



# **Bioactive Compounds from Ayurvedic, Traditional Chinese, and African Medicinal Systems: Chemical Characterisation, Pharmacological Activities, and Implications for Modern Drug Discovery**

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**ABSTRACT:** Traditional medical systems such as Ayurveda, Traditional Chinese Medicine (TCM), and African Traditional Medicine (ATM) represent rich reservoirs of therapeutic knowledge developed over thousands of years. These systems primarily rely on medicinal plants containing diverse bioactive compounds responsible for their pharmacological effects. With growing interest in natural products for safer and multi-target therapies, scientific validation of traditional medicines has become increasingly important. This review critically examines the major bioactive compounds reported in Ayurvedic, Chinese, and African traditional medicines, focusing on their chemical nature, pharmacological activities, and molecular mechanisms of action. Emphasis is placed on neuroprotective, anti-inflammatory, antioxidant, antimicrobial, and metabolic regulatory activities, along with their relevance to modern drug discovery. Challenges related to standardization, safety, and clinical validation are discussed, and future research directions are proposed. Integrating traditional knowledge with modern pharmacology may accelerate the development of novel therapeutic agents.

**KEYWORDS:** Traditional medicine; Bioactive compounds; Ayurveda; Traditional Chinese Medicine; African Traditional Medicine; Phytochemicals; Drug discovery; Modern validation

## **1. INTRODUCTION**

Traditional medicine systems have served as the backbone of healthcare for human civilization for thousands of years. Long before the emergence of modern synthetic drugs, communities across the world relied on medicinal plants and natural substances to treat diseases, maintain health, and promote longevity. Even in the 21st century, the World Health Organization (WHO) estimates that nearly 80% of the global population continues to depend on traditional medicine for primary healthcare, particularly in developing regions of Asia, Africa, and Latin America.<sup>[27,28]</sup>

Among the many traditional medical systems, Ayurveda (India), Traditional Chinese Medicine (TCM), and

African Traditional Medicine (ATM) represent three of the most ancient, comprehensive, and widely practiced healthcare traditions. These systems are founded on holistic principles that view health as a balance between body, mind, and environment, and employ complex herbal formulations to restore physiological harmony. Modern scientific research has increasingly validated the therapeutic claims of these systems by identifying bioactive compounds responsible for their pharmacological actions.<sup>[6,7,21]</sup>

Bioactive compounds are naturally occurring chemical constituents in plants that exert biological effects on living organisms. These compounds include alkaloids, flavonoids, terpenoids, phenolics, glycosides, saponins, and essential oils, many of which have demonstrated potent antioxidant, anti-inflammatory, antimicrobial, anticancer, neuroprotective, and cardioprotective activities.<sup>[29,30,32]</sup>

The isolation of landmark compounds such as morphine, quinine, artemisinin, digoxin, and curcumin from traditional medicinal plants has revolutionized modern pharmacotherapy and highlights the enormous drug discovery potential inherent in traditional medicine systems.<sup>[1,2,3]</sup>

This review aims to provide a comprehensive and comparative analysis of the major bioactive compounds identified in Ayurvedic, TCM, and African medicinal systems, their chemical characterization, pharmacological activities, and role in contemporary drug discovery. The review further addresses challenges in standardization and safety evaluation and proposes future research directions.<sup>[4,5]</sup>

## 2. OBJECTIVES OF THE STUDY

The present review was conducted with the following specific objectives:

1. To identify and classify major bioactive compounds reported in Ayurvedic, Chinese, and African traditional medicinal systems.
2. To summarize the natural sources (plants, minerals, and animal-derived products) used in these traditional systems for therapeutic purposes.
3. To analyze the pharmacological activities of identified bioactive compounds, including anti-inflammatory, antioxidant, antimicrobial, anticancer, neuroprotective, and antidiabetic effects.
4. To compare the mechanisms of action of key bioactive compounds across the three traditional medical systems.
5. To evaluate the scientific evidence and experimental validation supporting the traditional uses of these medicines.
6. To highlight the role of traditional medicine-derived bioactive compounds in modern drug development and pharmaceutical research.
7. To discuss the safety, toxicity, and quality control challenges associated with traditional medicines.
8. To identify research gaps and future perspectives for integrating traditional medicine into evidence-based healthcare.

## 3. OVERVIEW OF TRADITIONAL MEDICINE SYSTEMS

### 3.1 Ayurvedic System of Medicine

Ayurveda is one of the oldest medical systems in the world, originating in India more than 5,000 years ago. The term Ayurveda is derived from the Sanskrit words Ayus (life) and Veda (knowledge), meaning the science of life. This system is based on the balance of three fundamental energies or doshas: Vata, Pitta, and Kapha. According to Ayurvedic philosophy, disease arises when these doshas are imbalanced, and treatment involves restoring equilibrium using herbal medicines, diet, lifestyle modification, and detoxification therapies.<sup>[6,7,10]</sup>

Medicinal plants form the foundation of Ayurvedic therapy. Classical Ayurvedic texts such as Charaka Samhita, Sushruta Samhita, and Ashtanga Hridaya document over 7,000 medicinal plants, many of which are

still used today. Commonly used plants include *Curcuma longa* (turmeric), *Withania somnifera* (ashwagandha), *Bacopa monnieri* (brahmi), *Azadirachta indica* (neem), and *Tinospora cordifolia* (guduchi). These plants are rich in bioactive compounds such as curcuminoids, withanolides, bacosides, and diterpenoids, which have been scientifically proven to possess multiple therapeutic activities.<sup>[8,9,10]</sup>

### 3.2 Traditional Chinese Medicine (TCM)

Traditional Chinese Medicine is a holistic healthcare system that has evolved over 2,500 years. It is based on the concepts of Yin-Yang balance, Qi (vital energy), and meridian pathways that regulate physiological functions. TCM employs herbal medicines, acupuncture, moxibustion, and dietary therapy to restore harmony within the body.<sup>[14,20]</sup>

Chinese herbal medicine is one of the most sophisticated botanical systems in the world, utilizing more than 13,000 medicinal substances. Herbal formulations typically contain multiple herbs designed to act synergistically. Key medicinal plants include *Panax ginseng*, *Artemisia annua*, *Ephedra sinica*, *Glycyrrhiza glabra*, and *Scutellaria baicalensis*. Bioactive compounds such as ginsenosides, artemisinin, ephedrine, and baicalin have demonstrated significant pharmacological effects and have contributed to modern drug discovery, most notably through the Nobel Prize-winning discovery of artemisinin as an antimalarial agent.<sup>[15,16,19,20]</sup>

### 3.3 African Traditional Medicine (ATM)

African Traditional Medicine is a diverse and deeply rooted system of healing that varies across regions, cultures, and ethnic groups. It relies heavily on ethnobotanical knowledge passed down through generations and is practiced by traditional healers who use medicinal plants, minerals, animal products, and spiritual rituals to treat illness.<sup>[21,22,23]</sup>

Africa is home to over 45,000 plant species, many of which possess medicinal properties. Commonly used medicinal plants include *Cryptolepis sanguinolenta*, *Prunus africana*, *Hibiscus sabdariffa*, *Vernonia amygdalina*, and *Aloe vera*. These plants contain bioactive compounds such as alkaloids, flavonoids, terpenoids, and phenolics, which exhibit antimicrobial, antimalarial, anti-inflammatory, and anticancer activities. Despite their therapeutic potential, African medicinal plants remain comparatively underexplored relative to Ayurvedic and Chinese systems, representing a rich source for future drug discovery.<sup>[22,23,24,25]</sup>

## 4. MAJOR CLASSES OF BIOACTIVE COMPOUNDS IN TRADITIONAL MEDICINES

Medicinal plants used in traditional systems contain a wide variety of secondary metabolites responsible for their therapeutic properties. These compounds are broadly classified into several major categories, each with distinct chemical structures and biological activities.<sup>[29,30,31,32]</sup>

### 4.1 Alkaloids

Alkaloids are naturally occurring nitrogen-containing organic compounds, predominantly basic in character. Nitrogen is typically integrated into a heterocyclic ring system, which is critical for their chemical reactivity and biological activity. These compounds are primarily derived biosynthetically from amino acids such as ornithine, lysine, tyrosine, and tryptophan, through decarboxylation, methylation, oxidation, and cyclization reactions. Their molecular weight ranges from approximately 100 to 900 Da. Alkaloids may exist as free bases soluble in organic solvents or as salts soluble in water, and many are optically active due to chiral centers.<sup>[29,30,32]</sup>

Alkaloids are classified as true alkaloids (nitrogen in a heterocyclic ring derived from amino acids), protoalkaloids (nitrogen outside the ring), and pseudoalkaloids (not derived from amino acids). Pharmacologically important examples include morphine (analgesic), quinine (antimalarial), berberine (antimicrobial and

antidiabetic), ephedrine (bronchodilator), and cryptolepine (antimalarial and anticancer). These compounds exhibit a wide spectrum of CNS, antimicrobial, and cytotoxic activities.<sup>[1,3,32,36]</sup>

#### 4.2 Flavonoids

Flavonoids are polyphenolic compounds characterized by a 15-carbon skeleton (C6-C3-C6), comprising two aromatic rings (A and B) connected via a heterocyclic pyran ring (C). Their structural diversity arises from variations in the degree of oxidation of the C ring, the position of hydroxyl or methoxy substituents, and glycosylation patterns. They are biosynthesized via the phenylpropanoid pathway from phenylalanine and malonyl-CoA, with chalcone synthase and chalcone isomerase as key enzymes. Molecular weights range from 250 to 600 Da, with strong UV absorption at 250 to 380 nm.<sup>[29,31,35]</sup>

Major subclasses include flavones, flavanones, flavanols, isoflavones, and anthocyanidins. Flavonoids are renowned for their potent antioxidant and anti-inflammatory properties. Representative compounds include quercetin, kaempferol, luteolin, and epigallocatechin gallate (EGCG), which protect cells from oxidative stress, modulate inflammatory cytokines, and demonstrate anticancer, cardioprotective, and antimicrobial effects.<sup>[33,35,36]</sup>

#### 4.3 Terpenoids

Terpenoids constitute the largest class of plant secondary metabolites and are derived from isoprene (C<sub>5</sub>H<sub>8</sub>) units assembled in a head-to-tail fashion. They are biosynthesized via the mevalonate (MVA) pathway in the cytoplasm or the methylerythritol phosphate (MEP) pathway in the plastid. Classification is based on the number of carbon atoms: monoterpenoids (C<sub>10</sub>), sesquiterpenoids (C<sub>15</sub>), diterpenoids (C<sub>20</sub>), triterpenoids (C<sub>30</sub>), and tetraterpenoids (C<sub>40</sub>). They are predominantly lipophilic with poor water solubility, and lower molecular weight terpenoids are volatile.<sup>[29,30,31]</sup>

Terpenoids exhibit a broad spectrum of biological activities. Artemisinin, a sesquiterpenoid endoperoxide from *Artemisia annua*, is a landmark antimalarial drug. Ginsenosides (triterpenoid saponins) from *Panax ginseng* are immunomodulatory and adaptogenic. Limonoids and diterpenoids possess significant anticancer and anti-inflammatory activities. Withanolides from *Withania somnifera* function as adaptogens and immunomodulators.<sup>[16,36]</sup>

#### 4.4 Phenolic Compounds

Phenolic compounds are characterized by the presence of one or more aromatic rings bearing hydroxyl groups. They range in structural complexity from simple phenols and phenolic acids to polyphenols, stilbenes, lignans, and coumarins. Biosynthetically, they are derived from the shikimate pathway linked to phenylalanine metabolism. Their molecular weight ranges from 150 to 500 Da; they are polar compounds with high redox potential and serve as strong hydrogen-bond donors.<sup>[29,30,35]</sup>

Phenolic compounds exhibit potent antioxidant activity by scavenging reactive oxygen species (ROS) and chelating metal ions. Resveratrol (stilbene) demonstrates cardioprotective and chemopreventive effects; gallic acid and ellagic acid exhibit antimicrobial and anticancer properties; and coumarins have demonstrated anticoagulant and anti-inflammatory activities.<sup>[35,36]</sup>

#### 4.5 Saponins

Saponins are glycosidic compounds consisting of a non-sugar aglycone (sapogenin) linked to one or more sugar chains. The sapogenin may be triterpenoid (C<sub>30</sub>) or steroidal (C<sub>27</sub>) in nature, conferring an amphiphilic character to the molecule. Saponins are biosynthesized from acetyl-CoA via the mevalonic acid pathway, with cyclization forming the triterpene or steroid core. Their molecular weight ranges from 600 to 2000 Da; they are highly polar due to sugar chains and form stable foams in aqueous solutions.<sup>[29,34]</sup>

Pharmacologically, saponins exhibit immunomodulatory, anticancer, antimicrobial, and anti-inflammatory

activities. Ginsenosides (triterpenoid saponins) from *Panax ginseng* are among the most well-studied examples. Saponins from *Astragalus membranaceus* (astragalosides) enhance immune function, while the steroidal glycoside P57 from *Hoodia gordonii* acts as an appetite suppressant used in weight management.<sup>[34,36]</sup>

#### 4.6 Tannins

Tannins are high-molecular-weight polyphenolic compounds capable of forming stable complexes with proteins and metals. They possess multiple phenolic hydroxyl groups that confer strong hydrogen-bonding ability and protein-precipitating properties. Tannins are classified as hydrolysable tannins (based on gallic or ellagic acid) and condensed tannins (flavan-3-ol polymers). They are synthesized through the shikimate and phenylpropanoid pathways via polymerization of phenolic units. Their molecular weight ranges from 500 to over 3000 Da; they are highly water soluble and possess astringent properties.<sup>[29,30,31]</sup>

Tannins exhibit antimicrobial, astringent, antioxidant, and wound-healing activities. Punicalagin and chebulinic acid from *Terminalia chebula* are potent antioxidants. The protein-binding property of tannins underlies their astringent and antidiarrhoeal effects, while their metal-chelating capacity contributes to their antioxidant mechanism.<sup>[29,32]</sup>

### 5. BIOACTIVE COMPOUNDS IN AYURVEDIC MEDICINE

Ayurvedic medicinal plants are rich in diverse bioactive compounds with scientifically validated pharmacological effects. Curcumin, the principal polyphenol from *Curcuma longa*, exhibits strong anti-inflammatory, antioxidant, anticancer, and neuroprotective properties, primarily through inhibition of NF- $\kappa$ B signaling and modulation of multiple inflammatory pathways.<sup>[6,7,36]</sup>

Withanolides from *Withania somnifera* act as adaptogens and immunomodulators, improving stress tolerance and immune response through regulation of the hypothalamic-pituitary-adrenal (HPA) axis. Bacosides A and B from *Bacopa monnieri* enhance memory and cognitive function by promoting neuronal communication and synaptic plasticity, and have demonstrated anxiolytic and neuroprotective effects relevant to Alzheimer's disease and other neurodegenerative conditions.<sup>[8,9]</sup>

Azadirachtin from *Azadirachta indica* exhibits broad-spectrum antimicrobial and immunostimulant activities, while piperine from *Piper nigrum* functions as a bioavailability enhancer for co-administered drugs. Other important Ayurvedic bioactive compounds include tinocordifolioside from *Tinospora cordifolia* (immunostimulant and anti-pyretic), gymnemic acids from *Gymnema sylvestre* (antidiabetic), arjunolic acid from *Terminalia arjuna* (cardioprotective), and boswellic acids from *Boswellia serrata* (anti-inflammatory and anti-arthritic). These compounds work synergistically in polyherbal formulations, a hallmark of Ayurvedic therapeutic design. Notably, traditional dietary staples such as millets, which are consumed widely in South Asian Ayurvedic dietary traditions, have also been shown to influence the pharmacokinetics and pharmacodynamics of antidiabetic drugs such as gliclazide, highlighting the importance of diet-drug interaction assessment in traditional medicine contexts.<sup>[46,47,48,9,11,12]</sup>

**Table 1: Bioactive Compounds and Pharmacological Activities of Selected Ayurvedic Medicinal Plants**

Plant Name (Common Name)	Major Chemical Constituents	Pharmacological Actions	Diseases / Conditions Treated
Withania somnifera (Ashwagandha)	Withanolides, alkaloids	Adaptogenic, anti-inflammatory, immunomodulatory	Stress, arthritis, insomnia, weakness
Tinospora cordifolia (Guduchi)	Diterpenoids, polysaccharides	Immunostimulant, anti-pyretic, antidiabetic	Fever, infections, diabetes
Curcuma longa (Turmeric)	Curcumin, curcuminoids	Anti-inflammatory, antioxidant, anticancer	Arthritis, skin disease, cancer
Embllica officinalis (Amla)	Vitamin C, tannins	Antioxidant, rejuvenating, immunostimulant	Anaemia, gastric disorders, immunity
Terminalia arjuna (Arjuna)	Arjunolic acid, flavonoids	Cardioprotective, antihypertensive	Heart diseases, hypertension
Gymnema sylvestre (Gurmara)	Gymnemic acids	Antidiabetic, anti-hyperglycaemic	Diabetes mellitus
Bacopa monnieri (Brahmi)	Bacosides A and B	Nootropic, neuroprotective, anxiolytic	Memory loss, anxiety, epilepsy
Azadirachta indica (Neem)	Azadirachtin, nimbin	Antibacterial, anti-inflammatory, antifungal	Skin diseases, infections
Glycyrrhiza glabra (Yashtimadhu)	Glycyrrhizin, flavonoids	Anti-ulcer, anti-inflammatory, expectorant	Cough, ulcers, liver disorders
Mucuna pruriens (Kapikacchu)	L-DOPA, alkaloids	Neuroprotective, tonic, aphrodisiac	Parkinson's disease, infertility
Asparagus racemosus (Shatavari)	Saponins, shatavarin	Galactagogue, rejuvenative, adaptogenic	Female disorders, immunity
Ocimum sanctum (Tulsi)	Eugenol, ursolic acid	Antimicrobial, adaptogenic, anti-stress	Cold, cough, stress
Zingiber officinale (Ginger)	Gingerols, shogaols	Digestive, anti-inflammatory, antiemetic	Nausea, indigestion, arthritis
Boswellia serrata (Shallaki)	Boswellic acids	Anti-inflammatory, anti-arthritic	Arthritis, joint pain
Terminalia chebula (Haritaki)	Tannins, chebulinic acid	Laxative, detoxifying, antimicrobial	Constipation, detoxification

## 6. BIOACTIVE COMPOUNDS IN TRADITIONAL CHINESE MEDICINE

TCM is characterized by complex herbal formulations containing compounds with diverse biological activities. Artemisinin, derived from *Artemisia annua*, is one of the most significant contributions of traditional medicine to modern pharmacotherapy, serving as the foundational scaffold for front-line antimalarial drugs including artesunate and artemether. Its discovery by Professor Tu Youyou was recognized with the Nobel Prize in Physiology or Medicine in 2015, exemplifying the translational potential of ethnopharmacology.<sup>[16,19,20]</sup>

Ginsenosides from *Panax ginseng* represent a structurally complex family of triterpenoid saponins that modulate immune function, reduce fatigue, improve cognitive performance, and demonstrate cardioprotective

effects. Baicalin and its aglycone baicalein from *Scutellaria baicalensis* exhibit potent antiviral, anti-inflammatory, and anticancer activities, partly through inhibition of cyclooxygenase-2 (COX-2) and modulation of the JAK/STAT signaling pathway.<sup>[14,15,16]</sup>

Berberine from *Coptis chinensis* has attracted considerable pharmaceutical interest for its antidiabetic, antimicrobial, and anti-inflammatory effects, with mechanisms involving activation of AMP-activated protein kinase (AMPK) and inhibition of inflammatory mediators. Glycyrrhizin from *Glycyrrhiza uralensis* exerts anti-inflammatory, antiviral, and hepatoprotective effects. Tanshinones and salvianolic acids from *Salvia miltiorrhiza* are important cardioprotective agents, while andrographolide from *Andrographis paniculata* demonstrates potent anti-inflammatory and antiviral properties. The synergistic interactions between multiple phytochemicals in TCM formulations are increasingly being explored through the framework of network pharmacology.<sup>[14,15,17,18]</sup>

**Table 2: Bioactive Compounds and Pharmacological Activities of Selected TCM Medicinal Plants**

Plant Name (Common Name)	Major Chemical Constituents	Pharmacological Actions	Diseases / Conditions Treated
<i>Curcuma longa</i> (Jiang Huang)	Curcumin, demethoxycurcumin	Anti-inflammatory, NF-κB inhibition	Arthritis, inflammation, cancer
<i>Scutellaria baicalensis</i> (Huang Qin)	Baicalin, baicalein, wogonin	Anti-inflammatory, antioxidant, antiviral	Respiratory infection, hepatitis, fever
<i>Glycyrrhiza uralensis</i> (Gan Cao)	Glycyrrhizin, liquiritigenin	Anti-inflammatory, immunomodulatory	Cough, gastric ulcer, liver disorders
<i>Panax ginseng</i> (Ren Shen)	Ginsenosides	Adaptogenic, anti-inflammatory, immunostimulant	Fatigue, immune disorders, diabetes
<i>Camellia sinensis</i> (Green Tea)	EGCG, catechins	Antioxidant, anti-inflammatory, chemopreventive	Metabolic disorders, cancer prevention
<i>Coptis chinensis</i> (Huang Lian)	Berberine	Antimicrobial, anti-inflammatory, antidiabetic	Diarrhoea, diabetes, infections
<i>Astragalus membranaceus</i> (Huang Qi)	Astragalosides, polysaccharides	Immunostimulant, anti-inflammatory, adaptogenic	Weak immunity, chronic fatigue
<i>Salvia miltiorrhiza</i> (Dan Shen)	Tanshinones, salvianolic acid	Cardioprotective, anti-inflammatory	Cardiovascular diseases
<i>Paeonia lactiflora</i> (Bai Shao)	Paeoniflorin	Anti-inflammatory, analgesic, antispasmodic	Autoimmune diseases, pain
<i>Andrographis paniculata</i> (Chuan Xin Lian)	Andrographolide	Anti-inflammatory, NF-κB inhibition, antiviral	Fever, infections, inflammation

## 7. BIOACTIVE COMPOUNDS IN AFRICAN TRADITIONAL MEDICINE

African medicinal plants are a rich and comparatively underexplored source of novel bioactive compounds. Cryptolepine, an alkaloid from *Cryptolepis sanguinolenta*, exhibits potent antimalarial and anticancer properties through intercalation into DNA and inhibition of topoisomerase II. *Prunus africana* contains phytosterols and pentacyclic triterpenes that are effective in managing benign prostatic hyperplasia (BPH) and is among the few African medicinal plants with an established European pharmaceutical market.<sup>[22,23,24]</sup>

Vernonia amygdalina is rich in sesquiterpene lactones (vernodaline, vernolide) with antimicrobial, anti-inflammatory, and antihelminthic activities. Hibiscus sabdariffa contains anthocyanins and organic acids that improve cardiovascular health by reducing blood pressure and lipid peroxidation. Aloe vera contains polysaccharides (acemannan) and anthraquinones (aloin) with wound-healing, immunomodulatory, and laxative effects, respectively.<sup>[21,22]</sup>

Vinca alkaloids (vincristine and vinblastine) isolated from Catharanthus roseus, a plant of Malagasy origin widely used in African folk medicine, are among the most successful anticancer natural products, forming the basis of combination chemotherapy regimens for leukaemia and lymphoma. Paclitaxel (Taxol) from Taxus species similarly represents a landmark contribution of plant-derived compounds to oncology. These successes underscore the enormous untapped potential of African biodiversity for drug discovery.<sup>[1,2,25,26]</sup>

**Table 3: Bioactive Compounds and Pharmacological Activities of Selected African Traditional Medicinal Plants**

Plant Name (Common Name)	Major Chemical Constituents	Pharmacological Actions	Diseases / Conditions Treated
Catharanthus roseus (Madagascar Periwinkle)	Vincristine, vinblastine (vinca alkaloids)	Anticancer, anti-leukaemic	Leukaemia, lymphoma, tumours
Taxus species (African Yew)	Paclitaxel (Taxol)	Anticancer, antimitotic	Breast, ovarian, lung cancer
Hoodia gordonii (Namibia, South Africa)	P57 steroidal glycoside	Appetite suppressant	Obesity, weight management
Euphorbia hirta	Flavonoids, tannins, triterpenes	Anti-inflammatory, antidiarrhoeal, antimicrobial	Asthma, diarrhoea, respiratory infections
Cassia occidentalis	Anthraquinones, flavonoids	Anti-inflammatory, hepatoprotective	Fever, malaria, liver disorders
Argemone mexicana	Berberine, protopine (alkaloids)	Antimicrobial, anti-inflammatory	Malaria, skin diseases, jaundice
Sickle cell herbal formulations (Nigeria, Ghana)	Polyphenols, flavonoids, alkaloids (mixed extracts)	Anti-sickling, antioxidant	Sickle cell anaemia
Malarial herbal mixtures (Benin, Mali, Nigeria)	Terpenoids, alkaloids, quinone derivatives	Antimalarial	Malaria fever
Hypertension plants (Cameroon, Nigeria)	Flavonoids, saponins	Antihypertensive, vasodilatory	High blood pressure
Diabetes medicinal plants (West Africa)	Phenolics, glycosides	Antidiabetic, insulin-sensitising	Diabetes mellitus
HIV opportunistic infection plants (Cameroon)	Alkaloids, tannins	Antimicrobial, immunomodulatory	Opportunistic infections in HIV/AIDS

### 8. COMPARATIVE PHARMACOLOGICAL ACTIVITIES

A comparative analysis of the bioactive compounds from all three traditional medicine systems reveals significant overlap in therapeutic targets and mechanisms of action, reflecting convergent evolution of

medicinal knowledge across diverse cultures. Anti-inflammatory activity is a common feature, mediated through inhibition of cyclooxygenase (COX), lipoxygenase (LOX), and NF- $\kappa$ B pathways by compounds such as curcumin (Ayurveda/TCM), baicalin (TCM), withanolides (Ayurveda), and sesquiterpene lactones (ATM).<sup>[32,33,36]</sup>

Antioxidant activity is exhibited broadly across all three systems. Key antioxidants include curcumin, quercetin, and resveratrol (Ayurveda/TCM), EGCG from green tea (TCM), and anthocyanins from *Hibiscus sabdariffa* (ATM). These compounds scavenge reactive oxygen species, upregulate endogenous antioxidant enzymes (superoxide dismutase, catalase, glutathione peroxidase), and chelate pro-oxidant metal ions.<sup>[35,36]</sup>

Antimicrobial activity is conferred by berberine (TCM/ATM), cryptolepine (ATM), azadirachtin (Ayurveda), and allicin (common to multiple systems). Antimalarial activity is primarily associated with artemisinin (TCM) and quinine alkaloids (ATM). Neuroprotective effects are demonstrated by bacosides (Ayurveda), ginsenosides (TCM), and curcumin (Ayurveda/TCM), through mechanisms involving synaptic plasticity, neuroinflammation reduction, and amyloid-beta inhibition. The anticancer potential of curcumin, artemisinin, vinca alkaloids, paclitaxel, and berberine spans all three systems and represents a particularly active area of translational research.<sup>[1,2,3,36]</sup>

## 9. MODERN VALIDATION AND DRUG DISCOVERY

### 9.1 Concept and Scope

Modern validation refers to the systematic scientific evaluation of traditional medicinal knowledge using contemporary analytical, biochemical, and molecular techniques. For global acceptance and therapeutic integration, traditional remedies must be validated through standardized scientific methodologies that bridge ethnopharmacological knowledge and evidence-based medicine, ensuring that bioactive compounds are chemically characterized, reproducible in composition, mechanistically understood at the molecular level, and suitable for pharmaceutical development.<sup>[37,38,39]</sup>

### 9.2 Phytochemical Profiling and Analytical Techniques

Comprehensive phytochemical profiling is the essential first step in modern validation. Advanced chromatographic methods (HPLC, UPLC, GC-MS, LC-MS/MS) and spectroscopic techniques (NMR, FTIR, UV-Vis) allow identification of marker compounds, detection of synergistic phytochemical networks, and standardization of extracts for reproducibility. Metabolomics-based approaches provide holistic chemical fingerprinting that aligns well with the multi-component nature of traditional formulations.<sup>[11,19,45]</sup>

### 9.3 Bioactivity-Guided Fractionation and Structural Elucidation

Modern drug discovery often begins with bioactivity-guided fractionation, in which plant extracts are progressively fractionated while monitoring biological activity to pinpoint active chemical constituents. Structural elucidation using advanced spectroscopic tools enables structure-activity relationship (SAR) studies critical for drug optimization. This approach has yielded numerous drug leads including artemisinin, taxol, and vincristine.<sup>[1,2,4,26]</sup>

### 9.4 Mechanism-Based and Network Pharmacology Approaches

Unlike traditional empirical use, modern validation focuses on understanding mechanisms of action at the molecular and cellular levels, using enzyme inhibition assays, receptor-binding studies, signal transduction pathway analysis, gene expression profiling, and protein modulation studies. Molecular docking and in silico pharmacokinetic modeling accelerate target identification and drug optimization.<sup>[41,42,43]</sup>

Traditional medicines often rely on multi-component formulations that cannot be adequately explained using single-target drug models. Network pharmacology addresses this complexity by analyzing interactions

between multiple compounds and multiple targets, explaining synergistic and additive effects that are consistent with the holistic therapeutic concepts underlying Ayurvedic and TCM formulations.[<sup>14,15,17,44</sup>]

### **9.5 Ethnopharmacology-Guided Drug Discovery**

Ethnopharmacology plays a critical role in modern drug discovery by providing prioritized leads based on traditional usage, offering reduced time and cost for lead identification compared to random high-throughput screening, and higher success rates due to cultural and historical validation. By integrating ethnobotanical knowledge with modern screening platforms, researchers can efficiently identify drug-like phytochemicals with proven therapeutic relevance. Successful examples include artemisinin (TCM), galantamine (folk medicine), and pilocarpine (ethnobotanical lead), all of which entered mainstream medicine through ethnopharmacological guidance.[<sup>4,13,25</sup>]

### **9.6 Lead Optimization and Semi-Synthetic Derivatives**

Once bioactive compounds are identified, modern drug discovery focuses on optimizing their pharmacokinetic and physicochemical properties through chemical modification to improve stability and bioavailability, development of semi-synthetic analogs, and reduction of toxicity while retaining or enhancing efficacy. Artesunate (semi-synthetic artemisinin derivative), docetaxel (taxane analog), and curcumin nanoformulations exemplify this translational pipeline from natural scaffold to marketed pharmaceutical.[<sup>2,5,41</sup>]

### **9.7 Quality Control, Standardization, and Regulatory Validation**

For traditional medicines to enter modern healthcare systems, they must meet regulatory standards. Modern validation includes establishment of chemical fingerprints and reference markers, batch-to-batch consistency testing, and compliance with pharmacopoeial specifications. Regulatory agencies including the FDA, EMA, and WHO increasingly require scientific validation to ensure safety, efficacy, and quality.[<sup>37,38,39,40</sup>]

Guidelines from the WHO on herbal medicine assessment provide frameworks for global harmonization and regulatory acceptance of phytopharmaceuticals. Standardization using validated analytical methods and the establishment of reference standards for marker compounds are essential prerequisites for clinical translation and international market approval.[<sup>27,28,39</sup>]

## **10. CHALLENGES AND FUTURE PERSPECTIVES**

### **10.1 Challenges**

Despite significant progress, several challenges impede the full integration of traditional medicine-derived bioactive compounds into modern healthcare. Standardization and quality control remain major concerns, as the chemical composition of herbal materials varies with geographic origin, harvest season, processing methods, and storage conditions, leading to inconsistencies in biological activity. The complexity of polyherbal formulations makes definitive attribution of therapeutic effects to specific compounds difficult.[<sup>11,37,38</sup>]

Safety and toxicity evaluation present significant challenges, as many traditional preparations contain compounds with narrow therapeutic windows or hepatotoxic potential. Furthermore, food-drug interactions represent an underappreciated safety concern, as commonly consumed traditional dietary staples including millets can significantly alter the pharmacokinetics and pharmacodynamics of concurrently administered conventional drugs, potentially affecting therapeutic efficacy and safety.[<sup>46,47,48</sup>] The absence of rigorous clinical trial data for many traditional remedies limits their evidence-based acceptance. Intellectual property concerns, bioprospecting ethics, and benefit-sharing frameworks present additional regulatory and geopolitical challenges, particularly for African and indigenous knowledge systems.[<sup>22,23,27,28</sup>]

Sustainability of medicinal plant resources is a growing concern, as increasing commercial demand has led to overexploitation of many plant species, threatening both biodiversity and the long-term availability of natural drug leads. The lack of systematic documentation and conservation of traditional knowledge, particularly among aging traditional healers, represents an irreplaceable loss of potential pharmaceutical information.<sup>[13,22,26]</sup>

## 10.2 Future Perspectives

Emerging technologies hold considerable promise for overcoming existing challenges and unlocking the full therapeutic potential of traditional medicines. Artificial intelligence (AI) and machine learning are increasingly applied to predict bioactive compound-target interactions, identify novel drug candidates from natural product databases, and optimize pharmacokinetic profiles *in silico*.<sup>[41,42,43]</sup>

Omics-based validation approaches, including genomics, transcriptomics, proteomics, and metabolomics, provide comprehensive mechanistic insights into how bioactive compounds modulate complex biological networks, facilitating systems-level understanding of traditional formulations. Novel drug delivery systems, including nanoparticle formulations, liposomes, and self-emulsifying systems, are being developed to enhance the bioavailability and targeted delivery of phytochemicals with poor pharmacokinetic profiles, such as curcumin and quercetin.<sup>[44,45]</sup>

Collaborative international research frameworks that integrate ethnobotanical documentation, pharmacological screening, clinical evaluation, and bioinformatics analysis will be essential for the systematic development of traditional medicine-derived therapeutics. Equitable frameworks for benefit-sharing and intellectual property protection will be critical for ensuring that communities whose traditional knowledge underpins drug discovery receive appropriate recognition and compensation.<sup>[13,21,27]</sup>

## 11. CONCLUSION

Ayurvedic, Traditional Chinese, and African traditional medicine systems constitute vast and invaluable reservoirs of bioactive compounds with diverse chemical structures and broad pharmacological potential. Scientific investigations have confirmed that classes of phytochemicals such as alkaloids, flavonoids, terpenoids, saponins, tannins, and phenolic compounds play critical roles in mediating antioxidant, anti-inflammatory, antimicrobial, neuroprotective, antidiabetic, and anticancer activities.

Modern validation approaches, including advanced phytochemical profiling, molecular mechanism studies, network pharmacology, and ethnopharmacology-guided drug discovery, have significantly strengthened the scientific credibility of traditional medicinal knowledge. Despite this progress, challenges related to standardization, quality control, safety evaluation, and regulatory acceptance remain major barriers to global integration.

Future research integrating artificial intelligence, omics technologies, and novel drug delivery systems is expected to enhance the clinical translation and pharmaceutical applicability of traditional medicine-derived bioactive compounds. The rational integration of traditional knowledge with modern scientific methodologies holds great promise for the development of safe, effective, and multi-target therapeutic agents for contemporary healthcare needs.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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