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Antimicrobial Therapeutic Plants of the Darjeeling Himalayas: A Comprehensive Review of Ethnobotanical Diversity, Phytochemical Profiles, and Pharmacological Activities

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Abstract:
The treasure of North Bengal, Darjeeling Himalayas is a region with great ecological and cultural significance, act as a crucial repository for antimicrobial therapeutic plants. This review provides an in-depth analysis of the antimicrobial efficacy of regional flora. For centuries, local communities like Lepcha, Bhutia, and Nepalese are using these treasures for treating infections, skin conditions, fever, and respiratory ailments against *human pathogens like Staphylococcus aureus*, *Bacillus subtilis*, *Escherichia coli*, *Klebsiella pneumoniae*, and *Salmonella typhi* etc. offering promising alternative to conventional antibiotics. Various secondary metabolites of these medicinal plants such as phenols, flavonoids, alkaloids, tannins, and terpenoids exhibit diverse area of anti-microbial activities. This article examines the medicinal and cultural uses of medicinal plant species by local communities in Darjeeling Hills, illuminating the importance to document their knowledge for biodiversity conservation. Furthermore, the review identifies future research areas emphasizing the need for isolation of bioactive compounds and clinical validation to address the global challenge of antimicrobial resistance.

Keywords: Darjeeling Himalayas; Antimicrobial Activity; Ethnobotany; Phytochemistry; Medicinal Plants; Ethno-pharmacology; Antimicrobial Resistance.

1. Introduction

Known as one of the global hot spots of biodiversity in Eastern Himalayan region of West Bengal, the region displays variety of microclimates that support the extraordinary growth of therapeutic plants. The unique altitudinal range—from the tropical plains of the Terai to the alpine heights of the Singalila Range is the reservoir of unique medicinal plants (Das, 2014). This region is not only an ecological treasure but also a cultural one, where ancient traditional knowledge systems have persisted for centuries.

Driven by the alarming rise of antimicrobial resistance (AMR) to conventional antibiotics, there is a gradual shift towards the antimicrobial therapeutic plants, which has rendered many modern drugs ineffective. The overuse and misuse of antibiotics have led to the emergence of "superbugs" that are resistant to multiple drugs, complicating the treatment of common infections (Avasthi et al., 2021). This has compelled the scientific community to look for natural environment friendly alternatives and what could be better option than these therapeutic plants of Himalayan region. Unique environmental stressor has resulted in the production of novel secondary metabolites that could serve as effective therapeutic agents (De et al., 2015; Avasthi et al., 2021).

The traditional healers in Darjeeling Himalayan region including the *Jhankri, Bijuwa, Phedangma,Gorkhas* and *Lepchas,* utilize diverse form of local plants to treat microbial infections, respiratory diseases and skin conditions (Bantawa et al., 2009). These plants are used as "immunity boosters" and "instant remedies" for fevers (Subhasis, 2022). With increasing scientific reports exploring the antimicrobial properties of angiosperms, pteridophytes and bryophytes, scientific validation for this practice are accelerating (Saha et al., 2011; Kumarpal, 2013; De et al., 2015). By synthesizing these findings, this review aims to bridge the gap between traditional knowledge and modern pharmacological research.

2. Methodology

This review covers research data published during 2000 to 2023 through a systematic search and analysis of peer-reviewed literature and ethnobotanical surveys. The study was constrained to the flora found in the Darjeeling district and its adjacent Himalayan foothills. The primary databases used for literature retrieval included Google Scholar, PubMed and the NBU Journal of Plant Sciences. Specific search terms such as "Darjeeling medicinal plants," "Himalayan ethnobotany," "antibacterial activities Darjeeling," and "phytochemistry of Himalayan herbs" were utilized.

3. Ethnobotanical Diversity in the Darjeeling Himalayas

The Darjeeling Himalayas are a biodiversity hotspot which exhibit a rich repository of ethnobotanical knowledge, preserved by the various ethnic groups that inhabit the region and utilize several species of plants which are used in folk medicine with a high dependency on herbaceous flora. The key research involves documentation of traditional knowledge, analysing plant use and address threat to this biodiversity.

3.1 Traditional Knowledge Systems

Study report reveals distinct medicinal traditions among the Nepalese, Lepcha, and Bhutia communities. The Bhutias for example exhibits a well documented system of traditional knowledge deeply integrated into their cultural practices (Das, 2019). Rural areas like Mulgaon and Pandam, rely on on "Janguru" (traditional healers) and "Ojha" (medicine men) (Das, 2014)

3.2 Taxonomic Richness

The taxonomic richness of therapeutic plants is remarkable (Figure: 1). Database of *PhytoResp* shows 329 enlisted medicinal plants from the Darjeeling district which are traditionally used to treat respiratory disorder of microbial origin (Sarkar & Panda, 2022). A survey conducted in Teesta Valley reveals remarkable use of plant leaves by ethnic herbalists, as the community believes that leaves are the storehouse of high concentrations of bioactive phytochemicals (Subba et al., 2022). A recent survey in Alubari Jungle Busty have documented around 24 wild plant species which are used by Nepalese individual. These are potential immunity boosters and are used for treating various symptoms associated with fever, bronchitis, diarrhea and blood pressure. These reports also highlight the role of traditional knowledge, which is not static, but it continues to adapt to contemporary health needs (Subhasis, 2022).

Significant plant groups include Figure 1.

Plant Group	Species Examples	Family	Key Usage	Reference
Pteridophytes (Ferns)	*Adiantum capillus-veneris, Nephrolepis cordifolia*	Pteridaceae, Nephrolepidaceae	Frond extracts contain antimicrobial potential.	(Kumarpal, 2013)
Bryophytes (Liverworts)	*Marchantia polymorpha*	Marchantiaceae	Unique metabolites, particularly in	(De et al., 2015)

			high-altitude populations.	
Angiosperms	*Osbeckia stellata*	Melastomataceae	Part of the largest group of medicinal plants.	(Das et al., 2013; Nabi et al., 2022)
	Skimmia anquetilia	Rutaceae	Known for diverse phytochemical properties.	
	Prunus cerasoides	Rosaceae	Widely utilized in traditional ethnomedicine.	

4. Major classes of phytochemicals of Therapeutic Species

To survive in the harsh Himalayan environment, the local flora of Darjeeling is highly adapted and to survive, they synthesise a variety of secondary metabolites and hence serve as "chemical factors". Diversity of phytochemicals have been reported by various research works.

4.1 Dominant Bioactive Classes (Figure: 2)

Phytochemical	Sources	Primary Biological Activity	Mechanism of Action	Reference
Phenols & Flavonoids - most studied classes	Crude extracts (various species)	antibacterial	Disrupts cell walls and inhibits metabolic enzymes.	(Das, 2019)
Alkaloids	*Aloe barbadensis, Maesa macrophylla*	Antimicrobial-Cytotoxic	Broad spectrum pharmacological effects.	(Mandal, 2023; Tiwary et al., 2015)
Tannins	Leaves and bark	Broad-spectrum antibacterial	Binds to proteins and inactivates microbial enzymes.	(Subba et al., 2022)
Terpenoids	*Skimmia anquetilia*- Essential oils	Broad-spectrum antimicrobial	Effective against plant and human pathogens.	(Nabi et al., 2022)

4.3 The Role of Altitudinal Variation

Environmental factors like UV intensity, temperature and other environmental stress plays a critical role which triggers the production of unique phytochemicals with therapeutic value. Himalayan medicinal plants produce secondary metabolites as an adaptation in response to extreme environmental stressors (Sharma & Kumar, 2023). For example, in *Marchantia polymorpha* the efficacy of the active principle having antibacterial and antioxidant properties vary according to the altitude, indicating that elevation triggers the production of potent phytochemicals (Chettri et al., 2018).

Darjeeling Himalayas shows vertically stratified floristic diversity (Yonzone et al., 2012c). There is a great species richness with increasing altitude where some inventories have recorded 281 species (Chhetri et al., 2005b) and 218 species (Yonzone et al., 2012c), which are used in local medicine. Also, there is Altitudinal zoning where the highest concentration of medicinal species has been recorded in the lower altitudes while from the Alpine region, fewer but highly specialized species have been recorded (Yonzone et al., 2012c). Regarding the taxonomic dominance, families such as Ericaceae, Orchidaceae (25 species) and many pteridophytes (22 species) are well documented with many representative members having medicinal properties (Rahamtulla et al., 2020; Ghosh et al., 2008)

5. Antimicrobial Activities and Mechanisms

Driven by the unique high stress environment of Darjeeling Himalayas, research works conducted on the antimicrobial and antifungal activities of this flora has identified a rich array of bioactive compounds. Scientific validation of these Therapeutic plants involves rigorous in vitro testing against standardized bacterial and fungal strains.

5.1 Antibacterial effects:

A landmark work on the antibacterial activities of Eastern Himalayas Darjeeling flora has highlighted a rich ethnobotanical tradition against multi-dru resistant pathogens and urinary tract infections. The investigation screened 33 folk medicinal plants and found that 63% were active against *Bacillus subtilis*, 48% against *Staphylococcus aureus*, 54% against *Escherichia coli*, and 24% against *Salmonella typhi* (Sharma, 2013). Research works often focuses on screening medicinal plants which are used by local communities and tribes, and efficacy is evaluated using MIC and MBC techniques.

Similarly, other investigation reports the sensitivity of gram positive and gram negative bacteria. Out of 33 screened medicinal plants, many are found to be 63% active against *Bacillus subtilis*, 48% against *Staphylococcus aureus*, 54% against *Escherichia coli*, and 24% against *Salmonella typhi* (Sharma, 2013). Extracts from *Bergenia ciliata*, *Aloe barbadensis*, and *Marchantia polymorpha* inhibits the growth of *Bacillus subtilis (*Mandal et al., 2023; Mandal, 2023; De et al., 2015). Gram-Negative bacteria *Escherichia coli* and *Klebsiella pneumoniae* when targeted with species like *Skimmia anquetilia* shows exceptional zones of inhibition (Nabi et al., 2022).

5.2 Antifungal Potential:

The primary focus of antifungal research on the Flora of Darjeeling Himalayas is primarily concentrated on bioprospecting for natural plant- based alternative, alternative to synthetic fungicides, particularly through studying ethnomedicinal plants and their associated endophytes. Study highlights the rich biodiversity of the region and its potential for providing bioactive compounds to combat both human and plant pathogenic fungi (Saha et al., 2011). The petroleum ether extract of *Osbeckia stellata* demonstrated significant activity against the common mold *Aspergillus niger* (Das et al., 2013).

5.3 Specialized medical conditions (Figure: 3)

Medical condition	Target	Medicinal plants	Reference
Gastrointestinal	Gastritis, stomach colic	*Zanthoxylum acanthopodium*, *Bergenia ciliata*	(Das, 2014)
Metabolic Care	Diabetes	Antidiabetic species- 37	(Chhetri et al., 2005a; Chhetri et al., 2008)
Liver Care	Liver disorders (Antihepatopathic)	Antihepatopathic species-36	(Chhetri et al., 2005a; Chhetri et al., 2008)

Dermatological	General skin problems	dedicated species (Kalimpong)-14	(Kandari et al., 2023)
Dental Hygiene	Dental disorders, toothaches	*Zanthoxylum* spp. fresh roots	(Yonzone, 2016; Sharma et al., n.d.)
Bone Setting	Fractures and bone setting	Paste of *Barleria cristata*, *Cissampelos pareira and Viscum album* applied to fractures and ,*Dendrocalamus hamiltonii* (Splints) used for supporting structures.	(Chettri et al., 2018)

5.4 Mechanisms of Action

The mechanisms through which these plants exert their antimicrobial effects are diverse:

a) Disruption of cell wall and cell membrane - phenols and saponins in high concentrations can leakage of cellular contents by disrupting the cellular membrane and cell one, as observed in studies of *Osbeckia stellata* (Das et al., 2013).

b) In-silico Validation: For mapping, how specific phytocompounds binds to microbial targets modern computational tools are being used, providing a molecular explanation for the efficacy of traditional treatments (Das et al., 2022).

c) Enzyme Inhibition: Flavonoids and tannins can inhibit essential microbial enzymes by disrupting DNA replication or protein synthesis (Das,2019).

6. Case Studies of some species

6.1 Bergenia ciliata (Haw.) Sternb.

Locally known as *Pakhanbed*, *Bergenia ciliata*, a perenneal rhizomatous herb is highly valued in both traditional medicine and modern pharmacology. Aqueous and acetone extract of these plants have been studied in the Darjeeling Himalayas for their phytochemistry and antimicrobial properties due to its high polyphenol content. (Mandal et al., 2023).

6.2 Aloe barbadensis

Study shows that acetone and ethanol extracts from *Aloe barbadensis* commonly known as *Ghiu Kumari* is highly effective against *Bacillus subtilis* while *Klebsiella pneumoniae* is inhibited by the chloroform extracts. Diverse form of phytochemicals, including coumarins and anthraquinones with broad-spectrum potential have been reported (Mandal et al., 2023).

6.3 Skimmia anquetilia

Skimmia anquetilia, family Rutaceae, is an aromatic shrub used to treat snake or scorpion bites, headache, rheumatism, fever, smallpox etc. Plant extracts, which particularly constitutes skimmin and skimminan (coumarins) shows significant activity against *Pseudomonas aeruginosa*, *E. coli*, and *S. aureus* (Nabi et al., 2022)

6.4 Ethnomedicinal Ferns (Nephrolepis, Adiantum, Pteris)

Packed with potent bio active phytochemicals like flavonoids, tannins, phenols, saponins, steroids and terpenoids, ferns like *Nephrolepis cordifolia* (Jaishee & Das, 2020)., *Adiantum capillus-veneris*, and *Pteris vittata* are widely used in regional ethno-pharmacology of Darjeeling Himalayas. Decent antimicrobial activity has been reported against both Gram-positive and Gram-negative bacteria in agar diffusion assays (Kumarpal, 2013;)

7. Medicinal Plants

There are several therapeutic plants reported from athe Darjeeling Himalayas. The following table summarizes the key medicinal plants of the Darjeeling Himalayas with reported antimicrobial activity and various medicinal uses. (Figure:4)

Figure:4 (Antimicrobial activity of therapeutic plants).

Scientific name	Local name/ common name	Family and parts used	Uses	References
Artemisia nilagirica (C. B. Clarke) Pamp	Titapati	Leaves	Helpful in reducing blood pressure and also use in some religious practises.	(Das, 2014)
Astilbe rivularis	Burokhoti	Rhizome	Used in traditional bone setting, formulations,	(Chettri et al., 2018)
Barleria cristata L.	Jhinti	Bark	vital component of the herbal paste, used for treating bone fractures.	
Bergenia ciliata	Pakhan bet	Leaves, Roots	Treatment for uterine bleeding, gonorrhea, and throat pain.	(Das, 2014)
Bixa orellana	Simrik	Seeds	treating bone fractures.	(Chettri et al., 2018)
Cissampelos pareira L.	Batulepate	Root	Used for treating fevers, urinary tract infection, skin diseases and wounds.	
Curcuma longa L.	Beshar	Rhizome	Topical application for bone fractures.	
Ficus nemoralis Wall.	Dudhilo	Stem, bark, leaves and latex.	High medicinal value and important component of the sacred grooves.	(Das, 2014; Panda, 2017)
Gaultheria fragrantissima Wall.	Machino	Leaves	Used for its essential oils. Potent analgesic and anti-	(Bantawa et al., 2008)

			inflammatory action. Beneficial in topical application for arthritis, joint pain etc.	
Gynocardia odorata R. Br.	Bandrey	Seeds	To treat skin diseases psoriasis, eczema. Seed oil is used by local communities like the Khasi.	(Das, 2014)
Lepidium sativum L.	False chaulmoogra	Seeds	crushed and applied for bone fractures.	(Chettri et al., 2018)
Nephrolepis exaltata	Paniamla	Bulb / Fronds	Useful in urinary infections.	(Das, 2014)
Ocimum sanctum L.	Tulsi	Leaves	Widely used for various general health issues- cold, cough etc.	(Das, 2014)
Oroxylum indicum (L.) Kurz	Totola (broken bone tree)	Bark	Used in formulations for bone healing.	(Chettri et al., 2018)
Prunus nepaulensis	Bilon / Arupate	Fruits	Used in "Jharphuck" rituals for pain relief.	(Das, 2014)
Solanum verbascifolium L.	Burbee	-	Checks high blood pressure	(Das, 2014)
Swertia chirayita	Chirayito	Whole Plant	endangered medicinal plant- used for fever and as a tonic.	(Panda, 2017)
Viscum album L.	Lisso(Nepali)	Stem	Important component of complex pastes for bone fractures.	(Chettri et al., 2018)
Zanthoxylum acanthopodium DC.	Bokay Timbur(Nepali)	Fruit, Bark, Seeds, Roots	Gastritis, stomach colic, liver issues, toothache, antimicrobial,	(Yonzone, 2016)

			antioxidant and anthelmintic uses, potent antihepatopathic actions.	
Zingiber officinale	Aduwa	Rhizome	Common ingredient in medicinal preparations for bone care	(Chettri et al., 2018)

8. Conclusion

The medicinal plants of Darjeeling Himalayas represent an invaluable treasure for both the local people and potential pharmacological development. Several research has documented hundreds of therapeutic plants and their traditional uses in day-to-day life. However, a significant portion of such ancient knowledge remains unexplored by the modern medicine. The future research can focus on the phytochemical characterization of therapeutic plants which are used by herbal healers, folk medicine and local communities for centuries. Further, documentation of vanishing knowledge and implementation of sustainable harvesting practices of these biotic resources. *In situ* conservation strategies like establishment and protection of sacred groves and setting up more medicinal plant nurseries are necessary for conservation of antimicrobial therapeutic plants of Darjeeling for our future generations.

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