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Traditional Uses and Big Data Approaches: A Semi-Systematic Review on the Refoundation of Tropical Ethnopharmacology and Pharmacognosy under WHO Frameworks

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Abstract

Background: Ethnopharmacology plays a central role in the discovery and validation of medicinal plants and their molecular compounds, particularly in tropical regions where biodiversity and traditional knowledge are highly concentrated. **Aim**: This semi-systematic review aims to examine how ethnopharmacology and pharmacognosy are being reshaped under WHO frameworks and data-driven approaches. **Methods:** A PRISMA-informed semi-systematic review of peer-reviewed literature was conducted across major scientific databases and WHO sources. **Results**: Our research included one hundred and sixteen studies, revealing partial convergence between traditional uses and pharmacognostic validation, alongside significant methodological heterogeneity. **Conclusion**: Integrative and ethically grounded frameworks are required to ensure scientific rigor, cultural legitimacy, and sustainability in tropical ethnopharmacology.

Keywords

Ethnopharmacology, Medicinal Plants, Traditional Knowledge, Pharmacognosy, WHO, Big Data

1. Introduction

1.1. Global Health, Ethnopharmacology and Tropical Biodiversity

Ethnopharmacology lies at a crucial nexus of traditional medicine and contemporary biomedical science, especially in tropical environments where biological diversity in biology and cultural diversity meet at a unique level. These areas accumulate a large fraction of the world's medicinal plant species and have a long tradition in traditional medicine systems that are still crucial for the care of millions of people around the world [1] [2]. In lower- and middle-income countries in sub-Saharan Africa, Southeast Asia, and the Amazon basin, traditional plant-based remedies are also often the most accessible, accepted, and economically feasible form of health care. This relevance has broader global health concerns, and there are also local therapeutic practices that involve ethnopharmacology. Medicinal compounds have been the cornerstone of drug discovery with a direct or indirect role in a substantial part of modern pharmaceuticals [3]. Traditional uses have been a major target for systematic investigation, and their usefulness as a heuristic tool for detecting bioactive compounds has been continuously confirmed, particularly in the contexts where knowledge has been developed through a series of time-tested observations and the application of techniques. Amidst this growing global demand for scientifically validated safe, effective therapeutics, ethnopharmacology is under growing scrutiny. Traditional knowledge systems may be filled with qualitative insights, yet they commonly miss the reproducibility, standardized documentation, and quantitative rigour required in contemporary biomedical and regulatory frameworks. One particularly strong manifestation of this tension can be observed in the recent encouragement from international organizations such as the World Health Organization to mainstream traditional medicine into the national medical systems (as supported by evidence-based models).

1.2. Pharmacognosy as a Bridge between Traditional Knowledge and Biomedical Validation

Pharmacognosy is a fundamental mediating platform to bridge this epistemological deficit. Packing the academic expertise of a discipline aiming at the discovery, characterization, and biological testing of natural products, pharmacognosy has provided the methodological instruments to develop the traditional applications into scientific products. Traditional pharmacognostic approaches for botanical identification, phytochemical analysis, and bioactivity-guided fractionation have proven essential in ensuring the quality, safety, and uniformity of plant-derived preparations [4] and [5]. However, pharmacognosy per se is subject to inherent limitations in the practice of traditional medicines. The heterogeneity with respect to the chemical compositions and the pharmacological effects of plants may be a key source of variability observed. This variability hinders the pursuit of standardization and reproducibility, the indispensable prerequisites for regulatory approval and clinical translation [6] and [7]. Limitations notwithstanding, the convergence of ethnopharmacology and pharmacognosy continues to be an established route forward in the

pursuit of medicinal plant research. Rather than being thought of as antagonistic systems, traditional knowledge and biomedical science have been placed in a context of growing importance from modern-day scholarship where complementary aspects are emphasized. It is in this perspective that traditional uses serve as a basis for hypothesis generation, but pharmacognostic and pharmacological methods will represent the basis for systematic validation and mechanistic insight [8].

1.3. The Need for Evidence, the Necessity of Using WHO Frameworks and the WHO Frameworks

The increasing institutionalization of traditional medicine has been strongly reinforced by World Health Organization-produced normative frameworks. The WHO has promoted a rational approach toward the rational integration of traditional and other forms of medicine based on proven quality, safety, and efficacy through multiple incremental strategies and technical recommendations through a number of strategies and guidelines. These frameworks form part of a wider global trend toward the promotion of evidence-based medicine and regulatory uniformity. Nevertheless, the use of WHO standards for ethnopharmacological information poses difficult methodological and ethical issues. Conventional knowledge systems have been enshrined in holistic worldviews that do not easily respond to a reduction to a single pharmacological action. There is a danger in applying purely biomedical validation guidelines to marginalize culturally grounded practices or omit remedies that lack regular clinical trials despite many years of empirical use. The above tension highlights the urgency of adaptive validation models that can address both scientific rigour and cultural specificity, as well.

1.4. New Big Data Methodologies and Integrative Analytical Framework

In the last few decades, developments in data science, bioinformatics, and artificial intelligence have unlocked new technologies for solving some of these issues. Big data approaches allowed for integration of heterogeneous datasets, such as ethnobotanical records, phytochemical profiles, pharmacological activity, and clinical observation. These tools have the potential to improve the prediction and analysis of ethnopharmacological research [9] and [10] by enabling large-scale pattern recognition and cross check/validation. At the same time, the digitization and unification of traditional knowledge raise novel ethical issues on data ownership, consent, and benefit sharing. But without governance mechanisms, big data initiatives run the risk of reproducing historic models of biopiracy and knowledge extraction, particularly in post-colonial contexts. These issues emphasize the need for technological innovation to comply with the international ethical body of instruments such as the Convention on Biological Diversity and the Nagoya Protocol.

1.5. Objectives and Scope of This Review

Within this structure, the current semi-systematic review sets out to interrogate

the reshaping of the ethnopharmacology and pharmacognosy of tropical medicinal plants under the frameworks of WHO and the rise of data-driven practices. As such, this review aims to:

1) synthesize existing ethnopharmacological insight on traditional plant use in tropical contexts;

2) review the pharmacognostic and pharmacological strategies used for validation;

3) assess inclusion of big data strategies in integrative analysis; and

4) explore ethical and regulatory considerations for sustainable and culturally relevant research.

Utilising a PRISMA-informed semi-systematic review, this review aspires to achieve a structured yet flexible synthesis that can be viewed as appropriate considering the complexity of ethnopharmacological knowledge and that meets the scientific criteria in the Journal of Ethnopharmacology.

2. Materials and Methods

2.1. Study Design

This study was conducted as a semi-systematic review based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. This methodological decision demonstrates the epistemological and practical limitations of ethnopharmacology studies, as heterogeneity of study designs, cultural context, and outcome measures can frequently preclude full quantitative synthesis or meta-analysis [1] and [11]. A semi-systematic design was deemed particularly suitable to be able to reconcile methodological transparency, reproducibility and conceptual flexibility, and to enable a critical synthesis across a range of forms of evidence, including ethnobotanical studies, pharmacognostic analyses, pharmacological studies and regulatory frameworks. This methodology is being taken up to a greater extent in ethnopharmacology and natural-products research when grappling with complex, interdisciplinary research questions [12] and [13].

2.2. Source Study Data and Search Strategy

The comprehensive literature search was performed using various international scientific databases to facilitate a broad coverage of ethnopharmacological and pharmacognostic studies of tropical medicinal plants. They systematically queried the following databases:

1) PubMed/MEDLINE

2) Scopus

3) Web of Science

4) ScienceDirect

Additionally, key institutional documents and technical reports from the World Health Organization were consulted to capture normative and regulatory perspectives on traditional medicine integration [14] and [15]. The search strat-

egy was designed to combine controlled vocabulary terms and free text keywords concerning ethnopharmacology, pharmacognosy, traditional medicine, and validation frameworks. For instance, the core search string in various databases has been:

("ethnopharmacology" OR "ethnobotany") AND ("pharmacognosy" OR "medicinal plants") AND ("validation" OR "standardization" OR "WHO") AND ("tropical" OR "tropical regions"). Search terms were modified based on the indexing necessity of each database. Key articles and review references were also screened in a manual manner by snowballing to find other relevant publications not included in the original search approach [16]. A systematic literature search was conducted to identify studies on ethnopharmacology and pharmacognosy in tropical areas. PubMed/MEDLINE, Scopus, Web of Science Core Collection, and ScienceDirect (4 major bibliographic databases) were systematically searched for publications published between 1 January 2000 and 31 March 2026; a final search was performed on 31 March 2026. A search strategy was derived following guidelines for transparent and reproducible evidence synthesis [11] [12] and [17]. Relevant studies were searched using a combination of controlled vocabulary, including Medical Subject Headings (MeSH) in PubMed and well-selected free-text terms (e.g., in ethnopharmacology, ethnobotany, traditional medicine, pharmacognosy, medicinal plants, phytochemistry, validation, standardization, quality control, WHO, and tropical regions). The use of this dual strategy has been suggested for enhancing the sensitivity and breadth of literature searches within biomedical and interdisciplinary research [18]. The search structure was tailored to the indexing and retrieval purposes of individual databases (e.g., MeSH, Title/Abstract within PubMed, TITLE-ABS-KEY in Scopus, Topic (TS) in Web of Science), but the search principles were aligned across the databases to allow for methodological comparability across databases. An equivalent keyword-based strategy was used in ScienceDirect. To further minimize the risk of missing important titles, all relevant or eligible article and key review paper references were checked manually using backward snowballing; this technique is known to increase the completeness of retrieving evidence [16]. Furthermore, WHO reports on traditional medicine and technical documentation were manually searched for key policy and regulatory literature. To ensure transparency and reproducibility, full database-specific search strategies, including the exact search strings for PubMed, Scopus, and Web of Science, are available in Appendix A (Supplementary Material). While peer-reviewed scientific papers formed a key evidence base for this review, WHO reports, strategies, and technical guidelines were also consulted, ensuring a global perspective on the regulatory and policy environment surrounding traditional medicine [14] and [15]. These documents were deemed ineligible studies, never passed the PRISMA-informed study selection process to be included, and were therefore excluded from the qualitative analytic dataset of 116 studies identified. Instead, they were used only as a framing device to orient the discussion of the interpretation of findings to the interpretation and analysis of

the alignment of recent ethnopharmacological research with WHO guidelines, the international quality standards, as well as the international regulatory landscape on traditional and complementary medicine [14] and regulatory systems [14] [15]. **Figure 1** summarizes the reproducible document research strategy.

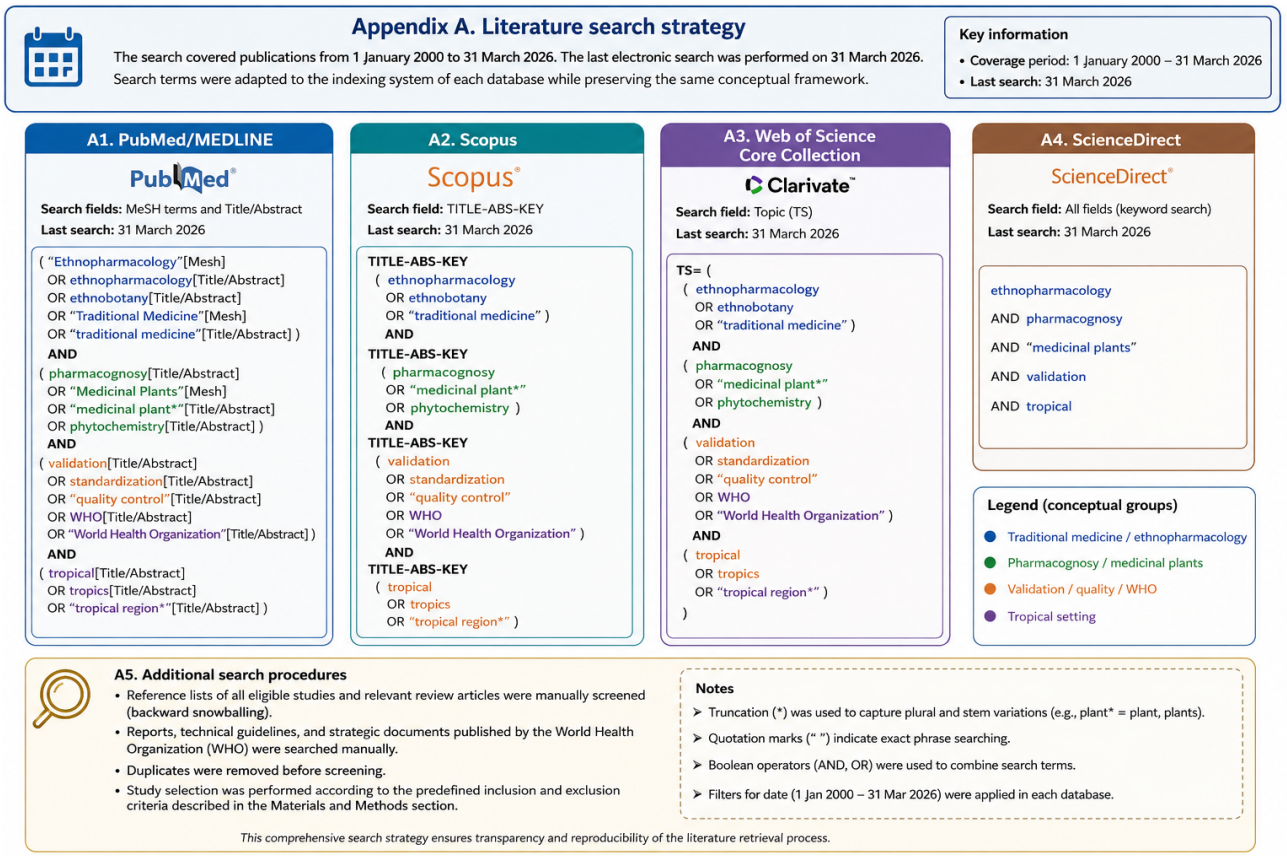

Figure 1. Reproducible literature search strategy, including database-specific search syntax, search period, and complementary search procedures.

2.3. Eligibility Criteria

2.3.1. Inclusion Criteria

Studies were eligible for inclusion if they met all of the following criteria: 1) Published in peer-reviewed scientific journals. 2) Focused on ethnopharmacological or ethnobotanical investigations conducted in tropical or subtropical regions. 3) Included pharmacognostic, phytochemical, pharmacological, or clinical elements related to medicinal plant validation. 4) Explicitly documented traditional uses of medicinal plants or plant-derived preparations. 5) Published in English or French. Both qualitative and quantitative studies were considered, reflecting the multidisciplinary nature of ethnopharmacological research [2] and [19]. Only peer-reviewed original research articles meeting the predefined eligibility criteria were included in the qualitative synthesis. WHO reports, data, and other institutional documents were excluded from the analytic dataset and were used solely as contextual and regulatory references.

2.3.2. Exclusion Criteria

The following categories of publications were excluded:

1) Articles lacking primary ethnopharmacological data or clear methodological descriptions.

2) Studies based solely on anecdotal or non-documented traditional claims.

3) Non-peer-reviewed sources, including popular literature and commercial reports.

4) Studies focusing exclusively on synthetic compounds without reference to traditional plant use.

These criteria were applied to ensure methodological rigor and relevance to the objectives of this review.

2.4. Study Selection Process

All records retrieved from the database searches were imported into a reference management system, and duplicate entries were removed. This study selection process was conducted in two stages. In the first stage, titles and abstracts were screened for relevance based on the predefined inclusion and exclusion criteria. In the second stage, full-text articles were assessed to confirm eligibility. Discrepancies during the selection process were resolved through iterative review and consensus-based evaluation, following established best practices for systematic reviews [20]. A PRISMA flow diagram was used to document the selection process, including the number of records identified, screened, excluded, and included in the final synthesis.

2.5. Definitions, Validation Framework and Data Extraction

2.5.1. Operational Definition of Big Data and Artificial Intelligence Approaches

For this review, big data approaches were defined as computational strategies designed to integrate, manage, and analyse large, heterogeneous, and multidimensional datasets that exceed the capacity of conventional analytical methods [21] and [10]. Within the field of ethnopharmacology, these datasets encompass ethnobotanical records, phytochemical profiles, metabolomic and genomic data, pharmacological assays, clinical information, and biodiversity or chemical databases. The integration of these complementary data sources has been recognized as a key driver for accelerating medicinal plant research and natural product discovery [9] and [10]. In the present review, artificial intelligence (AI) approaches were operationally defined as computational methods capable of identifying patterns, generating predictions, or supporting decision-making from complex biological datasets. These approaches included machine learning algorithms, network pharmacology, molecular docking, bioinformatics pipelines, data mining, and predictive modelling, all of which have become increasingly important for identifying bioactive compounds, elucidating mechanisms of action, and prioritizing candidate medicinal plants for further investigation [22] and [23]. During data extraction, studies were screened to determine whether they employed one or more of these computational approaches, the types of data analysed, and their primary applica-

tions in ethnopharmacological and pharmacognostic research.

2.5.2. Botanical Taxonomy Standardization

Botanical nomenclature was standardized across all included studies to ensure taxonomic consistency, accuracy, and comparability, following international best-practice recommendations for ethnopharmacological research [1] [24]. Scientific plant names were harmonized according to currently accepted taxonomic references, primarily the World Flora Online (WFO) Consortium and, where necessary, Plants of the World Online (POWO, Royal Botanic Gardens, Kew), both of which are recognized as authoritative global taxonomic resources for vascular plants [25]. Synonyms reported in the original publications were replaced with their currently accepted scientific names to ensure nomenclatural consistency, while the original names were retained in the extraction database when necessary to maintain traceability to the source publications. Information was learned for each of the included studies on how botanical authentication was carried out, *i.e.*, voucher specimens were deposited, the herbarium accession number and identification by qualified taxonomists or otherwise documented methods of taxonomic verification were recorded. Particular reference to voucher specimen depositions was paid in order to ensure not only their repeatability and reliability, but also to allow long-term reproducibility and reliability of ethnopharmacological and pharmacognostic experiments with high-level evidence [1] for long-term validity.

2.5.3. Validation Framework

In order to develop a structured evaluation of the degree of scientific evidence for traditional medicinal practices, studies were prioritized on the basis of a four-tier validation framework based on best practice of ethnopharmacology and pharmacognosy [1] and [15].

Tier 1: Studies limited to botanical authentication, pharmacognostic characterization, phytochemical screening, or chemical fingerprinting, without biological testing.

Tier 2: *In vitro* biological evidence: studies evaluating one or more *in vitro* pharmacological or toxicological assays demonstrating biological activity of plant extracts or isolated compounds.

Tier 3: (*In vivo* preclinical evidence): Experimental animal studies that report on efficacy, toxicity, pharmacodynamics, or pharmacokinetics.

Tier 4: (Clinical evidence): human or observational studies, or clinical trials that evaluate safety and/or therapeutic efficacy.

2.5.4. Data Extraction Techniques

Relevant data were extracted using a standard extraction framework for each included study. The following variables were systematically recorded:

- Geographic location and ecological context.
- Botanical identification and taxonomic confirmation.
- Documentation of traditional uses and preparation methods.
- Pharmacognostic parameters (e.g., part use, extraction techniques, phyto-

chemical profiles).

- Pharmacological or bioactivity data.
- Reference to WHO guidelines or regulatory frameworks.
- The ethics of using traditional knowledge.

The data were synthesized by thematic and comparative analytic methods enabling the recognition of commonalities, methodological trends and gaps in knowledge between studies. Attention was paid to the concordance of traditional usage and pharmacologic evidence and to the level of standardization achieved in pharmacognostic procedures [6] and [7].

2.6. Assessment of Methodological Quality and Limitations

The results can be concluded based on a mixed-method protocol. Evaluation of methodological quality and limitations. While the formal systematic review tools for risk of bias used in clinical systematic reviews also were not able to be applied in all aspects of our study, the methodological quality of this investigation is still qualitatively assessed through transparency of data collection, botanical authentication procedures, reproducibility of extraction methods, and clarity of pharmacological assays. Such an approach is in line with similar ethnopharmacological reviews that deal with heterogeneous datasets [1] and [26]. Potential limitations in publication bias, regional underrepresentation, and variation of methodological rigor were recorded and pointed out in the discussion.

2.7. Ethical Considerations

Ethics were taken into consideration during the review, with particular regard to documentation and secondary use of traditional knowledge. Studies that focused explicitly on informed consent, community engagement, and benefit-sharing mechanisms (as defined in the principles, guidelines, frameworks, and principles of international ethical frameworks such as the Convention on Biological Diversity and the Nagoya Protocol [27]-[29]) were determined and analyzed.

3. Results

3.1. Outcomes of the PRISMA Flow and Study Selection

The database search retrieved 1,246 records (PubMed/MEDLINE, Scopus, Web of Science, ScienceDirect). After discarding 312 duplicates, 934 records were screened by title and abstract. Of those, 642 were excluded for lack of relevance to ethnopharmacology and/or primary data on traditional use of medicinal plants. We screened 292 articles in full-text format, concluding that 176 included studies were excluded for lack of methodological transparency, no pharmacognostic or pharmacological validation, or a narrow emphasis on non-tropical settings. In the end, 116 studies met all inclusion criteria and were retained for qualitative generation. The 116 included studies were exclusively peer-reviewed scientific publications. These WHO reports and technical documents were obtained during the process of review, but these were not analyzed in the analytic framework as they

were only used in context and as regulatory references. These figures are in line with PRISMA-informed reporting standards and comparable with past semi-systematic reviews of ethnopharmacology [1] and [11].

3.2. Geographic and Ecological Distribution of Included Studies

Included studies were located in some major tropical regions. Sub-Saharan Africa dominated the studies at around 41 percent, which was then further followed by South and Southeast Asia (34 percent) and then by the Amazonian region of South America (25 percent). This distribution indicates the high biodiversity of these regions and their heavy reliance on the traditional medicine sector for primary healthcare [14] and [15]. Ecologically, most included lowland tropical forests, savannah-forest mosaic, and agroforestry systems. Numerous authors stressed the ecological context of disturbed or anthropogenic ecosystems that define available medicinal plants and their accessibility under certain regimes of anthropogenic use, conveying the dynamic interrelationship of ecological change with traditional pharmacopoeias [19] and [26].

3.3. Taxonomic Diversity and Plant Parts Used

Across the 116 included studies, 512 medicinal plant species belonging to 98 botanical families were recorded. It is in support of global ethnopharmacological trends ([13] and [3]), and the majority of observed families were Fabaceae, Asteraceae, Lamiaceae, Euphorbiaceae and Rubiaceae. Leaves (≈46%) were the dominant plant part, followed by roots (≈24%), bark (≈15%) and other plant parts such as seeds, fruits or whole plants.

3.4. Categories of Therapeutics and Traditional Indications

The traditional uses cited in the studies were then divided into key therapeutic classes. The most common indications were infectious diseases (such as malaria, gastrointestinal infections and respiratory diseases), inflammatory and pain-related diseases, metabolic disorders (like diabetes) and central nervous system disorders. Several studies described multi-purpose species employed over multiple therapeutic categories, indicating the holistic character of traditional medical systems and some medicinal plants having polyvalent pharmacological characteristics [2] and [8]. For a significant portion of cases, overlap between evidence-based and experimentally established biological applications occurred.

3.5. The Ethnobotanical Indices and Their Quantitative Significance

Ethnobotanical indices were examined from reviewed studies to evaluate the relative cultural status and agreement on medicinal plant utilization. Use Value (UV), Relative Frequency of Citation (RFC), and Informant Consensus Factor (ICF) were the most widely applied indices. Values with high UV and RFC were more indicative of species commonly used for common and recurrent health conditions, including fe-

brile illnesses and gastrointestinal disorders. High ICF values were found for disease categories recognized by a well-defined symptomatology, indicating a considerable agreement amongst informants regarding plant selection and therapeutic applications [13] and [30]. Ethnobotanical indices were applied to identify priority species for further pharmacognostic and pharmacological investigation, especially when strong consensus coincides with early experimental validation [31].

3.6. Trends in Pharmacognostic and Pharmacological Validation

In this study, 68% of studies reported some pharmacognostic or pharmacological validation. These validations included basic phytochemical screening, *in vitro* bioassays, and (more seldom) *in vivo* models. Pharmacognostic characterization generally comprised macroscopic and microscopic identification, extraction protocols, and qualitative phytochemical analyses. But the quality of those assessments was uneven, and only a few studies included such broad standards that could be employed for assessing the regulations [4] and [7].

3.7. The Framework of Validation and Scientific Evidence Levels

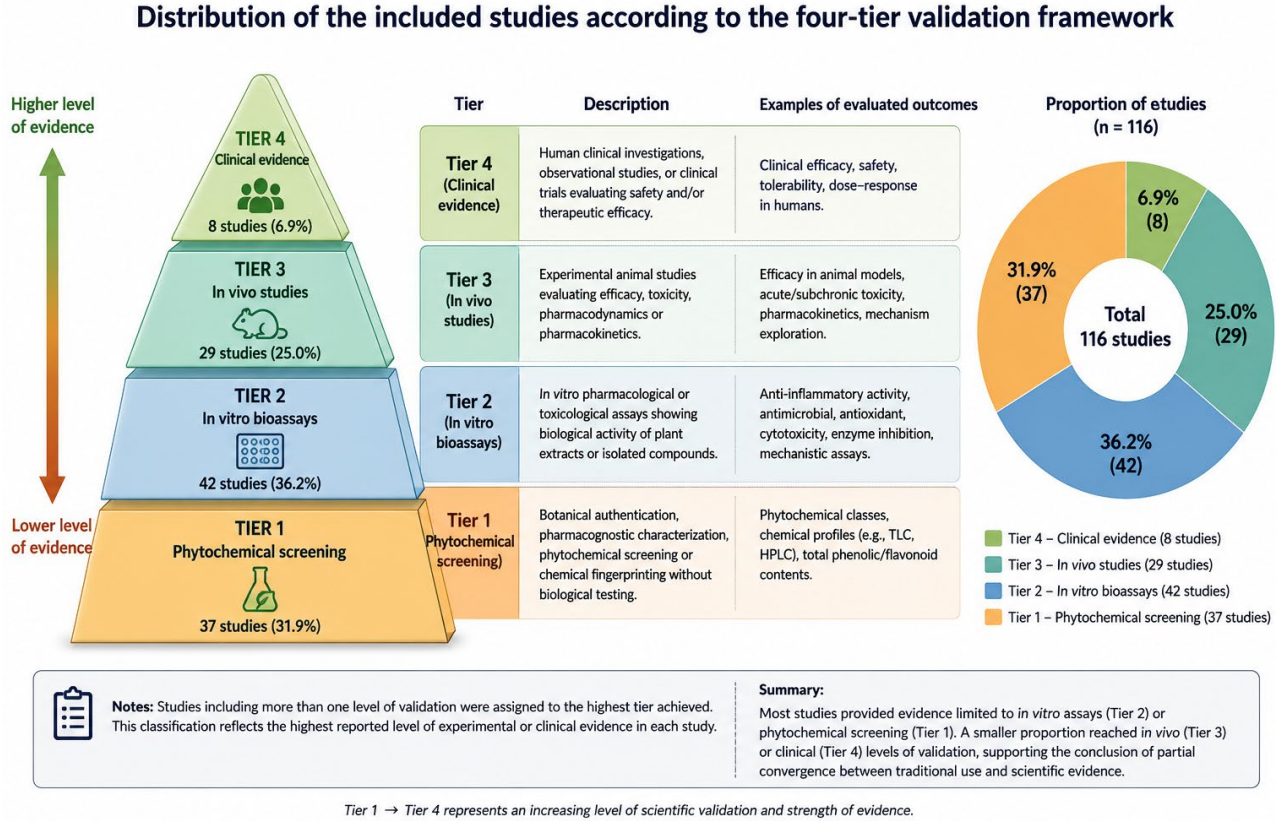

Figure 2. Classification of the included studies according to the level of validation.

Using a four-tier validation framework derived from international recommendations for ethnopharmacological and pharmacognostic research [1] and [15], substantial heterogeneity in the scientific evidence base for traditional medicinal use

was observed. Of the 116 studies included, 37 studies (31.9%) were classified as Tier 1 (phytochemical and pharmacognostic characterization), 42 studies (36.2%) as Tier 2 (*in vitro* biological evidence), 29 studies (25.0%) as Tier 3 (*in vivo* preclinical studies), and only 8 studies (6.9%) as Tier 4 (clinical evidence) (**Figure 2**). This is consistent with the findings of previous reviews of medicinal plant studies [3] [9], and [10], which suggested that most ethnopharmacological studies are only just entering the stage of scientific validation, and relatively few have achieved or reached full preclinical or clinical evaluation. Results provide support for the notion of a partial convergence between traditional medicinal knowledge and modern biomedical evidence. Although traditional therapeutic applications are becoming increasingly validated by phytochemical characterization and experimental pharmacology, the movement from lab-based validation to clinical application is still largely limited, and this reflects a major challenge identified by the WHO Traditional Medicine Strategy and recent best-practice recommendations [14], [1] and [15] in ethnopharmacology.

3.8. Synthesis Table of Representative Studies

Table 1 provides a summary of representative ethnopharmacological studies included in this review. For each study, information is presented on the geographical setting, medicinal plant species investigated, traditional therapeutic applications, level of scientific validation according to the four-tier validation framework, and key pharmacognostic and pharmacological findings. This synthesis illustrates both the diversity of ethnopharmacological research conducted in tropical regions and the current state of evidence supporting the translation of traditional medicinal knowledge into scientifically validated therapeutic applications.

Table 1. Summary of representative ethnopharmacological studies included in the review.

Region	Plant species	Traditional indication	Ethnobotanical index	Validation approach	Key reference
Sub-Saharan Africa	*Azadirachta indica*	Febrile illness, malaria	UV, RFC	Phytochemical screening, antiplasmodial assay	[6]
Southeast Asia	*Andrographis paniculata*	Inflammation, infection	UV, ICF	*In vitro* anti-inflammatory assays	[13]
Amazon Basin	*Uncaria tomentosa*	Inflammatory disorders	RFC	Phytochemical profiling, immunomodulatory tests	[8]
South Asia	*Curcuma longa*	Pain, metabolic disorders	UV, RFC, ICF	Standardized extract, *in vivo* models	[7]

Note: Table content synthesized from included studies; values and methods reported as described by original authors.

3.9. Botanical Authentication and Taxonomic Standardization

To ensure that all medicinal plant species included in the studies had been re-

ported under their presently recognized scientific names, and to prevent variation due to synonymous nomenclature and improve the comparability of the evidence base, taxonomic harmonization of references was applied, according to the study's authors. Such approaches are in line with global consensus that standardized botanical nomenclature and authoritative taxonomic databases should be used in ethnopharmacological research [1] [25]. Among 116 studies, 74 (63.8%) explicitly reported the placement of voucher specimens or gave herbarium accession numbers, 21 (18.1%) reported botanical identification performed by qualified taxonomists but without voucher specimens, while 21 (18.1%) did not describe any formal process of botanical authentication. The description of voucher specimens is considered the gold standard for the traceability, reproducibility, and long-term confirmation of medicinal plant studies [1] [24]. Altogether, 95 studies (81.9%) reported at least one formal botanical authentication technique. Nevertheless, the absence of voucher specimens or equivalent documentation in nearly one-fifth of the studies represents an important limitation for reproducibility and taxonomic reliability. Similar limitations were pointed out in earlier assessments of ethnopharmacological literature, with insufficient botanical documentation as a major source of bias that may compromise species identifications, data comparability, and reproducibility of pharmacognostic investigations [1] and [24].

3.10. Big Data and Artificial Intelligence Approaches in the Included Studies

According to the operational framework used in this review, a small number of the included studies applied computational techniques that were consistent with big data or artificial intelligence methods. Most of these studies were conducted using heterogeneous datasets including ethnobotanical surveys, phytochemical databases, pharmacological screening, and, less commonly, genomic, metabolomic or clinical datasets. These integrative approaches have been increasingly acknowledged as useful instruments for integrating traditional medicinal knowledge with experimental findings and to enhance the efficiency of natural product discovery [9] [10]. The most common computational techniques reported were network pharmacology, molecular docking, bioinformatics analysis, and multivariate statistical modeling methods, and the application of machine learning algorithms was less frequent than in other research. Broadly speaking, the methods were largely applied to estimate biological targets, prioritize bioactive compounds, characterize phytochemical-target interactions, and synthesize evidence produced across biological levels. This is indicative of a trend at the ethnopharmacology level from descriptive to data- and systems-oriented analysis; however, the requirement for standardized data sets and transparent analytical methods [32], [33] is also highlighted.

3.11. Ethics-Related Reporting in the Included Studies

Ethics-related reporting was considered in 116 peer-reviewed studies by identify-

ing data pertaining to informed consent, community engagement, and benefit-sharing procedures across three principal categories. They were included as they are at the heart of international recommendations for ethnopharmacological research with traditional knowledge, local communities, and biological resources [1] [15] and [27]. This data highlights that ethical reporting is inconsistent across the reviewed literature. The most common item was informed consent, while benefit-sharing was more rarely reported, despite its consideration in relation to traditional knowledge protection and the Nagoya Protocol. These similar gaps were pointed to in [1] [27] and [28], noting that ethnopharmacological studies need to shift towards transparent, participatory, benefit-oriented practices rather than extractive documentation. Not many community engagement and benefit-sharing narratives, and the limited reporting of this has made me think that ethical governance has been a great weakness in tropical ethnopharmacology and can be improved for future studies.

3.12. Summary of Key Findings

Taken together, the application of this four-tier validation framework allows for a more nuanced interpretation of the relation between traditional knowledge and scientific evidence. Although around two-thirds of the included studies reached Tier 2 or higher, only a minority (Tier 4) provided clinical evidence. Therefore, this convergence can be considered as partial, indicating significant advances in the validation of phytochemical and experimental characteristics but a paucity in translation to clinical practice. These results underscore the promise (and challenges) of ethnopharmacological research in tropical settings, and thus, set a tone for a critical debate about methodological crossover, regulation and ethical control.

4. Discussion

4.1. Analysis of PRISMA-Grounded Results and Strength of Evidence

This semi-systematic review offers a structured synthesis of both ethnopharmacological and pharmacognostic studies on tropical medicinal plants, emphasizing the scientific value and methodological fragilities of the field. The systematic process of the selection using PRISMA not only allows for transparency and reproducibility, but it also indicates the degree to which minimum standards of documentation and validation of published works were unsatisfied in a significant way. Of the 1,246 previously identified records, less than 10% met the inclusion criteria at last, indicating that challenges with heterogeneity in study design, incomplete botanical authentication, and minimal pharmacognostic information remained. The same attrition rates have been encountered in other systematic and semi-systematic reviews of ethnopharmacology, where this limitation must be systemic rather than incidental [1] and [31]. PRISMA flow (textual description).

- Records identified through database searching: 1246.
- Records after duplicates removed: 934.

- Screened records (title and abstract): 934.
- Records excluded: 642.
- Full-text articles assessed for eligibility: 292.
- Excluded full-text articles with reasons: 176.
- Studies included in qualitative synthesis: 116.

This flow uncovers an important methodological conundrum: although ethnopharmacological data are plentiful, only a small number emerge in a form that is compatible with pharmacognostic validation and regulatory interpretation.

4.2. Convergence and Divergence between Traditional Knowledge and Pharmacognosy

One of the most striking findings of this review is that only partial but significant convergence has been achieved between traditional medicinal uses and pharmacognostic or pharmacological validation. Species with highly elevated ethnobotanical indices, especially higher Use Value (UV) and Informant Consensus Factor (ICF), were more likely to show measurable biological activity in experimental assays. Such an observation corroborates the established hypothesis that cultural consensus may serve as a heuristic signifier of therapeutic relevance [13] and [30]. But widespread convergence was far from the case. Some heavily used medicinal plants were not subjected to a rigorous pharmacognostic characterization, whilst others exhibited potent bioactivity even if limited in ethnobotanical importance. This discrepancy is indicative of the epistemological contrast between conventional health systems of experience-based systems, for whom experiential efficacy and symbolic congruence are sought, on the one hand, and pharmacognosy, for which reproducible chemical and biological processes can be observed with respect to procedures [2] and [8]. Pharmacognosy emerges hence as not a validating body or an authority that approves or denies traditional knowledge, but a mode of translation. Its purpose is to ground traditional claims in a regime which allows quality control, safety assessment, and mechanistic interpretation, without eliminating the cultural rationale of traditional practices.

4.3. Strength and Weaknesses of Pharmacognostic Rigor

The review showed considerable variation in pharmacognostic rigor between studies. Phytochemical screening or *in vitro* bioassays were common, but thorough pharmacognostic workflows (including botanical voucher deposition, standardized extraction protocols and quantitative phytochemical profiling) were relatively rare. This lack of standardization hampers the reproducibility of studies [4] and diminishes their translational potential when compared to other research [7]. Particularly, studies that followed pharmacognostic best practices were in better alignment with WHO quality and safety criteria. Usually, these studies consisted of:

- authenticated botanical identification on voucher specimens.
- defined extraction methods.

- chemical fingerprinting (e.g., chromatographic profiles).
- Bioassays dose-response relationships.

The uneven uptake of such methods highlights a systemic divide between ethnopharmacological fieldwork and laboratory-based pharmacognosy. Closing this gap calls not only for further technical capacity building, especially in low-resource settings, but at the design phase as well as a higher level of methodological cohesion in the study design phase itself. The relatively large proportion of studies with voucher specimens or other formal authentication procedures indicates increasing adherence to international standards of good ethnopharmacology practice. However, around one fifth of studies reported inadequate botanical authentication; a fact that restricted their reproducibility and had potential implications for taxonomic accuracy. These results were consistent with previous guidelines for compulsory voucher deposition for ethnopharmacological research [1] and [34].

4.4. Comparative Synthesis of Both Validation Methods

The ethnopharmacological validation procedures listed in the included studies are compared in Table 2. The comparison provides a contrast in levels of scientific substantiation, from phytochemical characterization of medicines to clinical evaluation, and also represents the range of scientific evidence employed to evaluate safety, efficacy, and quality of medicinal products.

Table 2. Comparative overview of ethnopharmacological validation approaches.

Dimension	Ethnopharmacological emphasis	Pharmacognostic emphasis	Integrated approach
Knowledge source	Oral tradition, cultural transmission	Laboratory-based analysis	Bidirectional
Validation criterion	Cultural consensus, experiential efficacy	Chemical and biological reproducibility	Consensus + reproducibility
Methodological tools	Interviews, indices (UV, ICF, RFC)	Phytochemistry, bioassays	Mixed methods
Strengths	Contextual relevance, sustainability	Mechanistic clarity, safety	Translational potential
Limitations	Subjectivity, variability	Reductionism, cost	Complexity

This comparative analysis demonstrates that no one approach is sufficient. Integrated frameworks that integrate ethnobotanical markers into pharmacognostic testing are in the best position to locate priority species without compromising cultural legitimacy or scientific robustness.

4.5. WHO Frameworks and Regulatory Implications

The World Health Organization has been a key figure in the framing of the integration of traditional medicine in world contexts. WHO also highlights quality, safety, and effectiveness as precursors of bringing traditional remedies into formal medical settings [14] and [15]. Such aims are conceptually congruent with most ethnopharmacological studies, but fewer support the level of evidence needed for

regulatory translation. Lack of standardized pharmacognostic parameters and clinical data is one of the notable gaps that are evident. Nevertheless, the WHO frameworks should not be taken as strictly biomedical frameworks. Instead, they can be flexibly operationalized, and tiered validation paths may be established that appreciate varying levels of evidence based on intended use and risk profile.

4.6. Big Data Approaches: The Opportunities and Epistemic Pitfalls

The integration of big data into ethnopharmacology has been viewed as a new method that has the potential to be very promising. With data-driven tools, patterns which cannot easily be detected in standard scrutiny of traditional studies can be uncovered by combining large and diverse datasets, for example, by means of correlation of ethnobotanical consensus with phytochemical diversity [9] and [10]. The review does note, however, that decontextualized data aggregation brings with it epistemic risks. The value of traditional knowledge can become outdated and reduced to database entries, and can lose vital cultural, ecological, and symbolic significance if it is reduced to database entries. There is also a greater risk of algorithm bias and unequal representation of under-documented regions and communities being further marginalized by algorithmic bias and unequal representation. It is such issues that underlie the necessity for ethical data governance consistent with global consensus as expressed in international biodiversity and benefit-sharing agreements based on global agreements on biodiversity and benefit sharing [27] and [28].

4.7. Ethical Governance and Sustainability

Ethical issues underpin ethnopharmacological research by not only impacting the scientific evidence generated but also the relationships between researchers and Indigenous Peoples and local communities, who are the holders of traditional medicinal knowledge. As stressed in [1] [15] and [27], ethical ethnopharmacological research involves transparent cooperation, informed consent before performing research, equitable provision of benefits, and respect for cultural and intellectual property rights. The quantitative evaluation from this review indicated that the ethical governance across the selected studies has not been adequately described. While informed consent was the most commonly mentioned ethical practice, community involvement, especially in terms of benefit-sharing mechanisms, was reported significantly inconsistently. This result implies that ethical reporting has not kept pace with methodological advances in pharmacognosy and pharmacology, even when they have clear international recommendations. Such limitations have profound consequences for the credibility of ethnopharmacological research as well as for its sustainability. The utilization of indigenous knowledge without appropriate documentation of consent, community involvement, and the sharing of research gains threatens the continuation of a tradition of knowledge appropriation and mutual mistrust between researcher and their local communities. It has

been proposed at the same level of concern by [1] [27] and [28] that the sense of ethical duty ought to be a fundamental part of scientific quality, rather than as an administrative obligation. Strengthening ethical governance and management in the future will require more than adhering to institutional ethics. Future studies must systematically consider the principles of informed consent, engagement of communities in the research process, and equitable and transparent sharing of benefits arising from the use of traditional knowledge. These practices are perfectly in line with the conventions of the Convention on Biological Diversity, the Nagoya Protocol, and the World Health Organization Global Report on [35]. Incorporating these principles into standard reporting by the profession would enhance transparency and reproducibility and, at the same time, promote the social legitimacy, scientific bona fides, and longevity of experimental ethnopharmacological research.

4.8. Toward an Integrated and Reflexive Model

According to the review results, big data and AI in ethnopharmacological research continue to exist in an early, yet changing stage. While only some of the included studies used computational approaches, the heterogeneity of the data and analytical methods suggests an evolving trend for integrative research frameworks. Similarly, [9] and [10] also pointed out that synergy between ethnobotanical knowledge and phytochemical, pharmacological, and omics datasets can substantially speed up the discovery of bioactive natural products. Among the computational approaches described, these were network pharmacology and molecular docking, which were the most commonly employed techniques, confirming an increasing role in elucidating multi-target mechanisms of action found in medicinal plants [33] and [32]. By contrast, real AI-based methods, supervised or unsupervised machine learning, were few, which may shed light on the nascent digital transformation of ethnopharmacology. As emphasized by [22] and [23], the broader use of AI will rely on the existence of well-defined, interoperable, and high-quality data sets. Thus, ethnopharmacological research from the future needs to reinforce harmonization of data, standardization of botanicals and open-data methods, in order to optimize the potential of computational techniques, with scientific reproducibility and ethical governance in mind.

5. Perspectives, Limitations, and Recommendations

5.1. Methodological Limitations of the Studies Included

Although there is a considerable ethnopharmacological focus on tropical medicinal plants, the current semi-systematic review highlights some common methodological limitations that limit the interpretability and translational value of findings published. The most serious limitations concern the heterogeneity in the study design, especially heterogeneity in study designs, including differences in sampling strategies, informant selection, data collection methods, and analytical frameworks. This heterogeneity further complicates comparisons across studies

and constrains the prospects of making quantitative synthesis possible with such comparisons [1] and [12]. A second significant limitation is related to botanical identification and standardisation of pharmacognostics and pharmacognostic methodology. Accurate plant identification is an essential component of pharmacognosy, yet a significant percentage of studies did not describe the deposits of each voucher specimen or did not provide adequate taxonomic detail. The lack of these features reduces reproducibility and increases the potential for misidentification, with consequences for efficacy and safety [4] and [26]. Moreover, the depth of pharmacological validation differed from one study to another. Most studies only included early *in vitro* assays but did not progress towards dose-response characterization, toxicity assessment, or *in vivo* models. Although these exploratory methods have proven useful for hypothesis generation, their limitations need to be understood as we carry these findings into clinical or regulatory situations [6] and [7].

5.2. Limitations Related to Data Availability and Representativeness

Ethnopharmacological research remains uneven from region to region and certain tropical areas, particularly those with political instability or limited research infrastructure, are underrepresented in scientific literature. Geographic bias risks biased global syntheses, and neglects knowledge systems that are under-reported but rich in therapeutic implications [19] [36] and [37]. Language bias is another limitation, as many ethnopharmacological studies are found in local or regional journals, which do not have access to major international databases and therefore have not been indexed. Although this review included English- and French-language publications, relevant studies in other languages may have been overlooked, potentially limiting the comprehensiveness of the synthesis.

5.3. Ethical and Epistemological Constraints

In addition to methodological issues, the review highlights ongoing ethical and epistemological constraints on the use of and disclosure in ethnopharmacological research. There was virtually no explicit record of informed consent, community participation, and benefit-sharing in the majority of studies, despite international ethical considerations for the use of customary knowledge [27] and [28]. The historical construction of health and the translation of that knowledge to biomedical categories may lead to a loss of context from an epistemological perspective. Reductionist interpretations separating single compounds or mechanisms risk obfuscating the holistic logics of traditional systems of medicine, which, in general, focus on synergistic interactions and symbolic aspects of healing [2] and [8].

5.4. Future Research Perspectives

In the face of this examination of the emerging field, the insights shared suggest that the results should point to a number of possible strategic directions for aca-

demic research that can help further develop the scientific and ethical foundations of ethnopharmacology. The first one is that methodological integration should be a priority given in the study design stage. Ethnopharmacological fieldwork, pharmacognostic analysis, and pharmacological testing should be the coextensive (in a sense) units of one integrated research structure instead of separate steps or discrete activities. This integrated approach increases coherence, efficiency, and translational significance [13] [31] [38] and [39]. Second, the broadened application of quantitative ethnobotanical indices, as well as rigorous pharmacognostic validation, provides a good avenue for ranking candidate species. By creating a strong cultural consensus, which directly leads to robust bioactivity and reproducibility, the potential for this identification among therapeutically relevant plants is significantly higher [40]. Third, such data-driven approaches such as big data analytics and artificial intelligence should be developed in a way that enhances, rather than displaces, traditional field-based research. Ethical governance of data, transparent algorithms, and equitable access to benefits have to be components of any digital ethnopharmacology project [9] and [10].

5.5. Best Practices Guidance

Following the synthesis described in this review, a number of suggestions could be made for researchers, institutions, and policymakers:

- Regulate and standardize the botanical and pharmacognostic reporting by the requirement of voucher specimen deposition and detailed extraction protocols.
- Adopt PRISMA-informed reporting approaches for ethnopharmacological reviews to enhance transparency and reproducibility.
- Enforce stronger ethical reporting requirements, integrating informed consent and the participation of the community in planning, implementing, and maintaining studies.
- Foster cross-disciplinary partnerships between ethnopharmacologists, pharmacognosists, pharmacologists, and data scientists.
- Support capacity building in under-represented tropical regions to reduce geographic and epistemological bias.

The recommendations go hand-in-hand with international efforts to promote responsible use of traditional medicinal knowledge.

5.6. Consequences for Policy and Global Health

Finally, the implications of this review reach beyond scholarly research. Integrated ethnopharmacological evidence can be used by policymakers and international organizations to guide scientifically sound and culturally sensitive regulatory frameworks. By valuing traditional medicine but demanding adequate validation, such frameworks can help lead to more equitable and sustainable systems of health [14] and [15].

6. Conclusion

Ethnopharmacological studies involving tropical medicinal plants exist strategically in traditional systems where knowledge synthesis, the protection of biodiversity, pharmacognosy, and global health converge. As [3] and more recently [10] have pointed out, medicinal plants continue to play a big part as one of the most promising sources of bioactive compounds for drug discovery, and traditional knowledge is still very important in the search for potential therapeutic resources. This review, a semi-systematic review, provides evidence that tropical ethnopharmacology is a scientific resource that is methodologically diverse and has been developed effectively despite the lack of standardization, reproducibility, and regulatory translation. The results of the synthesis of 116 peer-reviewed studies indicated that a moderate but significant blending was found between indigenous medicinal wisdom and recent scientific expertise. Using a four-tier validation framework from phytochemical characterization through clinical evidence, it showed that the majority of studies are still primarily found at the phytochemical and *in vitro* validation stage, while only a few progress to the mature preclinical or clinical evaluations. These results are in line with the review noting the translational divide between ethnopharmacological knowledge and evidence-based medicine ([1] [9] and [15]). The review also points to the need for methodological rigor to boost the credibility of medicinal plant research. Standardization of botanical nomenclature across internationally recognized taxonomic resources alongside the evaluation of voucher specimen accumulation and botanical authentication procedures showed promising trends toward compliance with best-practice guidelines. However, the lack of a formal botanical-based authentication process in a large percentage of the included studies still constitutes a major impediment to reproducibility and taxonomic consistency, underscoring the advice from the references to [1] and [24]. Besides the phytochemical and pharmacological verification, this review also showcases the increasing significance of big data and artificial intelligence in the field of ethnopharmacology. Even though these computational approaches are less frequently cited, they are becoming more helpful in connecting ethnobotanical, phytochemical, pharmaceutical, and molecular data sets to enable the characterization of bioactive products, prediction of therapeutic targets, and the prioritization of medicinal species. As pointed out in [9] [10] and [22], the future of natural product research will increasingly rely on the blending of computational approaches with high-resolution experimental data. Nonetheless, this digital shift must sit next to strong ethical governance on data ownership, benefit sharing, transparency, and respect for indigenous and local knowledge systems. An important methodological contribution of this review is the clear distinction between peer-reviewed scientific evidence and that found in WHO normative documents. In the qualitative synthesis, only peer-reviewed studies were included; WHO strategies and technical guidelines were only used as regulatory and policy literature, establishing an international framework for interpreting the findings without contrib-

uting to the analytical dataset. Making this distinction improves the methodological transparency and increases the reproducibility of the review. Thus, the synthesis of research evidence results in an integrated framework for tropical ethnopharmacology that perceives traditional knowledge as a complement to high-quality botanical authentication, rigorous pharmacognostic validation, and data-driven analysis in ways that are not rival or inimical to other aspects of medicinal plant research. This framework is closely linked with the WHO Global Traditional Medicine Strategy [15] and the ConSEFS best practice for ethnopharmacological research [1]. These complementary aspects can be integrated so future studies can create reproducible, ethically responsible, and clinically relevant evidence needed to sustainably integrate ancestral medicines into contemporary healthcare systems, promoting biodiversity conservation and innovation in global health.

Ethical Statement

This review did not explore direct experimentation on human subjects or animal samples. Data analyzed were published previously. Ethical issues of documentation and use of traditional knowledge were considered in accordance with international guidelines, including the Convention on Biological Diversity and Nagoya Protocol. One of the areas that we emphasized was informed consent, the development of community bonds, and benefit-sharing principles as reported in the original studies.

AI-Assisted Tool Disclosure

AI was used to assist with the language polishing of this manuscript, improving its fluency and clarity of expression.

Author Contributions

Conceptualization, Nabèrè Ouattara; methodology, Nabèrè Ouattara; software, Nabèrè Ouattara; validation, Nabèrè Ouattara, Samson Guenne, Alphonsine Ramdé-Tiendrébéogo and Roland Meda N.; formal analysis, Nabèrè Ouattara; investigation, Nabèrè Ouattara; resources, Roland Meda N.; data curation, Samson Guenne; writing—original draft preparation, Nabèrè Ouattara; writing—review and editing, Nabèrè Ouattara; visualization, Alphonsine Ramdé-Tiendrébéogo; supervision, Roland Meda N.; project administration, Nabèrè Ouattara; funding acquisition, Nabèrè Ouattara. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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