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Review Article

Phytochemistry and Pharmacological Activities of *Zingiber montanum*: An Integrative Overview

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Abstract

Zingiber montanum (syn. *Zingiber cassumunar* Roxb.) is a medicinal member of the *Zingiberaceae* widely utilised in Southeast Asian traditional systems. Increasing pharmacological investigation has generated substantial experimental evidence; however, interpretation remains limited by chemotypic variability, inconsistent extraction protocols, and heterogeneous experimental design. This review offers a comprehensive analysis of taxonomic verification, geographic distribution, phytochemical composition, and documented biological activities. Chemical analyses indicate a metabolite profile dominated by phenylbutenoids, curcuminoids, monoterpenes, and sesquiterpenes, with terpinen-4-ol and zerumbone frequently associated with bioactivity. Preclinical studies demonstrate redox modulation, anticancer and multidrug resistance–modulating effects, broad-spectrum antimicrobial and antibiofilm activity, immune regulation, metabolic enzyme inhibition, dermatological applications, and preliminary antimalarial observations. Nevertheless, most findings derive from *in vitro* assays or short-term animal models, with limited pathway elucidation, inadequate standardisation of chemical fingerprints, and minimal pharmacokinetic or toxicological characterisation. Variability linked to solvent polarity and plant origin further complicates reproducibility and cross-study comparison. Although the species exhibits multifaceted biofunctional properties with relevance to nutraceutical, cosmeceutical, and phytopharmaceutical applications, translational positioning remains provisional due to the absence of controlled clinical validation. Future investigations should prioritise chemotype-controlled metabolomic profiling, defined molecular target mapping, reproducible doseresponse evaluation, and rigorously designed preclinical and clinical studies. By critically consolidating current evidence, this review delineates both the mechanistic potential and the methodological constraints of *Z. Montanum*, providing a structured foundation for future biomedical and industrial development.

***Keywords**: Essential Oil Composition; Pharmacological Activities; Zingiber montanum*

Introduction

The family *Zingiberaceae* comprises approximately 1,500 aromatic species distributed throughout tropical and subtropical regions, with Southeast Asia recognised as a major centre of evolutionary and phytochemical diversity (Devkota *et al*., 2021). Among these taxa, *Zingiber montanum* (syn. *Zingiber cassumunar* Roxb.) has long been embedded in South and Southeast Asian ethnomedical systems, where its rhizomes are used to manage gastrointestinal disturbances and inflammatory conditions (Bai *et al*., 2019; Han *et al*., 2021). Although traditional applications for dyspepsia, abdominal distension,

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and musculoskeletal discomfort provide a pharmacological rationale for investigation, mechanistic correlations between therapeutic claims and specific phytochemical constituents remain incompletely defined (Baez *et al*., 2023). Ecological adaptability across diverse climatic zones may further influence metabolite composition, yet chemotypic variability is rarely standardised or systematically compared in experimental research (Thepthong *et al*., 2023). Importantly, despite increasing scientific interest in *Z. montanum* as a source of bioactive natural compounds, interpreting the literature remains challenging because investigations differ in plant origin, extraction strategy, depth of chemical characterisation, dosage selection, and experimental design (Du *et al*., 2026). Such heterogeneity contributes to apparently inconsistent findings across antioxidant, anti-inflammatory, antimicrobial, and other pharmacological evaluations, highlighting the necessity for structured comparison and analytical synthesis rather than descriptive compilation (Han *et al*., 2021). Accordingly, this review integrates current knowledge of the phytochemical profile of *Z. Montanum* with a critical appraisal of pharmacological evidence, systematically comparing extract types, biological models, and concentration ranges, while explicitly identifying methodological limitations, unresolved discrepancies, and priority research gaps to inform future translational advancement.

Occurrence and Distribution of Zingiber montanum

Zingiber montanum (J. König ex Retz.) Link ex A. Dietr. is widely distributed across Indochina and tropical Southeast Asia, with documented occurrences in Bangladesh, Thailand, India, and Indonesia, alongside extensive cultivation in Malaysia and parts of Indonesia, underscoring both its cultural relevance and economic value (Musdja, 2021; World Flora Online, 2026). The species is particularly associated with southern Indian states like Karnataka, Tamil Nadu, Kerala, and Andhra Pradesh, and it has notable ecological resilience in both tropical and warm-temperate settings (Paramita *et al*., 2018). Environmental variability, including soil composition, climate, agronomic management, and harvest time, makes it easier to integrate into different conventional medical systems despite its broad geographic range., may significantly affect secondary metabolite profiles, particularly the quantity of curcuminoid or phenylbutanoic compounds and components of essential oils. Such ecological variation significantly hinders pharmacological reproducibility. as variations in chemotype might affect biological activity in different research (Navabhatra *et al*., 2022). Geographic distribution maps (Figure 1) depict significant agricultural and native occurrence regions; nevertheless, these visual representations should be assessed in combination with phytochemical standardisation data rather than as indicators of consistent medicinal potential (Devkota *et al*., 2021). To increase translational validity and cross-study comparability, future research should make use of chemitypic characterization, georeferenced sampling, verified voucher specimens, and thorough cultivation information. This will improve pharmacological interpretation accuracy and reduce bias caused by variability (Bai *et al*., 2019).

Figure1: *Distribution of Zingiber montanum*

Synonyms and Vernacular Names of Zingiber montanum

Zingiber montanum (J. König ex Retz.) Link ex A. Dietr., a medicinally valued member of the *Zingiberaceae*, is native to tropical to subtropical Southeast Asia and has been disseminated beyond its native range, indicating strong environmental adaptability and sustained cultural use (Devkota *et al*., 2021; World Flora Online, 2026). Its wide geographic occurrence is mirrored by diverse vernacular terminology embedded in local traditions, as outlined in Table 1. In Malaysia, it is referred to as Kunyit Bongelai, while Indonesian usage includes Bengle, Bunglai, and Panglai (Wiart, 2020); the name Plai is common in Thailand (Chongmelaxme *et al*., 2017) Pale is reported among the Reang community in India (Das *et al*., 2024). Additional designations comprise Bengle and Pandhiyang in Indonesia, Bonglai putih in Malaysia, Meik-tha-lin and Hta-nah in Myanmar, Wan-fai in Thailand, and Gừng đen (Gung do) in Vietnam (Wiart, 2021). In Chinese sources, the plant is frequently recorded under the synonym *Zingiber cassumunar* Roxb. and is locally known as Cui guo shan jiang (催果山姜) (Bai *et al*., 2019), whereas the English term “Cassumunar ginger” reflects its recognised culinary and medicinal roles in South Asian settings (dos Santos *et al*., 2024). Given this variation in nomenclature, accurate taxonomic confirmation, supported by voucher specimens and standardised identification approaches, remains essential when aligning traditional knowledge with experimental findings to ensure consistency and reproducibility (Wulansari *et al*., 2025).

***Table1**: Vernacular Name of Zingiber montanum (J. Konig ex Retz.)*

Scientific Name: *Curcuma Aeruginosa* Roxb		
Country	**Local Name**	**References**
Malaysia	*Kunyit bongelai*	Bai *et al*., 2019
India	*Banada*	Das *et al*., 2024
Thailand	*Plai*	Chongmelaxme *et al*., 2017
China	Cui guo shan jiang	Bai *et al*., 2019
English	*Cassumunar ginger*	dos Santos *et al*., 2024
Bangladesh	Banada	Hassan *et al*., 2019
Indonesia	Bengle, Bunglai, Panglai	Wiart, 2020
Myanmar	meik-tha-lin, hta-nah	Wiart, 2021
Vietnam	gung do	Wiart, 2021

Taxonomy of Zingiber montanum

Zingiber montanum (J. König ex Retz.) Link ex A. Dietr., a rhizomatous member of the *Zingiberaceae,* can be recognised by a combination of morphological features, including lanceolate leaves, a short bifid ligule, and yellow inflorescences with gently undulated margins (Bai *et al*., 2019; Das *et al*., 2024). Its taxonomic interpretation has been refined over time, with earlier literature assigning the species to alternative names before its current designation was standardised (Devkota *et al*., 2021; World Flora Online, 2026). While the defining characteristics remain stable, variation in certain structural traits has been observed among populations, likely reflecting adaptation to differing environmental conditions (Bai *et al*., 2025). A summary of its hierarchical classification is presented in Table 2.

***Table 2:** Taxonomic Classification of Z. Montanum (J. Konig ex Retz.)*

Taxonomy	
Root	Root
Kingdom	Plantae
Phylum	Tracheophyta
Class	Liliopsida
Order	Zingiberales
Family	Zingiberaceae
Genus	Zingiber
Species	*Zingiber montanum* (J. Koenig) Link ex A. Dietr.

Morphological Characteristics of Zingiber Montanum

Zingiber montanum (J. König ex Retz.) is a perennial rhizomatous herb belonging to the *Zingiberaceae* family, characterised by distinctive morphological traits that facilitate taxonomic identification. The species possesses a fleshy, horizontally growing rhizome (1–2 cm thick) with a deep yellow interior and a pronounced camphor-like aroma (Windarsih *et al*., 2021). The plant typically reaches 1–1.5 m in height, producing pubescent shoots and linear to lanceolate leaves measuring 20–35 cm long and 3–4 cm wide (Bai *et al*., 2019). The inflorescence arises on a separate peduncle (10–20 cm) enclosed by pubescent sheaths, forming an ovate spike (6–8 × 3–4 cm) composed of vividly coloured bracts ranging from scarlet to dark crimson (Bai *et al*., 2019; Windarsih *et al*., 2021). Floral structures include a pale-yellow corolla tube (2.3–2.5 cm) and a yellowish-white, three-lobed labellum with crisped margins. The species exhibits moderate intraspecific variation in rhizome pigmentation and bract colouration, likely influenced by environmental conditions (Bai *et al*., 2019; Li *et al*., 2019).

Traditional Medicinal Uses of Zingiber montanum

Zingiber montanum (J. König ex Retz.), commonly known as 'bonglai', has been widely utilised in traditional medicinal systems across Southeast and South Asia. The rhizome is traditionally used to manage inflammatory disorders, musculoskeletal pain, respiratory ailments, and gastrointestinal disturbances and is also applied topically for wound healing (Al-Amin *et al*., 2020). In Thai traditional medicine, the essential oil is incorporated into therapeutic massage formulations due to its analgesic and anti-inflammatory properties (Saising *et al*., 2022). Similarly, Indian, Chinese, and Arabic medicinal traditions describe its use as a carminative, antispasmodic, digestive stimulant, and circulatory enhancer. Regional ethnobotanical documentation reports its use in Indonesia for headache relief, in Malaysia as a postpartum remedy, in Laos for febrile and dermatological conditions, and in Northeast India for dyspeptic symptoms (Musdja, 2021; Tunit *et al*., 2025). Preparation methods typically involve the direct application of crushed rhizomes or oil extracts produced through thermal processing (Ouchi *et al*., 2023). Contemporary pharmaceutical formulations, such as Polygalas cream, further demonstrate their translational relevance in managing traumatic inflammation and joint pain (Garg *et al*., 2024).

Phytochemical investigations of *Z. montanum* have revealed a chemically diverse metabolite profile, dominated by terpenoids, phenolic compounds, and bioactive volatile compounds (Septama *et al*., 2023; Yit & Zainal-Abidin, 2024). Essential oil analyses consistently identify zingiberene, sesquiphellandrene, citral, camphene, and related mono- and sesquiterpenes as principal components contributing to its characteristic aroma and bioactivity (Li *et al*., 2019; Mujahid *et al*., 2024). In addition to volatile terpenoids, phenolic derivatives represent an important fraction of the rhizome extract. The relative abundance of these phenolic constituents varies according to processing conditions; gingerols predominate in fresh rhizomes, whereas shogaols increase following drying or thermal treatment due to dehydration of precursor compounds (Mao *et al*., 2019; Navabhatra *et al*., 2022). These ethnobotanical uses are summarised in Table 3.

***Table 3:** Ethnobotanical Applications of Zingiber Montanum Across Different Countries*

Country / Region	Traditional Uses	Preparation/Application	References
Southeast & South Asia (General)	Management of inflammatory disorders, musculoskeletal pain, respiratory ailments, gastrointestinal disturbances, and topical wound healing	Crushed rhizome applied directly; oil extracts	Al-Amin *et al*., 2020
Thailand	Analgesic, anti-inflammatory, sedative; relief of muscle pain and sprains	Essential oil incorporated into massage therapy formulations	Saising *et al*., 2022
India	Carminative, antispasmodic, digestive stimulant; circulatory enhancer; dyspepsia and bloating (Northeast India)	Oral administration of rhizome preparations	Tunit *et al*., 2025

China	Carminative, digestive aid, expectorant	Rhizome-based decoctions and extracts	Hussein & Abdulhameed, 2025
Arabic medicinal systems	Digestive stimulant, circulatory enhancer, antispasmodic	Rhizome-based preparations	Jitpromma *et al.*, 2025
Indonesia	Headache relief	Poultice or topical rhizome application	Deng *et al.*, 2022
Malaysia	Postpartum care; vermifuge remedy	Traditional rhizome preparations	Deng *et al.*, 2022
Laos	Treatment of fever, dermatological conditions, and intestinal disorders	Topical and oral preparations	Deng *et al.*, 2022
Modern pharmaceutical application	Management of traumatic inflammation, joint and muscular pain	Polygalas cream (standardised formulation)	Garg *et al.*, 2024

Extraction methodology further influences phytochemical yield and composition. Polar solvents, such as methanol and ethanol, preferentially extract phenolic acids and flavonoids, while non-polar solvents enrich volatile terpenoid fractions (Ersedo *et al.*, 2023; Navabhatra *et al.*, 2022). Moreover, quantitative profiling indicates that geographical origin, environmental factors, and post-harvest processing significantly contribute to metabolite variability (Devkota *et al.*, 2021; Prastya *et al.*, 2023). Collectively, these phytoconstituents provide the biochemical basis for the antioxidant, antimicrobial, and anti-inflammatory activities reported in pharmacological investigations, supporting the plant's translational relevance in functional food, nutraceutical, and phytopharmaceutical industries (Yongkhamcha *et al.*, 2024).

Chemical Composition of Zingiber montanum

Phytochemical investigations have demonstrated that the rhizomes of *Z. montanum* are rich in diverse bioactive constituents, including alkaloids, saponins, flavonoids, tannins, phenolic compounds, terpenoids, glycosides, and steroids (Joram *et al.*, 2018; Thepthong *et al.*, 2023). Essential oil analyses further reveal a chemically complex profile dominated by monoterpenes and sesquiterpenes. The detailed phytochemical composition of leaf and rhizome essential oils is summarised in Table 4, while the structural representations of the major identified constituents are illustrated in Figure 3. Major volatile compounds reported across studies include α-thujene, γ-terpinene, p-cymene, α-phellandrene, sabinene, terpinene-4-ol, and terpinyl acetate (Han *et al.*, 2021; Shukurova *et al.*, 2020). Comprehensive GC–MS characterisation has further highlighted distinct compositional differences between plant parts. Rhizome oil has been reported to contain β-phellandrene, triquinacene, 1,4-bis(methoxy) derivatives, β-sesquiphellandrene, γ-terpinene, terpinen-4-ol, (Z)-ocimene, and cis-sabinene hydrate, whereas leaf oil is predominantly composed of sabinene, β-pinene, caryophyllene oxide, and caryophyllene (Yongkhamcha *et al.*, 2024). Notably, among *Zingiber* species evaluated in Thailand, *Z. montanum* exhibited the highest rhizome essential oil yield, along with elevated concentrations of terpinen-4-ol and curcuminoids (Nahid & Bhuiyan, 2024).

Table 4: *The Chemicals Extracted from the Rhizomes of Z. montanum*

Extraction Solvent	Identified Compounds	References
Hexane extract	$C_{12}H_{16}O_3$ (1), $C_{14}H_{18}O_4$ (2), $C_{15}H_{22}O$ (15), $C_{24}H_{28}O_4$ (3), $C_{13}H_{18}O_3S$ (4), C_6H_5CO (5)	Yongkhamcha *et al.*, 2024
Chloroform extract	$C_{24}H_{28}O_4$ (6), $C_{13}H_{19}N$ (7), $C_6H_4O_2$ (8), $C_8H_8O_4$ (9), $C_{10}H_{18}O$ (10), $C_9H_{10}O_4$ (11), $C_{14}H_{20}O_8$ (25), $C_{23}H_{26}O_4$ (26), $C_{13}H_{16}O_3$ (27), $C_{12}H_{14}O_2$ (28), $C_{12}H_{16}O_3$ (29), $C_{14}H_{18}O_4$ (30)	Yongkhamcha *et al.*, 2024
Toluene extract	$C_{10}H_{14}O$ (12), $C_{12}H_{16}O_3$ (13)	Devkota *et al.*, 2021
Methanol extract	$C_8H_8O_4$ (9), $C_{12}H_{14}O_2$ (14), $C_9H_{10}O_3$ (24)	Navabhatra *et al.*, 2022
Acetone extract	$C_{33}H_{34}O_8$ (16), $C_{34}H_{36}O_9$ (17), $C_{24}H_{28}O_4$ (18), $C_{23}H_{26}O_4$ (19), $C_{11}H_{14}O_4$ (20), $C_{12}H_{16}O_3$ (21)	Musdja, 2021

Qualitative Pharmacological Properties of Zingiber montanum

Zingiber montanum has been investigated for its various pharmacological activities and has been reported to contain essential oils, extracts, and bioactive compounds (Priyadarshini *et al*., 2023). These include antioxidant, anticancer, antibacterial, antimalarial, immunomodulatory, anti-obesity, and antihypertensive properties of MAPs, as well as remarkable therapeutic potential in the treatment of depression and neurological disorders.

Numerous studies have emphasised the therapeutic value of such bioactive compounds, with the potential to prevent or treat disease (Pulukadang *et al*., 2024; Thepthong *et al*., 2023). The subsequent sections provide a thorough exploration of these pharmacological effects, elucidating the underlying mechanisms of action and potential implications for medicinal and pharmaceutical development, as shown in Figure 2.

Figure 2: *Qualitative Pharmacological Properties of Zingiber montanum*

Antioxidant Activity of Zingiber montanum

The antioxidant activity of *Z. montanum* has been evaluated using multiple chemical and biological systems. Experimental findings indicate that both crude extracts and isolated compounds exhibit radical-scavenging capacity, lipid peroxidation inhibition, and modulation of redox balance (Thepthong *et al*., 2023). However, reported efficacy varies according to extraction solvent, phytochemical profile, and assay design, underscoring the influence of methodological variability on outcome interpretation. Solvent-partition studies demonstrate that antioxidant performance is polarity-dependent (Allaq *et al*., 2025). Non-polar and semi-polar fractions showed greater hydrogen peroxide scavenging activity, whereas moderately polar extracts exhibited stronger DPPH radical neutralisation (Indrianingsih & Prihantini, 2018). Similarly, acetone-derived rhizome constituents inhibited lipid hydroperoxide formation in thiocyanate assays, supporting their capacity to disrupt oxidative chain reactions (Thepthong *et al*., 2023). These variations reflect differential phytochemical distribution rather than inconsistencies in intrinsic plant activity. Curcuminoids and phenylbutenoids are consistently identified as major contributors to antioxidant effects (Gundom *et al*., 2025). Essential oil components, including terpinen-4-ol and sabinene, have demonstrated attenuation of intracellular reactive oxygen species in monocyte models, suggesting biological relevance beyond cell-free assays (Devkota *et al*., 2021).

Nevertheless, inter-study comparison remains limited due to heterogeneity in assay conditions, concentration ranges, and reporting standards (Singharach *et al*., 2020). In vivo evidence remains comparatively scarce. Curcuminoid-enriched rhizome extracts enhanced endogenous superoxide dismutase activity in diet-induced oxidative stress models, indicating systemic redox modulation (Alolga *et al*., 2022; Mahfudh *et al*., 2024). Phenylbutanoid derivatives also suppressed nitric oxide production in activated macrophages, suggesting interaction between antioxidant and inflammatory pathways (Onkum *et al*., 2021).

Anticancer Activity of Zingiber montanum

The anticancer potential of *Z. montanum* has been investigated across multiple experimental cancer models, with accumulating evidence supporting cytotoxic, anti-metastatic, and multidrug resistance (MDR)-modulating activities (Panyajai *et al*., 2022; Soumya *et al*., 2023). These bioactivities are primarily attributed to phenylbutenoids, curcuminoids, and structurally related diarylheptanoids isolated from the rhizome (Taechowisan *et al*., 2018). Structural features, including methoxy substitution patterns, conjugated double bonds, and stereochemical configuration, appear to influence biological potency. However, variability in extraction methods and compound isolation procedures contributes to inconsistent reporting of efficacy (Júnior *et al*., 2025). Solvent-derived fractions, particularly chloroform and hexane extracts, have demonstrated cytotoxic activity against gastric, lung, breast, and fibrosarcoma cancer cell lines (Hassan *et al*., 2019). Mechanistic investigations reveal that these compounds induce G_0/G_1 phase cell cycle arrest by downregulating cyclins and cyclin-dependent kinases, accompanied by upregulation of p21 expression, suggesting modulation of cell cycle checkpoint regulation rather than nonspecific cytotoxicity (Khan *et al*., 2022; Rizzotto *et al*., 2021). Apoptosis induction represents a central mechanism underlying anticancer activity. Phenylbutenoid dimers have been shown to trigger S-phase arrest, DNA fragmentation, mitochondrial cytochrome c release, and activation of caspases 3/7 and 9. Concurrent modulation of pro- and anti-apoptotic proteins, including Bax and Bcl-2, supports involvement of the intrinsic mitochondrial pathway (Tan *et al*., 2018). Nevertheless, these mechanistic insights remain limited to selected *in vitro* cell models and lack confirmatory *in vivo* validation (Devkota *et al*., 2021). Beyond direct cytotoxicity, Z. Montanum demonstrates the capacity to modulate multidrug resistance by inhibiting P-glycoprotein (P-gp), a key efflux transporter responsible for chemoresistance. Hexane and chloroform fractions enhance the intracellular accumulation of daunomycin in resistant uterine and breast cancer cells, with activity comparable to that of established reference inhibitors in certain models (Tia *et al*., 2025; Várkonyi *et al*., 2025). Structure-activity analyses further suggest that methoxy substitution patterns and enantiomeric configuration significantly influence P-gp inhibitory potency, indicating stereoselective interaction with drug transport systems (Laiolo *et al*., 2021). Anti-invasive properties have also been reported. Selected phenylbutenoids suppresses invasion of fibrosarcoma cells while maintaining relatively low cytotoxicity, suggesting potential dissociation between antiproliferative and anti-metastatic mechanisms (Han *et al*., 2021). Collectively, the available evidence supports the anticancer potential of *Z. montanum* through multiple mechanisms, including cell cycle arrest, mitochondrial apoptosis, MDR reversal, and invasion suppression (Al-Amin *et al*., 2020; Rajabi *et al*., 2021).

Antibacterial Activity of Zingiber montanum

The antibacterial properties of *Z. montanum* have been extensively examined, with essential oils and solvent fractions showing efficacy against both Gram-positive and Gram-negative bacteria Figure 3. Observed potency is strongly influenced by extraction strategy, chemical profile, and bacterial susceptibility.

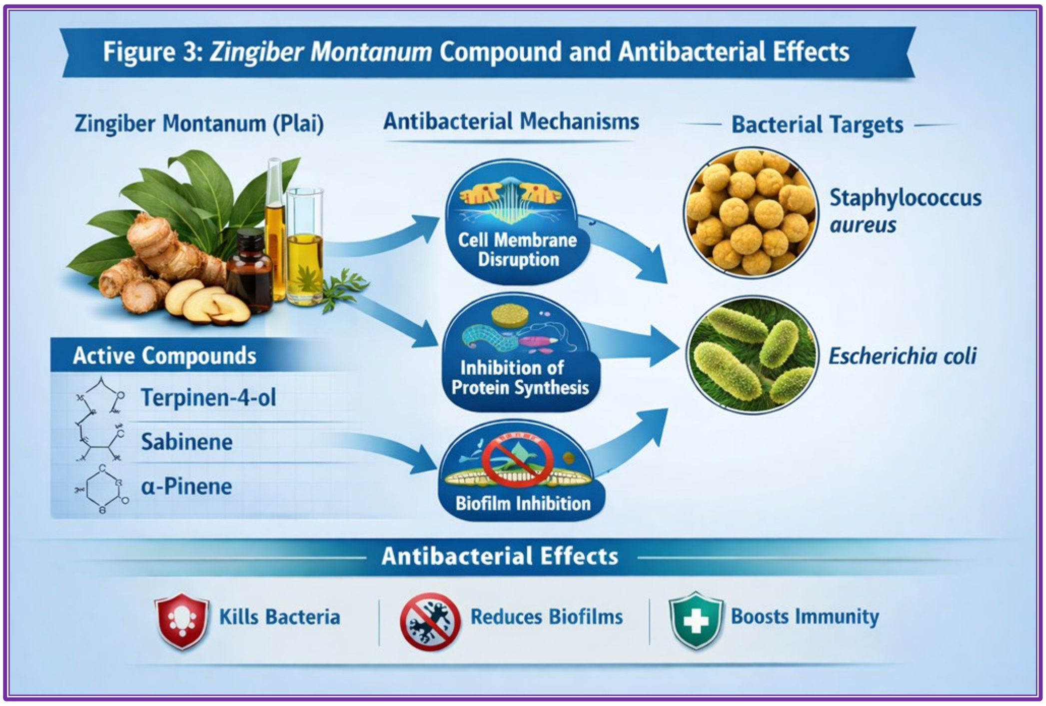

Figure 3: *Zingiber montanum Compound and Antibacterial Effects*

Comparative analyses indicate that chloroform fractions generally outperform methanolic extracts, suggesting that semi-polar to non-polar constituents contribute substantially to antimicrobial effects (Yongkhamcha *et al*., 2024). Rhizome-derived oils display broad-spectrum inhibition against enteric pathogens, including *Shigella flexneri and K. pneumoniae* (Sulieman *et al*., 2024). Expanded screenings further confirmed inhibition across diverse pathogenic species, with pronounced effects against *Bacillus subtilis, E. coli*, and *S. typhi* (Noshad *et al*., 2021). Importantly, efficacy against multidrug-resistant organisms, such as Acinetobacter baumannii, underscores its potential clinical relevance (Zeshan *et al*., 2023). Chemical investigations attribute these effects primarily to terpenoids, including sesquiterpenes and monoterpenes such as terpinen-4-ol, γ-terpinene, sabinene, and β-phellandrene (Siddique *et al*., 2019; Verma *et al*., 2018). Variations in terpinen-4-ol content appear to correlate with potency, supporting a compositional effect. Oils enriched in this constituent demonstrate bactericidal performance against clinically relevant strains of *S. aureus*, *S. pyogenes*, *P. aeruginosa*, and *P. acne* (Septama *et al*., 2023). Beyond membrane-targeting terpenoids, zerumbone and related sesquiterpenes contribute additional antimicrobial mechanisms. Zerumbone inhibits *methicillin-resistant Staphylococcus aureus* (MRSA) and other resistant strains, suggesting interference with resistance-associated pathways (Albaayit *et al*., 2022; Ashraf *et al*., 2019). It also reduces biofilm formation and modulates efflux-related resistance mechanisms, including suppression of BmeB12 expression in Bacteroides fragilis. These findings indicate that the effects extend beyond direct bactericidal action to include resistance attenuation and biofilm control (Kim *et al*., 2019). Although consistent *in vitro* findings, interpretation remains constrained by methodological heterogeneity. Most studies rely on disc diffusion or broth dilution assays without standard chemical fingerprinting (Verma & Balekar, 2023). Cross-extraction comparisons are limited, and molecular targets associated with membrane disruption, efflux modulation, or quorum sensing remain insufficiently defined. Moreover, *in vivo* validation and safety assessments are scarce, restricting translational conclusions (Uddin *et al*., 2024).

Antimalarial Efficacy of Zingiber montanum

Evidence supporting the antimalarial potential of *Z. montanum* remains limited and is currently confined to a single murine Plasmodium berghei model demonstrating dose-dependent suppression of parasitemia (Andika, 2018). Although these results confirm biological activity *in vivo*, the lack of mechanistic clarification, active constituent isolation, and pharmacokinetic characterisation substantially weakens translational credibility. In the context of escalating resistance among Plasmodium species (Otuu *et al*., 2020). The therapeutic positioning of *Z. montanum* cannot be justified without standardised extract validation and comparative benchmarking against established antimalarial agents (Ekasari *et al*., 2021; Phuwajaroanpong *et al*., 2025). The experience with antimalarial drug repurposing further underscores the need for rigorous validation before clinical extrapolation. Despite early *in vitro* antiviral activity, chloroquine and hydroxychloroquine ultimately demonstrated inconsistent clinical benefit and raised significant safety concerns (Cortegiani *et al*., 2020). Although the terpenoid- and flavonoid-rich phytochemical profile of *Z. montanum* provides a theoretical foundation for antiviral investigation, no direct antiviral screening, molecular docking, or mechanistic pathway analyses have been reported (Acharya & Satpathy, 2025; Musdja, 2021). As such, antiviral claims remain speculative and unsupported by empirical validation. Future investigations must prioritise defined molecular targets, reproducible chemical fingerprinting, and rigorously designed preclinical models before therapeutic relevance can be meaningfully assessed.

Immunomodulatory Efficacy of Zingiber montanum

Emerging evidence indicates that phenylbutenoid derivatives isolated from *Z. montanum* (syn. *Z. cassumunar*) exert measurable immunomodulatory effects under controlled *in vitro* conditions (Gundom *et al*., 2025). Exposure to three structurally distinct derivatives enhanced macrophage-mediated phagocytosis of *Staphylococcus epidermidis*, with one analogue showing superior potency, suggesting a structure-dependent immunomodulatory effect. However, the absence of signalling pathway analysis, standardised dose response evaluation, and molecular target identification limits mechanistic insight (Gundom *et al*., 2025; Adhila *et al*., 2019) reported concentration-dependent enhancement of macrophage and lymphocyte activity following administration of rhizome extract, with peak responses observed at higher concentrations. While these results indicate immunostimulatory potential, reliance on spectrophotometric assays without complementary molecular or gene expression validation restricts mechanistic resolution. Furthermore, the relative contribution of individual phytoconstituents within the crude extract remains unclear, preventing precise attribution of biological activity. The evaluation was expanded to include nitric oxide production, reactive oxygen intermediates, and cytokine profiling in macrophage cultures. Elevated oxidative intermediates alongside reduced nitric oxide levels suggest immunoregulatory modulation rather than nonspecific activation. Concurrent upregulation of anti-inflammatory cytokines supports the possibility of balanced immune signalling. Nonetheless, conclusions remain constrained by exclusive dependence on *in vitro* macrophage systems, without corroborating *in vivo* studies or toxicity assessment (Mahfudh *et al*., 2020).

Anti-Hypertensive and Anti-Obesity Potential of Zingiber montanum

Anti-obesity and antihypertensive effects of zerumbone and *Z. montanum* have been investigated in experimental models. Evidence suggests lipid-lowering activity in hyperlipidemic mice, potentially mediated through inhibition of HMG-CoA reductase, a key enzyme in cholesterol biosynthesis (Saad, 2024). These findings indicate possible modulation of lipid metabolism and metabolic regulation. In a rat model, animals were allocated to control, vehicle, simvastatin-treated, and extract-treated groups, receiving graded doses of rhizome extract Figure 4. The design enabled comparative evaluation of metabolic effects relative to a standard lipid-lowering agent.

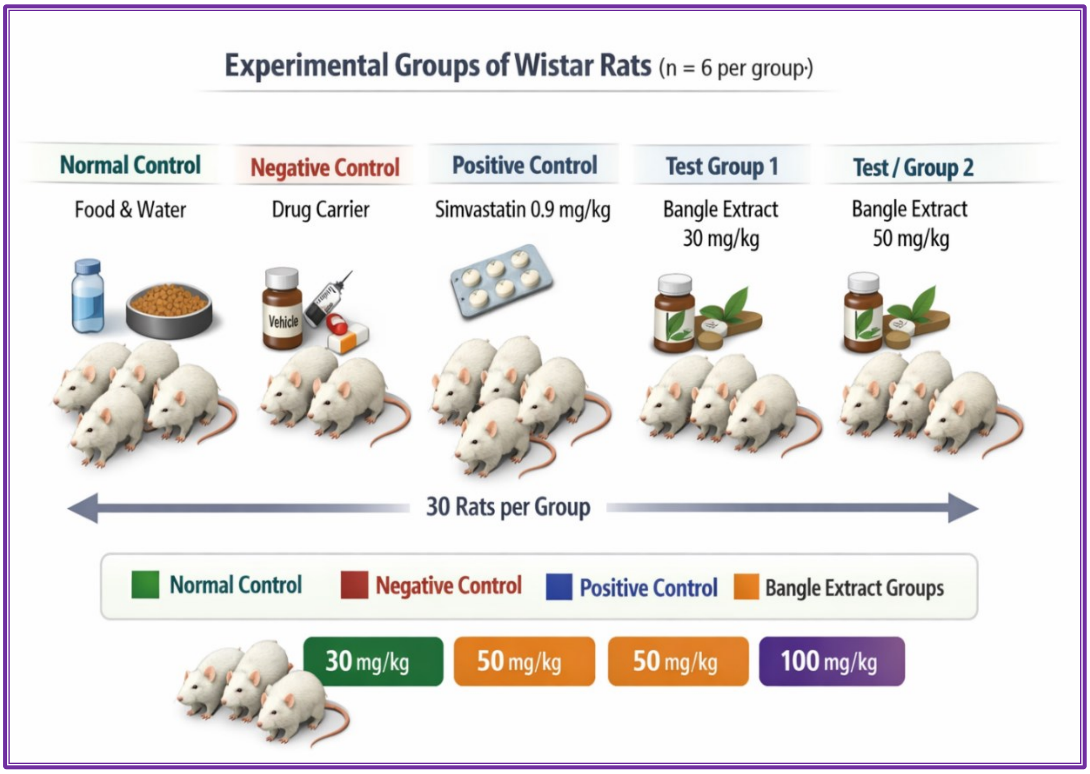

Figure 4: *The Experiment, Six Groups of 30 Wistar*

Induction of hyperlipidaemia through fructose supplementation produced marked alterations in lipid parameters, providing a controlled platform for assessing metabolic modulation (Hasimun *et al*., 2019). Administration of *Z. montanum* extract resulted in significant reductions in total cholesterol, triglycerides, and LDL levels, accompanied by elevated HDL concentrations relative to controls. Moreover, dose-dependent suppression of hepatic HMG-CoA reductase activity indicates direct interference with cholesterol biosynthesis (Musdja, 2021; Sajak *et al*., 2021). These findings collectively demonstrate a measurable regulatory effect on lipid metabolism rather than a nonspecific metabolic response. The anti-obesity potential has been further substantiated by pancreatic lipase inhibition assays (Sayed *et al*., 2023). Ethanolic rhizome extract exhibited superior inhibitory activity compared with reference controls under standardised conditions (Thepthong *et al*., 2023). This enzymatic suppression provides a plausible mechanistic basis for reduced dietary fat absorption and subsequent attenuation of lipid accumulation. Comparative analyses with other botanical extracts reinforce the relative potency of *Z. montanum* in this context (Paramita *et al*., 2018). Taken together, current evidence supports a dual mechanistic framework involving cholesterol synthesis inhibition and digestive lipase suppression (Musdja, 2021; Omari & Alkhalil, 2024). While these outcomes strongly suggest metabolic regulatory capacity, the predominance of preclinical models and limited pharmacokinetic characterisation constrain definitive therapeutic positioning. Rigorous mechanistic mapping, long-term safety evaluation, and controlled translational studies remain essential before clinical relevance can be established (Mehta *et al*., 2025; Tian *et al*., 2025).

Dermatological Activities of Zingiber montanum

Dermatological investigations of *Z. montanum* have identified phenylbutenoid derivatives with measurable effects on melanogenesis. Isolation of (E)-4-(3,4-dimethoxyphenyl) but-3-en-1-ol revealed stimulation of melanin synthesis through activation of ERK and p38 signalling pathways and increased tyrosinase expression via USF-1 modulation in B16-F10 melanoma cells (Han *et al*., 2021; Park *et al*., 2015). Hyperpigmentation observed in guinea pig models further supports targeted melanogenic activity *in vivo* (Dai *et al*., 2022).

Fraction-based evaluation of rhizome extracts demonstrated antioxidant, anti-inflammatory, and collagen-enhancing properties, with the ethyl acetate fraction showing superior performance relative to less polar extracts (Han *et al*., 2021; Hassan *et al*., 2019). Compound-level analysis identified specific constituents that significantly increased collagen secretion in human dermal fibroblasts, indicating relevance for skin regeneration strategies (Navabhatra *et al*., 2022). Related observations in other Zingiber species have shown protection against oxidative stress and stimulation of dermal papilla cell proliferation; however, extrapolation to *Z. montanum* requires cautious interpretation due to phytochemical variability across species (Ajao & Sadgrove, 2024; Devkota *et al*., 2021).

Conclusion

Zingiber montanum demonstrates pronounced phytochemical complexity, characterised by phenylbutenoids, curcuminoids, and terpenoid-rich essential oils. Experimental investigations consistently associate these constituents with redox modulation, cytotoxic and anti-metastatic responses, antimicrobial and antibiofilm effects, immune regulation, metabolic enzyme inhibition, and dermatological relevance, as well as limited *in vivo* antimalarial observations. Several isolated compounds exhibit defined mechanistic actions, including modulation of cell cycle checkpoints, activation of mitochondrial apoptotic pathways, interference with multidrug resistance transporters, inhibition of cholesterol biosynthesis, and suppression of pancreatic lipase activity. Despite these mechanistic indications, the current evidence base remains predominantly laboratory-derived and preclinical in scope. Variability in plant origin, extraction methodology, compound characterisation, and reporting standards constrain reproducibility and limits cross-study comparability, while pharmacokinetic behaviour, toxicological profiling, and long-term safety evaluation remain insufficiently addressed. Clinical validation has not yet been established. Advancement toward credible biomedical or industrial application, therefore, requires chemotype-standardised metabolomic profiling, validated molecular target mapping, integrated pathway analysis, and rigorously defined dose–response frameworks supported by robust animal experimentation and well-designed human trials. Until systematic validation is achieved, therapeutic positioning should be regarded as biologically plausible but not clinically substantiated. This synthesis delineates current evidentiary boundaries and defines strategic priorities for future phytopharmaceutical and industrial research development.

Conflicts of Interest

The authors declare that they have no competing interests.

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