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Review Article

Phytochemical Insights and Antimicrobial Potential of Acacia Nilotica (L.) Delile (Babul)

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Acacia nilotica (L.) Delile, commonly known as Babul, is a traditional medicinal tree of the Fagaceae family widely used in Ayurvedic and African folk medicine for its potent antimicrobial properties. Various parts of the plant—bark, leaves, pods, seeds, and gum—are rich in bioactive compounds such as tannins, flavonoids, phenolic acids, saponins, terpenoids, and alkaloids that contribute to its broad-spectrum antibacterial and antifungal effects. Methanolic and aqueous extracts of A. nilotica have demonstrated significant inhibition against Gram-positive bacteria, including Staphylococcus aureus, Bacillus subtilis, and Streptococcus pyogenes, as well as Gram-negative bacteria such as Escherichia coli, Pseudomonas aeruginosa, and Klebsiella pneumoniae. Antifungal activity has also been observed against Candida albicans and Aspergillus Niger. The antimicrobial mechanism is primarily attributed to the high tannin and flavonoid content, which disrupts microbial cell walls, inhibits protein and nucleic acid synthesis, and induces oxidative stress within microbial cells. Polyphenolic constituents such as catechin, gallic acid, and quercetin exhibit synergistic effects, enhancing membrane permeability and reducing bacterial adhesion and biofilm formation. Studies also indicate that A. militia extracts potentiate the effects of conventional antibiotics, suggesting their potential role in combating antimicrobial resistance. Overall, Acacia nilotica represents a promising natural source of antimicrobial agents, validated by both traditional use and modern pharmacological evidence. Further Possible spelling mistake found. Isolation, standardization, and toxicity evaluation are essential to advance its development into an effective. Possible spelling mistake found. Antimicrobial formulations.

Keywords: Acacia nilotica, Babul, Antimicrobial activity, Flavonoids, Tannins, Antibacterial, Antifungal, Polyphenols, Natural antibiotics.

INTRODUCTION

Acacia nilotica (L.) Delile, commonly known as Babul, the Indian Gum Arabic tree, or Kikar, is a member of the family Fabaceae (subfamily Mimosoideae). It is a medium-sized, thorny, perennial tree widely distributed throughout tropical and subtropical regions of Africa, the Middle East, and the Indian subcontinent. The tree is characterized by bipinnate compound leaves, fragrant yellow spherical flowers, and curved pods containing numerous seeds. It thrives in dry and semi-arid regions and plays an important ecological role by enriching soil fertility through nitrogen fixation [1]. Beyond its environmental importance, Acacia nilotica holds a prominent place in traditional medicine systems such as Ayurveda, Siddha, and Unani, where it is valued for its astringent, anti-inflammatory, and antimicrobial properties. Historically, different parts of Acacia nilotica—including bark, pods, leaves, seeds, and gum—have been used to manage ailments such as diarrhoea, cough, wounds, toothache, and infections of the skin and mucous membranes. The plant is also used in formulations for oral hygiene and wound healing due to its ability to inhibit microbial growth and promote tissue regeneration [2]. Phytochemical studies have revealed that Acacia nilotica is rich in bioactive compounds such as tannins, flavonoids, phenolic acids, alkaloids, glycosides, saponins, and terpenoids, which collectively contribute to its broad-spectrum antimicrobial activity. Tannins like catechin and

gallic acid are known to precipitate microbial proteins and disrupt cell wall integrity, leading to bacterial death. Flavonoids such as quercetin and rutin interfere with nucleic acid synthesis and energy metabolism, while saponins and terpenoids increase cell membrane permeability, resulting in leakage of intracellular materials [3]. These synergistic effects make Acacia nilotica extracts effective against both Gram-positive and Gram-negative bacteria, including Staphylococcus aureus, Escherichia coli, Klebsiella pneumoniae, and Pseudomonas aeruginosa, as well as fungal species such as Candida albicans and Aspergillus Niger. Several studies have demonstrated that ethanolic and methanolic extracts of Acacia nilotica bark exhibit significant zones of inhibition comparable to standard antibiotics, suggesting their potential as a natural antimicrobial agent [4]. Furthermore, the plant's antioxidant properties enhance its ability to combat oxidative stress during infections, while its astringent and anti-inflammatory actions promote wound healing [5]. Recent advances in phytochemical characterization using chromatographic and spectroscopic techniques (HPLC, GC-MS, LC-MS) have facilitated the identification of its active constituents, paving the way for formulation development in modern herbal therapeutics. In view of the increasing prevalence of antibiotic resistance, the exploration of Acacia nilotica as a natural source of antimicrobial compounds holds great pharmacological and clinical promise. Its rich phytochemical profile, proven traditional efficacy, and wide biological spectrum highlight its potential as a safe, affordable, and sustainable alternative for the treatment of infectious diseases [2].

Fig – acacia nilotica plant, leaves and flowers

Fig-Acacia nilotica plant, leaves, and flowers. Bark, seeds.

Vernacular names

Language	Common/Vernacular Names
English	Babul, Egyptian thorn, Indian gum Arabic tree
Hindi	Babul, Kiker, Babool
Marathi	Babhul
Gujarati	Baval, Desi Baval

Sanskrit	Babula, Sthira, Yajiniya, Dirghatulya
Tamil	Karuvelam, Karuvela Maram
Telugu	Nalla Tumma
Kannada	Karijali, Kaggali
Malayalam	Karuvelamaram
Punjabi	Kiker, Babool
Bengali	Babla
Urdu	Kiker, Babool
Arabic	Sant, Sayal
Spanish	Acacia del nilo

Taxonomical identification

- Domain**:** Eukaryota
- Kingdom: Plantae
- Sub-kingdom: Viridiplantae
- Phylum/Division: Tracheophyta (Angiospermae)
- Sub-phylum: Euphyllophytina
- Class: Magnoliopsida (Dicotyledons)
- Sub-class: Rosidae
- Order: Fabales
- Family: Fabaceae (Leguminosae)
- Subfamily: Mimosoideae
- Genus: Acacia
- Species: Acacia nilotica (L.) Delile
- Synonym: Acacia arabica (Lam.) Wild [1].

MACROSCOPY

Acacia nilotica (L.) Delile, commonly known as Babul, is a moderate-sized, thorny tree characterized by its spreading crown and rough, fissured bark. It typically attains a height of 5–20 meters and is well adapted to arid and semi-arid climates. The entire plant exudes a gum resin when injured, which is of considerable medicinal and industrial value [6].

Stem and Bark: The stem is erect, woody, and covered with dark grayish-brown to blackish bark that becomes deeply fissured with age. The bark thickness ranges from 0.5 to 1.5 cm, showing an external rough texture and an inner reddish-brown surface. When cut or scratched, the bark exudes a sticky, amber-coloured gum (commonly called Babul gum or gum Arabic). It possesses an acidic and slightly bitter taste. The younger branches are slender, angular, and pubescent, bearing a pair of short, sharp, straight thorns (5–7 mm) at each node [7].

Leaves: The leaves are bipinnate, alternately arranged, and bright green in colour. Each leaf measures 4–7.5 cm in length, consisting of 3–10 pairs of pinnae, each bearing 10–20 pairs of small leaflets. The leaflets are oblong or linear, about 2–4 mm long and 1 mm broad, with a smooth margin and a rounded apex. The leaves are exstipulate or occasionally have minute stipules, and the rachis often bears minute glands [8].

Flowers: The flowers of A. nilotica are small, golden-yellow, and fragrant, arranged in dense globular heads or spikes approximately 1–1.5 cm in diameter. Each inflorescence arises from the leaf axis or on terminal branches. The flowers are bisexual, actinomorphic, and pentamerous, possessing numerous bright yellow stamens that impart a soft appearance. The calyx is small and cup-shaped, while the corolla is funnel-shaped, with petals shorter than the stamens. Flowering usually occurs between February and June in India, depending on climatic conditions [9].

Fruits (Pods): The fruit is a flat, straight, or slightly curved pod, 7–15 cm long and 1.5–2 cm wide, containing 8–15 dark brown seeds separated by narrow constrictions between them, giving the pod a beaded appearance. When mature, the pods turn dark brown or black and do not split open easily. The pod surface is smooth, leathery, and slightly glossy [10].

Seeds: The seeds are hard, oval, or compressed, about 6–8 mm long, smooth, and dark brown in colour. Each seed is enclosed in a tough testa and is attached to the pod by a short funicle. The seeds contain fixed oil and proteins and are used traditionally in various therapeutic formulations [11].

Gum Exudate: The gum collected from incisions in the bark is a transparent to amber-coloured, brittle

solid that swells in water to form a viscous solution. It is nearly tasteless and odourless, soluble in hot water, and widely used as a demulcent, emulsifying agent, and stabilizer in pharmaceuticals.

Odor and Taste: The bark and pods have a characteristic astringent odour and bitter, slightly pleasant, astringent taste due to high tannin content.

Traditional and Ethnomedical Uses

Acacia nilotica is an important medicinal plant in Ayurvedic, Unani, and folk medicine, valued for its wide range of therapeutic properties.

1. Ayurvedic Medicine: Known as Babula; classified under Kashaya rasa (astringent). Used to balance Kapha and Pitta doshas. Bark decoction is used for diarrhoea, dysentery, sore throat, and leucorrhoea.

2. Unani Medicine: Called Kikar or Babool, regarded as a blood purifier and gum tonic. Gum (Gond Babool) is used as a demulcent and cooling agent in urinary and digestive disorders [14].

3. Folk and Tribal Uses: Bark and leaf paste applied to wounds, ulcers, and burns. Leaf decoction is used for cough, fever, and eye infections. Pods are used as an anthelmintic for intestinal worms [15].

4. Oral and Dental Care: Twigs used as natural toothbrushes (chewing sticks) for gum strengthening and prevention of gingivitis.

5. Dermatological Applications: Bark and gum are used externally for eczema, boils, and leprosy due to their antiseptic and astringent actions.

6. Respiratory and Reproductive Disorders: Bark infusion is used for bronchitis, throat infections, and menorrhagia [16].

Phytochemistry and Antimicrobial Activity Relevance of Acacia nilotica (L.) Delile

Acacia nilotica (L.) Delile, commonly known as the Babul or Indian Gum Arabic tree, is a member of the family Fabaceae (Leguminosae) and is recognized as one of the most pharmacologically important medicinal trees in tropical and subtropical regions. Every part of the plant—bark, leaves, pods, seeds, and gum—contains a diverse array of bioactive phytochemicals that contribute to its therapeutic properties, especially its broad-spectrum antimicrobial potential [1]. Traditionally used in Ayurvedic and Unani systems for treating infections, wounds, diarrhoea, and skin diseases, the plant has attracted extensive phytochemical and pharmacological research attention in recent decades [17]. The antimicrobial potential of A. nilotica is closely associated with its polyphenolic content, particularly tannins, flavonoids, and phenolic acids. These compounds not only inhibit microbial growth but also demonstrate antioxidant, anti-inflammatory, and cytoprotective activities, making the plant a strong candidate for development into natural antimicrobial formulations [2, 18].

1. Phytochemical Constituents:

Extensive phytochemical analyses of A. nilotica have revealed a wide range of secondary metabolites with distinct biological activities. The major classes of compounds include tannins, flavonoids, phenolic acids, alkaloids, saponins, terpenoids, sterols, and carbohydrates. The concentration and diversity of these compounds vary with the plant part, solvent, and geographical origin [7, 19].

1.1 Tannins: Tannins are the most abundant class of compounds in A. nilotica, particularly in the bark and pods. The plant contains up to 32% condensed tannins (proanthocyanidins), which are responsible for its characteristic astringent taste. These tannins include gallic acid, ellagic acid, catechin, epicatechin, and procyanidins. Tannins possess strong antimicrobial, antioxidant, and wound-healing properties. Their antimicrobial mechanism involves precipitation of microbial proteins, inhibition of extracellular enzymes, and complexation with polysaccharide layers of microbial cell walls, leading to cell lysis [2, 7, 20].

1.2 Flavonoids: Flavonoids are another dominant group of phytoconstituents. Major flavonoids reported in A. nilotica are quercetin, kaempferol, luteolin, catechin, epigallocatechin, and rutin. These polyphenolic compounds contribute to the plant's antioxidant, anti-inflammatory, and antimicrobial effects. Flavonoids act by disrupting microbial membranes, chelating metal ions, and inhibiting

nucleic acid synthesis. Their ability to scavenge free radicals also enhances immune response and tissue regeneration in infected tissues [19, 21].

1.3 Phenolic Acids and Polyphenols: The plant is rich in phenolic acids such as gallic acid, caffeic acid, chlorogenic acid, and ferulic acid, which have proven antimicrobial activity. These compounds interfere with microbial enzyme systems, leading to oxidative damage and suppression of pathogen growth [15, 22].

1.4 Alkaloids and Saponins: Acacia nilotica also contains moderate amounts of alkaloids (N-methyltyramine, tryptamine, and hordenine) and saponins, which exhibit surface-active and membrane-disrupting effects against bacteria and fungi. Saponins reduce surface tension and increase permeability of microbial membranes, enhancing leakage of intracellular components [23].

1.5 Terpenoids and Sterols: Terpenoids such as lupeol, β-amyrin, and betulin, and sterols like β-sitosterol are also present. These compounds contribute to the plant's anti-inflammatory, antifungal, and wound-healing properties by modulating inflammatory mediators and strengthening host defence mechanisms [2, 24].

1.6 Carbohydrates and Gum Exudate: The gum obtained from the bark is composed mainly of arabinose, galactose, rhamnose, and uronic acids, which have mild antimicrobial and demulcent properties. The gum forms viscous solutions that act as protective films on mucous membranes, thereby preventing microbial colonization and aiding wound healing [2, 25].

2. Analytical studies:

Advanced analytical techniques, including HPLC, GC–MS, LC–MS, FTIR, and NMR, have been employed to identify and quantify bioactive compounds in A. nilotica. HPLC analysis confirmed high concentrations of gallic acid and catechin in bark and pods. GC-MS studies revealed volatile compounds such as octadecanoic acid, hexadecanoic acid, and methyl esters, which exhibit antimicrobial and antioxidant effects. FTIR spectra indicated the presence of hydroxyl, carbonyl, and aromatic functional groups typical of polyphenols and flavonoids, confirming their structural diversity. These analytical studies support the correlation between phytochemical composition and biological activity, establishing A. nilotica as a chemically rich and pharmacologically potent plant [26,27].

3. Antimicrobial Activity:

The antimicrobial efficacy of A. nilotica has been extensively investigated against a variety of Gram-positive and Gram-negative bacteria, as well as fungal pathogens. Extracts prepared using different solvents—methanol, ethanol, acetone, and water—have shown varying degrees of inhibition depending on the polarity and solubility of active constituents.

3.1 Antibacterial Activity: Numerous studies report that A. nilotica extracts exhibit strong antibacterial activity against both Gram-positive bacteria, such as Staphylococcus aureus, Bacillus subtilis, and Streptococcus pyogenes, and Gram-negative bacteria, including Escherichia coli, Klebsiella pneumoniae, Pseudomonas aeruginosa, and Salmonella typhi. The methanolic bark extract has shown significant inhibition zones comparable to standard antibiotics like ciprofloxacin and ampicillin. Minimum inhibitory concentration (MIC) values generally range from 50 to 250 µg/mL, indicating strong bactericidal potential. The activity is primarily attributed to the synergistic action of tannins and flavonoids, which disrupt bacterial membranes, interfere with energy metabolism, and cause leakage of essential ions and proteins. Phenolic acids further inhibit bacterial enzymes and suppress nucleic acid replication [2, 28, 29].

3.2 Antifungal Activity: A. nilotica has also demonstrated potent antifungal activity against pathogenic fungi such as Candida albicans, Aspergillus Niger, Trichophyton mentagrophytes, and Fusarium oxysporum. The mechanism involves disruption of fungal cell walls, inhibition of ergosterol synthesis, and oxidative stress induction through the generation of reactive oxygen species (ROS). The presence of tannins and saponins plays a crucial role in altering fungal membrane permeability, leading to cytoplasmic leakage and cell death [29, 30].

3.3 Antiviral and Antiparasitic Effects: Although less studied, some reports suggest that A. nilotica

extracts exhibit antiviral activity against RNA viruses and antiparasitic effects against helminths. The polyphenols may inhibit viral replication enzymes and prevent parasite adherence to host tissues [31].

Phytochemical	Plant part	Class	Reported antimicrobial mechanism
Gallic acid	Bark, pods, leaves	Phenolic acid	Strong antibacterial and antifungal activity; inhibits E. coli, S. aureus, and Candida albicans by damaging cell walls and suppressing enzymes.
Catechin	Bark, pods	Flavonoid (Flavan-3-ol)	Inhibits Gram-positive bacteria such as Staphylococcus aureus and Bacillus subtilis; disrupts cell membrane integrity.
Epicatechin	Bark, leaves	Flavonoid	Exhibits antibacterial and antioxidant effects; interferes with bacterial adhesion and protein synthesis.
Quercetin	Leaves, Seeds	Flavonoid (Flavonol)	Broad-spectrum antibacterial and antifungal activity; inhibits DNA gyrase and reduces biofilm formation.
Kaempferol	Leaves	Flavonoid	Active against Pseudomonas aeruginosa and E. coli; increases membrane permeability and reduces oxidative stress.
Ellagic acid	Bark, pods	Polyphenolic compound	Antibacterial against S. aureus and Salmonella typhi; antifungal against A. Niger.
Tannic acid (Condensed tannins)	Bark, pods	Tannin (polyphenol)	Strong astringent and bactericidal properties; precipitates microbial proteins and disrupts membranes.
Proanthocyanidins	Bark, pods	Condensed tannins	Antibacterial against E. coli and K. pneumoniae; antifungal against Candida spp.
β-sitosterol	Seeds, leaves	Phytosterol	Moderate antibacterial and antifungal effects; enhances wound healing and membrane stabilization.
Lupeol	Bark leaves	Triterpenoid	Exhibits antibacterial and antifungal activity; modulates inflammatory pathways in infected tissues.
β-amyrin	Bark	Triterpenoid	Inhibits Gram-negative bacteria and fungal pathogens; has anti-inflammatory and healing properties.
Saponins	Seeds, bark	Glycosides	Causes membrane lysis and inhibits fungal spore germination; effective against Candida albicans and Trichophyton spp.
Alkaloids (N-methyltyramine, hordenine)	Bark, seeds	Alkaloids	Antibacterial and antifungal effects; inhibit microbial enzymes and growth.
Phenolic acid (ferulic acid, caffeic acid)	Leaves, bark	Phenolic acid	Antioxidant and antimicrobial; inhibit bacterial growth by oxidative stress induction.
Gum polysaccharides (Arabinose, galactose, rhamnose)	Gum exudate	Polysaccharides	Mild antibacterial and wound-protective activity; forms a protective film preventing microbial colonization.
Essential fatty acids (palmitic acid, linoleic acid)	Seeds	Fatty acids	Antibacterial and antifungal membrane-disrupting effects
Flavone glycosides	Leaves, flowers	Flavonoid glycosides	Inhibit bacterial cell wall synthesis and act synergistically with antibiotics.
Betulin	Bark	Pentacyclic triterpenoid	Antibacterial against S. aureus and E. coli; promotes tissue repair.
Stigmasterol	Seeds	Phytosterols	Moderate antibacterial effect; supports wound healing and cell regeneration.

Therapeutic and pharmaceutical relevance

The strong antimicrobial potential of A. nilotica makes it a valuable candidate for natural antimicrobial formulations in pharmaceuticals and personal care products. Topical preparations: Bark and gum extracts are used in wound-healing creams and mouthwashes.

Oral hygiene: Chewing sticks and herbal toothpaste formulations utilize their antimicrobial and astringent properties. Phytopharmaceuticals: Standardized extracts may serve as lead compounds for new antimicrobial drug development. Furthermore, its biocompatible gum has applications as a stabilizer, emulsifier, and excipient in drug formulations [32, 33, 34]**.**

Pharmacological mechanism of the antimicrobial activity of Acacia nilotica

The antimicrobial activity of Acacia nilotica can be categorized into five principal pathways:

1. Cell wall and membrane disruption
2. Enzyme inhibition
3. Nucleic acid interference
4. Oxidative stress induction
5. Inhibition of microbial communication and biofilm formation

Acacia nilotica is effective against a broad spectrum of microorganisms, including gram-positive and gram-negative bacteria, fungi, and certain parasites. A. nilotica exhibits multifactorial antimicrobial activity, reducing the likelihood of resistance development [35, 36].

1] Cell wall and membrane disruption

One of the primary mechanisms through which A. nilotica exerts its antimicrobial effect is the disruption of the microbial cell wall and cytoplasmic membrane. Tannins, the dominant phytochemicals in A. nilotica, form irreversible complexes with cell wall proteins and polysaccharides. These complexes weaken the peptidoglycan layer, leading to increased permeability and cell lysis. Saponins act as natural surfactants that bind to sterols in the microbial cell membrane, altering its structure and causing leakage of intracellular contents such as proteins, ions, and nucleotides. Flavonoids and terpenoids intercalate into the lipid bilayer, compromising membrane fluidity and electrical potential, ultimately resulting in loss of membrane function and cell death. Microscopic studies on bacterial cultures treated with A. nilotica extracts have revealed cell wall distortion, cytoplasmic shrinkage, and leakage of cytoplasmic material, confirming the direct damage to cell membranes as a key antimicrobial mechanism [37,38].

2] Enzyme inhibition

Another major antimicrobial mechanism involves inhibition of microbial enzymes and metabolic pathways essential for growth and survival. Tannins and phenolic acids inhibit extracellular microbial enzymes such as hydrolases, proteases, and amylases by forming stable enzyme–substrate complexes. This results in impaired nutrient acquisition and metabolic dysfunction. Flavonoids such as quercetin and catechin interfere with bacterial energy metabolism by inhibiting ATP synthase and oxidoreductase enzymes, reducing cellular energy production. Alkaloids (e.g., hordenine and N-methyltyramine) act as enzyme inhibitors and disrupt microbial signal transduction and cell division processes. Phenolic compounds also chelate essential metal ions like Fe^{2+}, Zn^{2+}, and Mg^{2+} that serve as cofactors for many microbial enzymes, thereby halting enzyme-catalysed reactions [39].

3] Nucleic acid interference

Several flavonoids and tannins in A. nilotica exert genotoxic and transcriptional inhibitory effects on microbes. Quercetin and kaempferol inhibit bacterial DNA gyrase and topoisomerase IV, enzymes critical for DNA replication and supercoiling, resulting in bacteriostatic or bactericidal effects. Flavone glycosides interfere with RNA polymerase, reducing mRNA synthesis and consequently blocking protein translation. Phenolic compounds can bind directly to nucleic acids, causing strand breakage and suppression of replication. These nucleic acid-targeted mechanisms explain the strong inhibitory effect of A. nilotica extracts on fast-dividing microorganisms such as Escherichia coli, Klebsiella pneumoniae, and Staphylococcus aureus [40].

4] oxidative stress induction

The pro-oxidant potential of certain phytoconstituents contributes to microbial cell death through oxidative damage. Polyphenols and flavonoids generate reactive oxygen species (ROS) such as hydrogen peroxide, hydroxyl radicals, and superoxide ions within microbial cells. These ROS attack cellular components, including lipids, proteins, and nucleic acids, leading to oxidative stress, membrane lipid peroxidation, and DNA fragmentation. Simultaneously, A. nilotica's antioxidant properties help protect host cells by neutralizing excess free radicals, offering dual protective and antimicrobial effects. In fungal pathogens like Candida albicans and Aspergillus Niger, oxidative stress induced by A. nilotica extracts results in mitochondrial dysfunction and inhibition of spore germination [41].

5] Inhibition of microbial communication and biofilm formation

Recent studies have shown that Acacia nilotica possesses significant anti-biofilm and quorum-sensing inhibitory activity, which plays a crucial role in reducing microbial virulence. Flavonoids and tannins interfere with autoinducer signalling molecules (AHLs) responsible for microbial communication, preventing coordination of virulence gene expression. The extracts inhibit biofilm maturation on both biotic and abiotic surfaces, such as dental plaques and medical devices. Reduction in biofilm formation has been observed in Pseudomonas aeruginosa and Staphylococcus epidermidis, two bacteria known for persistent biofilm-associated infections. By suppressing quorum sensing, A. nilotica not only inhibits microbial growth but also diminishes their ability to form resistant colonies, making them more susceptible to antibiotics and immune defences [42]. The antimicrobial mechanism of Acacia nilotica is complex, multifaceted, and highly effective. Its phytoconstituents act synergistically to target multiple microbial pathways simultaneously, including membrane integrity, enzyme activity, nucleic acid synthesis, and quorum sensing. This multi-target approach not only ensures potent antimicrobial efficacy but also minimizes the likelihood of resistance development.

Broad-spectrum antimicrobial efficiency of Acacia nilotica

Acacia nilotica exhibits strong broad-spectrum antimicrobial efficiency against a wide range of Gram-positive and Gram-negative bacteria and fungi. Methanolic and ethanolic extracts of the bark and pods show potent inhibition of Staphylococcus aureus, Bacillus subtilis, Escherichia coli, Pseudomonas aeruginosa, and Klebsiella pneumoniae, with inhibition zones ranging from 15 to 25 mm and MIC values between 50 and 250 µg/mL. The extracts also display antifungal activity against Candida albicans and Aspergillus Niger, mainly due to tannins and saponins that disrupt fungal membrane integrity. The synergistic action of tannins, flavonoids, phenolic acids, and alkaloids leads to multiple mechanisms—cell wall damage, enzyme inhibition, and oxidative stress induction. This multi-mechanism, broad-spectrum activity makes A. nilotica an effective natural antimicrobial source with potential applications in pharmaceutical, oral, and topical formulations, particularly against multidrug-resistant pathogens [2, 6, 15, 37].

Formulation and application of Acacia nilotica in antimicrobial activity

1. Mouthwash and Oral Formulations

Bark and pod extracts are formulated into herbal mouthwashes, toothpastes, and oral gels. Shows strong activity against Streptococcus mutans, Lactobacillus acidophilus, and Candida albicans. Help prevent dental plaque, gingivitis, and oral infections through tannin-mediated bacterial inhibition.

2. Topical Antimicrobial Preparations

Used in creams, gels, and wound-healing ointments for treating skin infections, burns, and acne. Flavonoids and saponins provide antifungal and antibacterial protection, reducing microbial colonization.

3. Pharmaceutical and Biomedical Formulations

Incorporated into nanoparticles, hydrogels, and emulsions to enhance stability and penetration. Offers

controlled antimicrobial release and improved bioavailability.

4. Antiseptic and Hygiene Products

Added to antimicrobial soaps, sanitizers, and surface disinfectants as a natural alternative to synthetic preservatives. Provides broad-spectrum efficacy against resistant bacteria and fungi [43,44].

Safety and toxicity of Acacia nilotica for antimicrobial activity

Acacia nilotica (L.) Delile, a member of the Fabaceae family, has been traditionally utilized for centuries in Ayurvedic, Unani, and African medicine for the treatment of microbial infections. Modern pharmacological studies have confirmed its potent antimicrobial properties against a wide range of bacterial and fungal pathogens. Importantly, its widespread medicinal use has been supported by several studies demonstrating low toxicity and high safety margins, which make it suitable for both pharmaceutical and cosmetic formulations [45].

Acute and Subacute Toxicity Studies: In animal studies, extracts of Acacia nilotica have shown an oral LD_{50} value greater than 2,000 mg/kg body weight, classifying it as practically non-toxic according to OECD guidelines. Subacute and chronic administration in experimental animals for 14 to 28 days revealed no significant changes in haematological or biochemical parameters, including liver and kidney function markers (ALT, AST, ALP, urea, and creatinine). Histopathological examinations also indicated no structural damage to major organs, confirming the systemic safety of the plant. These results demonstrate that A. nilotica extracts can be safely administered over prolonged periods at therapeutic doses without causing physiological or metabolic disturbances [2, 45, 46].

Cytotoxicity and Biocompatibility: In vitro cytotoxicity assays on human cell lines such as fibroblasts, keratinocytes, and macrophages have shown that A. nilotica extracts exhibit low cytotoxicity even at antimicrobial concentrations ranging from 100 to 500 µg/ml. The phytoconstituents responsible for antimicrobial activity—tannins, flavonoids, and phenolic acids—target microbial cell walls and enzymes selectively, sparing mammalian cells. The aqueous and methanolic extracts, which are commonly used in antimicrobial formulations, maintain high cell viability (>85%), indicating good biocompatibility and minimal cytotoxic potential [46,47].

Dermal and Mucosal Safety: Topical preparations containing A. nilotica extracts, such as creams, gels, and mouthwashes, are non-irritant and non-sensitizing in skin and mucosal irritation studies. Patch tests on human volunteers have reported no erythema, swelling, or burning sensations after repeated application. The astringent properties of tannins help tighten tissues and reduce microbial colonization without damaging epithelial layers. However, in rare cases, mild allergic reactions or dryness may occur in tannin-sensitive individuals, which are reversible upon discontinuation [48].

Genotoxicity and Mutagenicity: No mutagenic or genotoxic effects have been reported for A. nilotica extracts in bacterial reverse mutation (Ames) tests or chromosomal aberration assays. This confirms that the plant constituents do not interfere with genetic material or induce mutations, supporting its long-term safety in human use [2,49].

Human and Clinical Observations: Traditional use and limited clinical trials suggest that oral and topical preparations of A. nilotica are well tolerated, with no reported systemic toxicity or adverse drug reactions. Its inclusion in oral care products, such as herbal toothpastes and mouthwashes, has shown excellent safety in long-term daily use. The plant's constituents are metabolized naturally and excreted without bioaccumulation [50,51].

CONCLUSION

Acacia nilotica (L.) Delile is a well-established medicinal plant with exceptional broad-spectrum antimicrobial potential attributed to its rich phytochemical composition, including tannins, flavonoids, phenolic acids, alkaloids, and saponins. These bioactive constituents act synergistically to inhibit the growth of both Gram-positive and Gram-negative bacteria, as well as various fungal pathogens, through multiple pharmacological mechanisms such as cell wall disruption, enzyme inhibition,

interference with DNA replication, oxidative stress induction, and suppression of quorum sensing and biofilm formation. Formulations developed from A. nilotica—including mouthwashes, creams, gels, and nanoparticles—demonstrate effective antimicrobial activity in oral, dermatological, and pharmaceutical applications. Its natural astringent, anti-inflammatory, and antioxidant properties further enhance its therapeutic potential and formulation stability. Toxicological studies confirm that A. nilotica possesses a wide safety margin with minimal cytotoxicity and no mutagenic or systemic toxicity at therapeutic doses. Both preclinical and traditional evidence indicate that the plant is biocompatible and safe for oral and topical use, making it a promising candidate for natural antimicrobial formulations. Overall, Acacia nilotica represents a potent, safe, and eco-friendly alternative to synthetic antimicrobial agents. Its multi-mechanical action and low toxicity profile highlight its potential for development into standardized phytopharmaceutical products, contributing to the ongoing global search for sustainable and resistance-free antimicrobial therapies.

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