusses the recent developments of these techniques using the latest state-of-the-art techniques such as Ultra-High Performance Liquid Chromatography (UHPLC), hyphenated techniques (LC-MS/MS and HPTLC-MS), densitometric analysis and combination of chemometric approaches. It covers methodological approaches, its application in the standardization of herbal drugs and a comparison of the two approaches. The findings reveal that HPLC is more sensitive and accurate in quantitative analysis, whilst HPTLC is fast, cost-effective and high-throughput screening. In addition, chemometric techniques are important to interpret the data, which enables to categorize the data correctly and detect the adulteration. Regardless of these advances, current problems such as the variability of phytochemicals and the lack of standard reference materials remain to be addressed, implying that future advances will be made with the help of hybridized chromatographic methods in the era of new technologies such as artificial intelligence and metabolomics.

Keywords: Herbal medicines, Chromatographic fingerprinting, High-Performance Liquid Chromatography (HPLC), High-Performance Thin Layer Chromatography, Ultra-High Performance Liquid Chromatography

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1. INTRODUCTION

The use of herbs has resulted in herbal medicines becoming an important component of the health care system of most countries not only because of the traditional application of herbs but also because of the scientific rationale behind the use of herbs [1]. Widespread acceptance of the use of herbal medicines is exercised by the fact that the world health organization estimates that nearly 7080 percent of the population in developing countries uses herbal medicines as primary healthcare [2]. The global market of herbal medicine has also been increasing at a very fast pace with the current estimates being over USD 200-250 billion and the projection being that it will

be above USD 400 billion by the year 2030 due to the growing demand of natural and plant based medicines [3].

Unlike synthetic drugs, herbal medicines are complicated mixtures of phytochemicals that consist of alkaloids, flavonoids, terpenoids, glycosides and phenolic compounds. Medicinal plants have been estimated to have over 12,000 bioactive compounds, most of which are synergistic to produce a therapeutic effect. However, these compounds are highly diverse and they are also dependent on several factors such as geographical source, climatic, soils type, harvesting and processing processes. Studies have revealed that phytochemical composition can vary by 20-200 percent across different lots of the same plant species and therefore leads to variability in effectiveness and safety.

This is one of the major issues in standardization and regulation of the quality of the herbal medicines. It has been indicated that approximately 25-30 percent of herbal products at the global market are being faced with issues such as adulteration, substitution or heavy metal, pesticides and microbial toxin contamination. These questions have underscored the significance of valid and scientifically-tested modes of analysis to produce authenticity and consistency.

Chromatographic fingerprinting has emerged as a good solution to these issues. The methods that enable the simultaneous analysis of a range of phytoconstituents, and can provide detailed chemical profiles of herbal drugs are (HPLC) and High-Performance Thin Layer Chromatography (HPTLC). HPLC is sensitive and can detect down to the nanogram range (ng/mL) and can be used to determine accurately, whereas HPTLC can determine 20-30 samples simultaneously, hence used in high throughput and rapid screening [4].

1.1 Background of the Study

Herbal medicine has a long history of use in traditional health care systems such as Ayurveda, Traditional Chinese Medicine (TCM) and Unani. In recent decades, their usage has increased significantly in the whole world as a result of increased interest in natural remedies, increased interest in plant-based medications and the fear of side effects of synthetic medicines. As a result, herbal products have been widely used in preventive and curative healthcare [5].

Unlike traditional drugs, which typically contain only one active ingredient, herbal medicines are formulations containing multi-component mixtures of secondary metabolites, including alkaloids, flavonoids, terpenoids, glycosides, phenolic. These elements are likely to experience synergistic effects in order to achieve therapeutic effects. However, they are highly dynamic with respect to their chemical composition and are subject to many influences such as geographical location, weather, quality of soil, harvesting, and after harvest processing methods.

This natural heterogeneity poses significant challenges in ensuring consistency of batches to batches, quality control and therapeutic safety of herbal medicines. This has led to an increasing need to come up with advanced analysis techniques that can provide holistic chemical characterization of herbal products.

1.2 Objectives of the Review

This review is meant to give a critical and thorough review of the chromatographic fingerprinting methods in the analysis of herbal drugs. The targeted objectives list is as follows:

- The aim of the paper was to give a general account of the (HPLC) and High-Performance Thin Layer Chromatography (HPTLC) fingerprinting methods.
- To assess the latest developments and progress in chromatographic analysis.
- To critically evaluate the uses of these methods in the standardization of herbal drugs.
- To compare the advantages, shortcomings, and the analytical abilities of HPLC and HPTLC.
- To state the gaps in research that were found and suggest the way of how research could be done better

1.3 Importance of the Study

The herbal medicines should be standardized in such a way that they are safe, effective and acceptable across the world. Low quality and contaminants or adulterants can impair therapeutic effectiveness and endanger the population health. Therefore, identification and quality analysis should have plausible analytical methods [6].

Recommendations have indicated the application of chromatographic fingerprinting as an efficient and potent way of quality control of herbal drugs by the regulatory bodies such as the World Health Organization. The techniques generate comprehensive chemical profiles that facilitate the identification of active constituents, identify adulteration and determine batch to batch consistency.

With the increased rapidity in commercialization as well as globalization of herbal products, there is an increasing need to possess advanced, accurate and reproducible instruments of analysis. Thus, chromatographic fingerprinting through the assistance of HPLC and HPTLC has gained a huge popularity in the pharmaceutical sciences and pharmacognosy and this is why this issue is of significant concern as far as the realization of a modern research and industrial application is concerned.

2. CONCEPT OF CHROMATOGRAPHIC FINGERPRINTING IN HERBAL DRUG ANALYSIS

Chromatographic fingerprinting is an in-depth procedure of examination that can be implemented in characterizing the chemical composition of herbal drugs [7]. Unlike the old method of using single-markers to analyze, fingerprinting reflects the entire spectrum of phytoconstituents, as it demonstrates the possibility of synergy of herbal preparations [8].

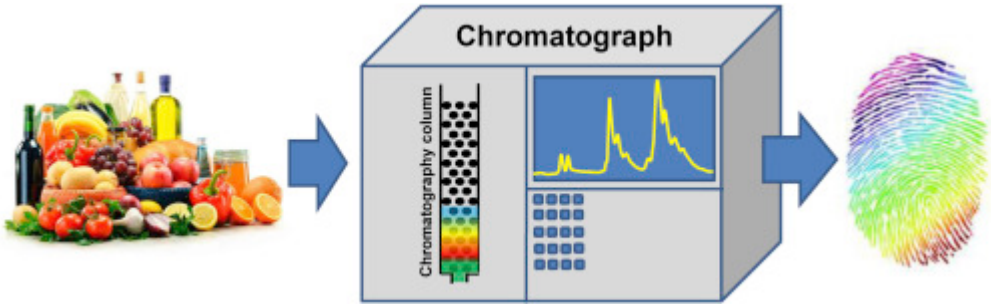

Figure 1: Chromatographic Fingerprinting [9]

Herb medicines are intricate combinations of secondary metabolites such as alkaloids, flavonoids, glycosides and terpenoids. The therapeutic action of these compounds normally depends on the interactions among the compounds and not on the activity of the individual compounds. Fingerprinting, therefore, is necessary in order to ensure the authenticity, quality and consistency.

The only chemical signature that will be utilized in the comparison of different batches, sources and formulations is the fingerprint profiles. The profiles are particularly important in determining adulteration, substitution and degradation.

2.1 High-Performance Liquid Chromatography

HPLC is an analytical technique that is widely used to separate, identify and quantify the phytoconstituents of herbal drugs. It operates under high pressure and separation of the various analyses can be effectively partitioned on basis of the interactions between the analyte and stationary/mobile phases [10].

The new HPLC systems have advanced detectors such as UV, Photodiode Array (PDA), and Mass spectrometry (MS) that assist in enhancing sensitivity and specificity.

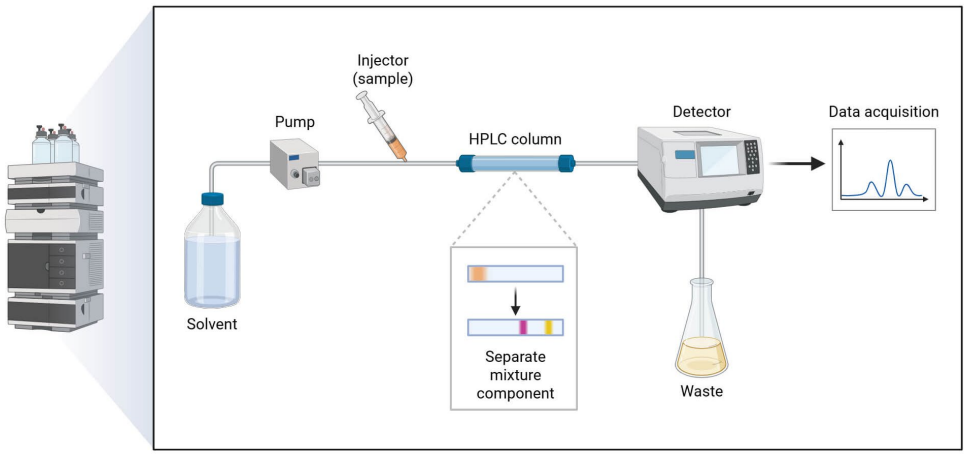

Figure 2: High-Performance Liquid Chromatography [11]

Newer developments such as Ultra-High Performance Liquid Chromatography (UHPLC) has immensely improved the resolution, reduced the duration of the analysis and reduced the volume

of solvent consumed. In addition, hyphenated techniques, like LC-MS/MS, provide structural information of the intricate phytochemicals.

HPLC fingerprinting is useful particularly in:

- Estimation of bioactive compounds in a quantitative way.
- Identification of impurities and contaminants.
- stability and degradation studies.
- Standardization of formulations with herbs.

2.2 High-Performance Thin Layer Chromatography (HPTLC)

HPTLC is a complex planar chromatography technique that allows the analysis of numerous samples simultaneously. It involves separation of precoated plates, and quantification is performed by densitometric scanning [12].

HPTLC is also cheaper and it can be applied in a rapid screening unlike HPLC. It also provides the graphical appearance of separated compounds and this may assist in a rapid identification.

The automated sample applicators, the digital imaging system, and hyphenation with mass spectrometry (HPTLC-MS) that offers more precise analysis are the new developments.

HPTLC is widely used in:

- Checking of crude herbal drugs.
- Detection of adulteration
- Comparison of formulations.
- High-throughput screening

2.3 Comparative Analysis of HPLC and HPTLC

HPLC and High-Performance Thin Layer Chromatography (HPTLC) are chromatographic methods that are highly used in the analysis of herbal drugs with peculiar features of analysis [13]. The sensitivity and high resolution of HPLC are very high to the extent that it can separate and quantify complex mixtures of phytochemicals in highly accurate manner even at very low concentrations. However, it is expensive to instrument, operation must be performed by experienced professionals and analysis is also time-consuming.

HPTLC on the other hand is a good resolution but moderate sensitivity planar chromatography technique. It is also less costly, allows a number of samples to be analyzed simultaneously and provides a direct view of separated compounds using a UV or visible detector. HPTLC is not as accurate in quantitative analysis, as HPLC, but it is most suitable in screening and comparative fingerprint analysis [14].

Table 1: Comparative Features of HPLC and HPTLC [15]

Parameter	**HPLC**	**HPTLC**
Sensitivity	Very High	Moderate

Resolution	Excellent	Good
Cost	High	Low
Throughput	Moderate	High
Quantitative Accuracy	High	Moderate
Visualization	Limited	Direct

The comparison reveals that HPLC is more suitable in those circumstances where high precision, sensitivity and precise quantification such as determination of marker compounds and phytochemical profiling is required. It plays a vital role in regulatory and quality control because of the ability to detect compounds at very low concentrations.

On the other hand, HPTLC is more suitable in the initial screening process, routine quality analysis and high-throughput analysis due to its cost efficiency and the potential to handle multiple samples simultaneously. The ability to directly visualize the HPTLC also makes it specifically useful with regards to determining adulteration and comparative analysis of herbs samples in a rapid fashion [16].

2.4 Role of Chemometrics in Fingerprinting

Chemometrics refers to the application of specialized statistical, mathematical and computer computational techniques to gain valuable information when faced with complex analytical data. When used to the study of herbal drugs, the chromatographic fingerprinting methods such as HPLC and HPTLC generate data of enormous and multi-dimensional magnitude and comprise of numerous peaks that are attributed to different phytoconstituents. The nature of herbal formulations is complex and variable, so such data is not readily amenable to manual interpretation, and is usually subjective. So, chemometric techniques become now an inevitable part of the adequate and objective data analysis [17].

Some of the most popular methods in chemometric assessment are Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA) and Partial Least Squares (PLS). PCA can be used to both reduce the dimensionality of data and identify patterns or differences between samples by projecting correlated variables into major components. HCA isolates samples based on their chemical similarities, and enables the classification and separation of authentic and adulterated samples. PLS, in its turn, can be utilized to locate the correlation between the chromatographic data and the quantitative variables to allow predictive modelling and the quantitative analysis [18].

One of the most important fields in the use of chemometric tools is pattern recognition, categorization of herbs, detecting adulteration and consistency between batches to batches. They can also be applied together in comparing a large number of samples, which increases efficiency during the quality control procedures. The chemometrics is applied to enhance the decision making process in the analytical studies by converting the difficult chromatographic data into the simplified visual data, such as score plots and dendrograms.

3. METHODOLOGIES AND FINDINGS

This section includes a general overview of methodological descriptions underway in (HPLC) and (HPTLC) of herbal drugs fingerprinting. It outlines the methodological steps of the sample preparation, chromatographic separation, detection and data interpretation and the role they have in the making of good reliable and reproducible chemical fingerprints [19].

In addition to describing the methodologies of analysis, this section will extrapolate the significant results of other research articles on how the methods were effective in the identifications, quantification and standardization of phytoconstituents of more complex herbal matrices. It also provides a comparative study of HPLC and HPTLC regarding the quality control with respect to analytical performance, efficiency, cost, and applicability and therefore illustrate the complementary roles.

In addition, a critical appraisal is also presented to elaborate on the benefits as well as the limitations of both techniques, taking into account certain practical problems, such as variability of herbal samples, instrumentation, and difficulties of data interpretation. Overall, this section will be used to bridge the gap between the methodology and the experimental results and provide a clear view of the position of chromatographic fingerprinting in standardizing, authenticating and quality assuring herbal medicines.

3.1 Methodological Approaches in HPLC Fingerprinting

(HPLC) fingerprinting is an analysis procedure that is highly controlled and systematic and geared towards achieving proper separation and quantification of phytoconstituents. The methodology could be separated into the following steps:

- **Sample Preparation:** Samples of the herbals are dissolved in the correct solvents such as methanol, ethanol or water depending on the polarity of the compound of interest. Good extraction will ensure the best extraction of bioactive components [20].
- **Chromatographic Conditions:** To achieve successful separation, it is carried out with the assistance of the use of appropriate stationary phases (that are usually C18 reverse-phase columns) and the best mobile phase combinations (e.g., water-acetonitrile or methanol-based systems).
- **Detection:** Compounds can be detected with either UV, Photodiode Array (PDA) or Mass Spectrometry (MS) detectors; this enables the qualitative and quantitative analysis of compounds.
- **Data Processing:** Chromatograms will be obtained and processed so as to ascertain the presence of peaks with different phytoconstituents. Peak area, retention time and spectral data are used to come up with fingerprint profiling.

3.2 Summary of Research Findings

The research studies in Table 2 all demonstrate the increasing significance of chromatographic fingerprinting, especially in the HPLC and HPTLC methods in the analysis of herbal drugs. Sima et al. (2018) also highlighted the combination of chemometric tools with chromatographic

methods in order to improve authentication and interpret data. Li et al. (2025) showed a holistic strategy of TLC, HPLC, and chemical pattern recognition to assess quality of herbal formulations of various geographical sources.

Bhardwaj and Kaushik (2015) recognized chromatographic fingerprinting to be an important part of quality control and chemotaxonomic classification of medicinal plants. Jain et al. (2014) dedicated their attention to the importance of using HPTLC as a current, effective, and multifaceted analytical method to conduct a chemical analysis. Dahiya et al. (2025) have also mentioned the use of HPTLC with multivariate analysis to assess plant samples in various locations with an emphasis on geographic variation as an important variable in phytochemical composition.

Table 2: Key Findings from Selected Studies

Author Name	Topic Covered	Research Study Title
Sima, I. A., Andrási, M., & Sârbu, C. (2018) [21]	Chemometric assessment in chromatographic fingerprinting for herbal authentication	Chemometric evaluation of chromatographic analysis of herbal medicines authentication and fingerprinting.
Li, Y., Su, Y., Liang, Y., Li, F., Lin, N., Jiang, L., & Chen, Q. (2025) [22]	Quality evaluation of herbal formulations using TLC, HPLC, and chemometric tools	TLC, HPLC fingerprinting, and quantitative analysis with chemical pattern recognition was used to evaluate quality of kidney tea granules of various origins.
Bhardwaj, D., & Kaushik, N. (2015) [23]	Chromatographic fingerprinting for quality control and chemotaxonomy of medicinal plants	Chromatographic fingerprinting: a new quality control and chemo-taxonomy instrument of medicinal plants and their drugs.
Jain, A., Parashar, A. K., Nema, R. K., & Narsinghani, T. (2014) [24]	HPTLC as a modern analytical technique for chemical analysis	High performance thin layer chromatography (HPTLC): A current analytical method of analysing chemical substances.
Dahiya, J., Mangal, A. K., Bolleddu, R., Kumar, D., Abdullah, S., Prasad, S. B., & Babu, G. (2025) [25]	HPTLC fingerprinting with multivariate analysis for plant characterization	HPTLC marker and fingerprint analysis and multivariate analysis of various components of Cyanthillium cinereum in various geographical areas.

The overall results of these trials show that there is a definite direction towards the combination of the chromatographic fingerprinting with the chemometric analysis techniques, as well as with

the multivariate techniques of analysis. This combination helps to work with complex data sets, increases the classification rates, and makes authentication procedures more resilient.

The methods based on HPLC are mainly linked to high precision, detailed identification of compounds, and quantitative analysis, and HPTLC-based methods are often utilized to conduct a rapid screening, cost-effective analysis, and comparative fingerprinting. The use of chemometric instruments also enhances the strength of the analytical process by reducing subjectivity and allowing the identification of patterns in large volumes of data.

These results indicate that the contemporary analysis of herbal drugs is shifting to a multidimensional framework, with chromatographic methods combined with statistical modeling to achieve better quality control. The papers also emphasize the need to take into consideration geographical and environmental differences in phytochemical profiling. Thus, a coherent and integrated approach to analysing is needed to ensure the quality and safety of herbal medicines and their quality standardisation.

3.3 Comparative Findings of HPLC and HPTLC

This comparison in Table 3 shows the major methodological variations between (HPLC) and (HPTLC) in the analysis of herbal drugs. The nature of HPLC is high precision and accuracy in quantification and thus it is applicable in the detailed analysis of phytoconstituents. Nevertheless, it usually takes more time to analyze and it is more expensive in terms of operations and instrumentation. Moreover, the HPLC systems are usually able to analyze a single sample at a time, and this restricts throughput.

Conversely, HPTLC provides quicker analysis and is more economical since it has a less complex instrumentation and reduces solvent usage. A key strength it has is that a number of samples can be analyzed on a single plate to a great extent, making it much more efficient. Nevertheless, it is relatively less quantitatively precise than HPLC, which could restrict its applicability in very sensitive analyses [26].

Table 3: Methodological Outcomes Comparison [27]

Aspect	HPLC Findings	HPTLC Findings
Accuracy	High precision quantification	Moderate precision
Speed	Moderate	Fast
Cost Efficiency	Expensive	Economical
Sample Analysis	Limited simultaneous analysis	Multiple samples analyzed simultaneously

It is also evident in the comparison that HPLC is the method of choice in the application of high accuracy, sensitivity, and precise quantification, especially in regulatory quality control and fine-scale phytochemical studies. Conversely, HPTLC is more beneficial in quick screening, routine and large scale sample processing since it is fast and cost effective [28].

Such results imply that the two methods are complementary and not substitutes. Practically, HPTLC may be utilized in initial screening and identification and HPLC in confirmatory analysis and accurate quantification. Hence, a combination of both methods offers a more functional and holistic method of standardization and quality of herbal drugs.

3.4 Critical Evaluation of Methodologies

Both HPLC and HPTLC have great merits in analysis of herbal drugs. HPLC is sensitive, has high resolution, and good quantitative abilities, making it suitable in comprehensive phytochemical profiling, and regulatory compliance [29]. Conversely, HPTLC is very beneficial in fast screening, cost effective analysis and processing of high throughput samples. All these methods are complementary and increase the overall reliability of chromatographic fingerprinting [30].

Although both techniques are advantageous, they are characterized by some limitations. HPLC is also costly to maintain, expensive to operate, and needs specialized staff and equipment which could make it inaccessible. HPTLC is cheap and efficient but its sensitivity and quantitative accuracy are less than that of HPLC. Moreover, variability of herbal raw materials may impact reproducibility and consistency in both methods, and this presents a standardization challenge [31].

4. DISCUSSION

The current review presents that chromatographic fingerprinting techniques particularly (HPLC), (HPTLC) have gained more and more importance in the analysis and standardization of herbal medicines [32]. The findings are rather categorical that the two approaches are complementary to the problems of complexity and variability of phytochemical constituents.

HPLC has been found to be more sensitive, resolutive and more accurate in quantification, hence it is highly applicable in the detailed profiling of phytochemicals and quality control. The fact that it can detect compounds at traces level ensures proper identification and quantification of bioactive components. On the other hand, HPTLC is quick, cost effective and high throughput and has the capability to process a batch of samples at a time, in addition to enabling the visualization of the separated material directly. This holds particularly in the everyday screening, identification, and adulteration detection [33].

A notable trend that can be seen in this review is the integration of chemometric techniques such as Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA), and partial least squares (PLS) with chromatographic methods. The tools are significant in the interpretation of complex datasets because they enable the identification of patterns, categorizing them and removing variability in analysis. The integration of chromatographic fingerprinting and chemometrics has emerged as a powerful technique to increase the reliability, reproducibility and objectivity of herbal drug analysis [34].

4.1 Interpretation and Analysis

The review results clearly show that chromatographic fingerprinting methods, especially HPLC and HPTLC have made a huge contribution to the field of herbal drug analysis. These methods

can be combined to achieve a comprehensive profiling of complex phytochemical mixtures, making this a necessity due to the multi-component nature of herbal medicines [35].

HPLC has become a very sensitive and specific method of analysis, which can detect and determine phytoconstituents at a very low concentration [36]. It is especially useful in comprehensive phytochemical studies, quality control, and in regulatory compliance. Conversely, HPTLC provides high throughput, cost-effective and fast analysis, which is appropriate in routine screening and comparative fingerprinting [37].

Analytical ability of chromatographic methods has been further improved by the inclusion of chemometric methods like PCA, HCA and PLS [38]. Such tools can be used to interpret complex datasets and identify patterns, classify them, and detect adulteration [39]. In the reviewed studies, the trend is towards the use of integrated analytical methods using a combination of chromatographic methods with statistical modeling to enhance reliability and reproducibility [40].

4.2 Implications and Significance

- Chromatographic fingerprinting with HPLC and HPTLC provides standardization, quality assurance, authentication and adulterant detection, as well as batch-to-batch consistency in herbal medicines.
- The methods make it more credible, acceptable globally, and compliant with regulations (e.g., World Health Organization guidelines), enabling the creation of reliable formulations, which enhances the therapeutic efficacy and consumer trust.
- They facilitate research progress with the ability to discover bioactive compounds, comprehend phytochemical variability, multi-component analysis, and synergistic interaction study.
- In general, they connect the traditional knowledge to the scientific validation and play a significant part in the pharmacognosy and pharmaceutical sciences.

4.3 Gaps and Future Research Directions

- Absence of standard reference materials and universally accepted protocols of analysis, which influence its reproducibility and consistency.
- Great phytochemical diversity under the impact of environmental, geographical and seasonal variations.
- High cost, complexity and unavailability of sophisticated methods like HPLC-MS/MS and UHPLC systems.
- More user-friendly, standardized, and efficient chemometric tools to analyze data are required.

5. CONCLUSION

Chromatographic fingerprinting has taken a leading role in the study, standardization and quality control of herbal medicines through (HPLC) and (HPTLC). This review highlights that HPLC is

sensitive, precise and provides a correct quantification of phytoconstituents and HPTLC is rapid, cheap and provides a high throughput screening capability with a direct visualization. The integration of chemometric tools also enhances the analysis of complex data, which becomes more reliable, authentic and adulteration sensitive. Despite all these advances, there are still problems of inconsistency in phytochemicals, lack of universal reference standards and inaccessibility of advanced methods of analysis. Therefore, new technologies such as artificial intelligence, metabolomics, and standardized protocols are required to integrate HPLC and HPTLC to obtain a complete and reproducible analysis of herbal drugs. Overall, these approaches have a role in improving the safety, efficacy and broad acceptability of herbal medicines and in advancing the scientific research in the pharmacognosy and pharmaceutical sciences.

5.1 Summary of Main Insights and Conclusions

This review indicates that chromatographic finger-printing techniques, in particular, (HPLC) and (HPTLC) are important tools used in the analysis, authenticity and standardization of herbals. HPLC is sensitive, specific and quantitative (accurately) of phytoconstituents, but HPTLC is rapid and economical, and has a visual fingerprinting ability. The combination of chemometric tools also enhances the interpretation of the data to establish patterns, classify and detect adulteration. These findings point out that HPLC-HPTLC is a more specific analysis technique but, nonetheless, the problem of phytochemical variations, lack of standard reference reagents, and technical limitations persist.

5.2 Reiteration of the Importance of the Review

- Renews the importance of chromatographic fingerprinting in guaranteeing quality, safety, and efficacy of herbal medicines.
- Describes the increasing significance of the techniques in the expanding world herbal market.
- Gives systematic information about recent developments in HPLC and HPTLC.
- Helps in enhancing standardization of herbal drugs and regulatory adherence.
- Lays stress on incorporating modern analytical and chemometrics tools to improve interpretation.
- Fills the gap between ancient wisdom of herbs and scientific verification.
- Increases the value and worldwide recognition of herbal products.

5.3 Recommendations

- Uniform reference material and internationally agreed analytical procedures to increase uniformity and reproducibility.
- More integration between the two HPLC and HPTLC techniques so as to have a qualitative and quantitative analysis.

- Incorporation of the latest technologies such as artificial intelligence, machine learning, and metabolomics in enhancing data analysis and predictive models.
- Improved access to analytical applications in resource constrained environments through low cost, pioneering solutions.
- International databases of herbal fingerprints developed to facilitate authentication and quality assurance.
- Promotion of interdisciplinary studies and partnerships to reinforce the standardization practice in herbal medicine.

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