



Medicinal Chemistry of Aloe Vera: Bioactive Constituents and Therapeutic Applications – A Review

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ABSTRACT

Aloe vera stands as a cornerstone of phytotherapy, esteemed across cultures for its versatile healing properties. This comprehensive review examines the extensive medicinal potential of *Aloe vera*, detailing its therapeutic applications and the pharmacological mechanisms of its bioactive constituents. The plant's efficacy is derived from a complex phytochemical profile, encompassing anthraquinones, polysaccharides, enzymes, vitamins, and minerals found in its leaf gel and latex. We systematically evaluate its core pharmacological activities: significant antioxidant capacity linked to high phenolic and flavonoid content; anticancer potential via induction of apoptosis and selective cytotoxicity against cell lines such as MCF-7 and HepG2; potent anti-inflammatory effects mediated through the inhibition of cyclooxygenase pathways and inflammatory mediators; and broad-spectrum antimicrobial action against bacterial and fungal pathogens. Evidence also supports its roles in wound healing, antidiabetic activity, and immunomodulation. The findings affirm *Aloe vera*'s value as a multifunctional natural therapeutic agent with applications in nutraceuticals, dermatology, and complementary medicine. However, translating this potential into standardized clinical practice requires further rigorous human trials, precise characterization of active compounds, and the development of optimized delivery systems. This review underscores *Aloe vera*'s enduring significance and charts a course for its future integration into evidence-based therapeutic strategies.

Keywords: *Aloe Vera*, Herbs, Antioxidant, Antidiabetic, Antimicrobial, Anticancer, Medicinal plants



INTRODUCTION

Herbal medicines, sourced from different parts of plants including leaves, roots, and flowers, have been integral to traditional healthcare practices for generations. As natural therapeutic agents, herbs have provided numerous health benefits [1]. *Aloe vera* (L.) Burm.f., belonging to the Asphodelaceae family, is one of the oldest and most widely used medicinal herbs, known as Ghritkumari, and is employed in Ayurvedic, homeopathic, and allopathic medicine [2]. *Aloe vera* contains a variety of vitamins, minerals, enzymes, amino acids, natural sugars, and bioactive compounds that may exhibit anti-inflammatory and antimicrobial effects. The combined action of these constituents is thought to underlie its therapeutic properties [3]. *Aloe vera* is widely cultivated for cosmetics and nutraceuticals. Its leaf yields yellow latex (aloe juice) and nutrient-rich pulp, mostly water, containing vitamins, minerals, enzymes, and polysaccharides, with acemannan being the main bioactive compound [4]. *Aloe vera* is a rich source of useful secondary metabolites [5]. *Aloe vera* shows numerous medicinal activities, such as anti-inflammatory, antimicrobial, antioxidant, wound healing, antidiabetic, and immunomodulatory effects [6]. Numerous clinical studies have investigated *Aloe vera*'s therapeutic effects, with ongoing research confirming traditional uses, clarifying mechanisms, and exploring its role in disease prevention and treatment [7].

This review objective is to summarize current research on *Aloe vera* as a natural source of antioxidants, anti-inflammatory, anticancer, and antimicrobial agents, highlighting its medicinal and therapeutic potential.

Medicinal Potential of Aloe Vera

Aloe vera is a perennial herb, named after the Arabic word *allaeh*, meaning 'brilliant bitter substances. Its leaves have long been used for food, cosmetics, and medicinal purposes, though the scientific basis of these benefits is not fully understood. The plant consists mainly of gel and latex, with the bitter yellow latex (also called aloe juice or sap) accounting for 20–30% of the leaf's weight [8]. In Ayurveda, *Aloe vera* (Kumari, 'Young Girl') is valued for rejuvenating effects, female reproductive support, and balancing Vata, Pitta, and Kapha. It is used internally for digestive, parasitic, and menstrual issues, and topically for skin disorders [9]. Research shows that *Aloe vera* consists of two distinct parts with different compositions and therapeutic properties. The inner parenchymal tissue produces clear, tasteless gel (mucilage) used topically and for minor therapeutic applications. The outer pericyclic tubules produce bitter yellow latex with strong laxative effects, commercially used for systemic catharsis [10]. Research supports its use in cosmetics, food, and medicine for humans and animals due to its wound healing, anti-inflammatory, immunomodulatory, antidiabetic, antioxidant, antimicrobial, antiviral, laxative, and antitumor properties [11]. *Aloe vera* is renowned for its therapeutic benefits, with over 200 bioactive compounds in its leaf gel responsible for antibacterial, antitumor, antidiabetic, and immune-supporting effects. Although the genus has 400+ species, only a few, including *Aloe vera*, are widely used. This review focuses on the gel's composition and its bioactive phytochemicals that promote health and prevent disease [12].

Overall, this study indicates *Aloe vera* is a medicinal herb with gel and latex that have distinct therapeutic properties. Its gel contains over 200 bioactive compounds responsible for antibacterial, anti-inflammatory, antitumor, antidiabetic, and immune-supporting effects.

Antioxidant Activity and Bioactive Phytochemicals in *Aloe vera*

Phytochemicals are naturally occurring plant compounds that influence the flavor, color, and aroma of foods. These bioactive molecules such as polyphenols, terpenes, and sulfur- or nitrogen-containing compounds exhibit antioxidant, anti-inflammatory, antiviral, and anticancer activities, contributing to disease prevention and overall health [13,14]. Bioactive compounds in *Aloe vera* exhibit anti-inflammatory effects, support metabolism, and help maintain healthy blood sugar, cholesterol, and body weight. Topically, it aids skin regeneration, and its antioxidants enhance food shelf-life, leading to wide use in cosmetics, pharmaceuticals, and food. This work highlights its antioxidant potential and health benefits. [15] Phytochemical analysis of *Aloe vera* revealed the presence of tannins, saponins, alkaloids, flavonoids, anthraquinones, terpenoids, steroids, and phlobatannins, with higher levels in ethanol extracts except for anthraquinones. These findings support its medicinal potential and highlight the need for further studies on individual phytochemicals [16]. *Aloe vera* (*A. vera*), a widely used medicinal plant, is



commonly employed worldwide for the prevention or treatment of cancer, metabolic disorders, cardiovascular diseases, and skin conditions [17]. *Aloe vera* gel has antioxidant properties but is hard to consume fresh. Powdered aloe prepared with 5% maltodextrin or gum arabic and oven-dried at 50°C showed the highest antioxidant activity (RSA 15.01% and 14.44%) with IC₅₀ values of 239.20 and 256.88 mg/ml, respectively, while higher filler amounts reduced activity [18]. Methanol, ethanol, and water extracts of *Aloe vera* gel were analyzed for phenolic, flavonoid, and antioxidant activity. Ethanol and methanol extracts had higher phenolic (25.28 and 23.80 mg GAE/g) and flavonoid content (28 and 18.56 mg QE/g) than aqueous extracts. Methanol extract showed the strongest DPPH scavenging (69.97%), followed by ethanol (67.77%) and water (45.63%), while ethanol had higher reducing power. Polyphenols, flavonoids, and tannins contributed to antioxidant activity, and solvent polarity influenced extract composition [19]. *Aloe vera* gel, rich in vitamins and minerals, enhances the antioxidant and nutritional properties of mango juice blends (7.5–25%). Higher Aloe content improved antioxidant activity, phenols, and flavonoids, though sensory acceptability decreased at 25%. In diabetic rats, Aloe-mango juice reduced serum glucose, cholesterol, liver enzymes, and oxidative stress. These findings support its use to boost juice nutrition and as a dietary aid for diabetics [20]. *Aloe vera* juice has antioxidant properties and potential health benefits. Aloe Jello made with the juice showed good sensory acceptability and stable pH, water activity, and color. These results support its use in food products and nutraceuticals to promote health [21]. Ethanolic *Aloe vera* gel extracts exposed to gamma irradiation (10–100 kGy) showed increased antioxidant activity, peaking at 40 kGy, due to the formation of a new compound (m/z = 132). The enhanced activity remained at higher doses, suggesting gamma irradiation can improve aloe's antioxidant potential for use in food, cosmetics, and pharmaceuticals [22]. HPLC–MS analysis of *Aloe vera* identified eight bioactive compounds. Acetone, methanol, and their fractions showed antibacterial activity against multiple pathogens (MIC 1.25–10 mg/mL). Chloroform and acetone extracts exhibited strong antioxidant and photoprotective effects, while acetone, chloroform, and ethyl acetate fractions showed cytotoxicity against brine shrimp, demonstrating broad therapeutic potential [23]. *Aloe vera* leaves from Nepal were dried, powdered, and extracted with methanol and ethanol to assess phytochemicals and antioxidant activity. Methanol extracts were richer in flavonoids and tannins, while ethanol extracts had higher phenols. Fresh leaves contained chlorophylls and carotenoids and showed strong antioxidant activity [24]. *Aloe vera*, rich in compounds like aloe-emodin and acemannan, shows anti-inflammatory, antimicrobial, and wound-healing properties. While preclinical studies demonstrate anti-cancer, digestive, and skin protective effects, more clinical trials are needed to evaluate its metabolites in human health [25]. *Aloe vera* has been traditionally used topically and orally. This study compared the antioxidant and immunomodulatory effects of inner leaf juice and decolorized leaf preparations, which are purified to remove latex, using in vitro assays [26]. *Aloe vera* flowers contain diverse phenolic compounds, with vanillic acid being predominant. Ethanol extracts exhibited strong antioxidant activity, preventing linoleic acid oxidation and DNA damage, and enhancing liver antioxidant enzymes in mice. These findings suggest *Aloe vera* flowers are a promising natural source of antioxidants [27].

Exploring the Anticancer Properties of *Aloe vera*

Cancer continues to be a major global health issue, impacting people worldwide. Medicinal plants, with their antioxidant and tumor-suppressing properties, present promising avenues for cancer prevention and therapy [28]. Bioactive compounds of *Aloe vera* inhibit tumor progression by modulating growth, survival, invasion, angiogenesis, and metabolic pathways. They affect various cancer types and interfere with key pro-oncogenic mechanisms [29]. *Aloe vera* plays a significant role in alternative therapy due to its antioxidant and cytotoxic properties. In vitro studies showed that *Aloe vera* gel inhibits HepG2 cancer cells in a dose- and time-dependent manner, while promoting proliferation in healthy L929 fibroblasts. Its moderate antioxidant activity further supports its potential as a complementary therapeutic agent for promoting cell health and targeting cancer cells [30]. *Aloe vera* crude extract (ACE) reduces viability of MCF-7 and HeLa cancer cells via apoptosis, with minimal effect on normal cells. ACE modulates cyclin D1, CYP1A1/1A2, bax, and p21, and shows synergistic growth inhibition when combined with cisplatin. These findings highlight *Aloe vera* as a promising plant-derived anticancer agent [31]. Ethanolic extracts of *Aloe vera* leaves showed strong anticancer activity against HepG2, HeLa, and A549 cells in MTT assays. The results suggest the presence of bioactive compounds with antiproliferative potential, highlighting *A. vera* as a promising source for anticancer agents and warranting further compound characterization



[32]. *Aloe vera* (AV) protein extract was tested for anti-proliferative effects on human neuroblastoma cell lines. In IMR-32 cells, AV treatment significantly reduced viable cell numbers by 1.98-fold at day 2 and 1.33-fold at day 5, decreased Ki-67(+) cells by 13%, and suppressed CCND2 mRNA expression by day 1. These results suggest that AV protein extract inhibits neuroblastoma cell proliferation, potentially through downregulation of CCND2 [33]. *Aloe vera* exhibits anticancer activity against 3D liver tumor spheroids in a microfluidic model. HepG2 spheroids treated with *Aloe vera* showed reduced viability and induced apoptosis, with IC₅₀ values of 31.25 mg/mL in 3D cultures. This study highlights *Aloe vera*'s potential as a natural anticancer agent and demonstrates the utility of microfluidic platforms for drug testing [34]. *Aloe vera*, known for its wound-healing and anti-inflammatory effects, was tested for anti-cancer activity in HT29 colon cancer cells. Processed *Aloe vera* gel (5–20%) was applied, and cell viability (MTT assay) and P53/BCL2 expression (ICC) were assessed. At 10% gel, cell proliferation increased, P53 decreased, and BCL2 remained unchanged. These results suggest *Aloe vera* may affect tumor suppressor pathways in colon cancer, warranting further study [35]. Hematite nanoparticles encapsulated with *Aloe vera* bioactives (ALE- α -Fe₂O₃NPs) showed anticancer activity against MCF-7 cells, reducing viability, disrupting mitochondrial function, increasing ROS, and inducing DNA damage and apoptosis. Apoptotic genes (p53, bax, caspase-3, caspase-9) were upregulated, highlighting their potential as a safe, cost-effective, and scalable anticancer nanoplatform [36]. *Aloe vera* (L.) Burm. f. is known for its skin, antioxidant, and anticancer benefits. This study tested leaf extracts and aloe emodin (AE) on skin cancer cells. All extracts showed selective cytotoxicity: AVG induced apoptosis in B16F10 melanoma cells, while AE caused necrosis. AVG delayed apoptosis in normal NIH3T3 cells, supporting its traditional use as a skin healer and highlighting its potential in anticancer drug development [37]. Many plant-derived compounds have anticancer properties. *Aloe vera* extract was tested on HL60 and MCF-7 cancer cells, showing significant, dose- and time-dependent reductions in viability. IC₅₀ values were 1 mg/mL (HL60) and 0.5 mg/mL (MCF-7). Morphology and TUNEL assays confirmed apoptosis, while normal cells were unharmed. These results suggest *Aloe vera* extract as a potential selective chemotherapeutic agent [38].

Phytotherapy in Focus: Anti-Inflammatory Activity of *Aloe vera*

Phytochemicals from plants act as important anti-inflammatory agents, with both crude extracts and isolated compounds shown to effectively modulate inflammatory responses [39]. Aqueous, chloroform, and ethanol extracts of *Aloe vera* gel showed anti-inflammatory activity in carrageenan-induced paw edema and neutrophil migration in rats. Aqueous and chloroform extracts reduced both edema and neutrophil infiltration, while the ethanol extract only inhibited neutrophil migration. The aqueous extract also suppressed prostaglandin E₂ production, suggesting cyclooxygenase inhibition. These findings indicate that *Aloe vera* exerts anti-inflammatory effects, likely via the arachidonic acid pathway [40]. *Aloe vera* gel extract exhibits significant acute anti-inflammatory activity and enhances immune responses in rats, without ulcerogenic effects. While effective in carrageenan-induced paw edema, it shows no activity in chronic inflammation models, suggesting it is a safe alternative to conventional NSAIDs for acute inflammation [41]. Crude *Aloe vera* gel reduces carrageenan-induced paw edema in rats, demonstrating significant acute anti-inflammatory and protective effects. Oral administration showed no cytotoxicity on macrophages and spleenocytes. These findings support its potential as a safe, natural alternative for managing acute inflammation [42]. Aqueous *Aloe vera* extract inhibited MMP-9 activity in peripheral blood mononuclear cells in vitro. Cytotoxicity was negligible, and both gelatin zymography and RT-PCR confirmed a concentration-dependent reduction in MMP-9 production, highlighting *Aloe vera*'s potential as an anti-inflammatory agent [43].

Antimicrobial Potential of *Aloe Vera*

Plant-derived compounds with strong antimicrobial properties are increasingly being explored as potential treatments for bacterial, fungal, viral, and parasitic infections. Plant extracts remain a valuable source for the development of effective antimicrobial agents [44]. The antimicrobial potential of *Aloe vera* leaf extracts was evaluated against bacteria and fungi. Hexane extract was most effective against *S. marcescens*, while TLC-bioautography pinpointed compounds at R_f 0.65 with strong activity. Phytochemical profiling confirmed that multiple bioactive compounds contribute to the observed antimicrobial effects [45]. *Aloe vera* extracts exhibited



dose-dependent antibacterial and antifungal activity. Methanol extract demonstrated maximum inhibition, petroleum ether moderate, but neither surpassed the effectiveness of Gentamycin [46]. *Aloe vera* gel extracts demonstrated antibacterial activity against common skin pathogens, including *Escherichia coli*, *Shigella*, *Salmonella* spp., and *Staphylococcus aureus*. Ethanol extracts of both leaf and root showed the highest antimicrobial efficacy, while crude leaf and root extracts exhibited moderate activity. These findings suggest that *Aloe vera* ethanol extracts could complement conventional antibiotics in managing skin infections [47]. The study evaluated the antimicrobial potential of *Aloe vera* and its ability to decontaminate gutta-percha cones. Agar well diffusion showed inhibition zones of 24 mm (*E. coli*), 21 mm (*E. faecalis*), and 24 mm (*S. aureus*). Fresh gutta-percha cones treated with *Aloe vera* gel for 1 minute showed no microbial growth after 48 hours, indicating effective decontamination [48]. The antibacterial activity of various *Aloe vera* extracts was assessed against pathogenic bacteria. Distillate extract was most effective, and fractions 5–7 from boiled skin extract inhibited MRSA and *S. aureus* at ≤ 0.134 mg/ml. Protein expression analysis confirmed substantial alterations in bacterial proteins after treatment [49]. *Aloe vera* extracts have been applied to cotton fabrics to enhance antibacterial properties. Using pad-dry-cure methods with concentrations of 60–100% at 60–80°C, the extracts were attached to cotton via carboxylic acid cross-linking. Treated fabrics demonstrated antimicrobial activity against *E. coli* and *S. aureus*, and also improved odor control, softness, comfort, and washing durability [50].

Pharmacological Activities of *Aloe vera*

Table 1. Pharmacological Activities of *Aloe vera*

Activity	Pharmacological effect	References
Antioxidant	Methanol/ethanol extracts highest phenolic/flavonoid content; strong DPPH scavenging; improved antioxidant status	[15,22]
Anticancer	Dose-dependent cytotoxicity; apoptosis induction; selective for cancer cells; synergistic with cisplatin	[28-32]
Anti-inflammatory	Reduced edema, neutrophil migration, PGE ₂ ; acute anti-inflammatory and immunomodulatory; safe, non-ulcerogenic	[39,43]
Antimicrobial	Methanol/ethanol most active; inhibited MRSA, <i>E. coli</i> , <i>S. aureus</i> , fungi; effective in decontamination and textile application	[44,50]

Table 1 indicates *Aloe vera* exhibits a range of pharmacological activities. Its antioxidant properties are primarily attributed to methanol and ethanol extracts, which contain the highest levels of phenolics and flavonoids, show strong DPPH radical scavenging, and improve overall antioxidant status [15,22]. The anticancer potential of *Aloe vera* is demonstrated through dose-dependent cytotoxicity, induction of apoptosis, selective action against cancer cells, and synergistic effects when combined with cisplatin [28–32]. Anti-inflammatory effects include reduction of edema, inhibition of neutrophil migration, suppression of prostaglandin E₂, and enhancement of immune responses, with acute activity noted and without ulcerogenic effects [39,43]. *Aloe vera* also displays significant antimicrobial activity, with methanol and ethanol extracts showing the greatest efficacy against MRSA, *E. coli*, *S. aureus*, and various fungi, and proving effective in decontamination of gutta-percha cones and antibacterial finishing of textiles [44–50].

CONCLUSION

Aloe vera exhibits diverse pharmacological properties, including antioxidant, anticancer, anti-inflammatory, and antimicrobial activities. Its bioactive constituents, particularly in methanol and ethanol extracts, contribute to strong free radical scavenging, selective cytotoxic effects against cancer cells, modulation of inflammation, and inhibition of pathogenic microbes. *Aloe vera* gel and extracts demonstrate therapeutic potential in both topical and systemic applications with minimal toxicity, supporting immune function, wound healing, and even enhancing the antimicrobial properties of textiles and medical materials. These findings reinforce its traditional medicinal use and highlight its potential as a safe, natural, multifunctional therapeutic agent.



Further studies are needed to isolate and characterize the individual bioactive compounds in *Aloe vera* and clarify their mechanisms of action. Clinical trials are essential to confirm efficacy and establish safe, effective dosages for humans. Development of novel formulations, such as nano-encapsulated bioactives, functional foods, and antimicrobial biomaterials, could expand its applications. Investigating potential synergistic effects with conventional drugs may offer safer, cost-effective strategies for managing oxidative stress, inflammation, infections, and cancer.

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AUTHOR CONTRIBUTION

Manuscript written by Fakeha Shaikh under the guidance of Ashish Uzgare.

CONFLICT OF INTEREST

Authors declare no competing or conflict of interest.

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