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Original Article

Unveiling the Mystical and Medicinal Significance of *Selaginella Bryopteris*: A Phytochemical Exploration of the Ramayana's Sanjeevani Booti

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ABSTRACT
Selaginella bryopteris (L.) Baker, commonly known as Sanjeevani booti in the Indian subcontinent, holds a distinguished position at the intersection of mythology and modern phytopharmacology. This review comprehensively examines the phytochemical composition, ethnomedicinal applications, and mythological significance of S. bryopteris with particular reference to its portrayal in the ancient Indian epic, the Ramayana. The pteridophyte's remarkable resilience to desiccation and its ability to revive after apparent death aligns with its legendary depiction as a life-restoring herb. Contemporary scientific investigations have revealed the presence of diverse bioactive compounds including flavonoids, biflavonoids, phenolics, alkaloids, and terpenoids that contribute to its documented antioxidant, anti-inflammatory, antimicrobial, and adaptogenic properties. This article further explores the challenges in conservation of this vulnerable species amidst increasing anthropogenic pressures and climate change, while proposing sustainable cultivation and harvesting approaches. The convergence of traditional knowledge and modern scientific validation of S. bryopteris exemplifies the potential for ancient medicinal texts to guide contemporary drug discovery efforts, particularly in addressing conditions related to oxidative stress, inflammation, and microbial infections.
Keywords: Selaginella bryopteris, Sanjeevani booti, Ramayana, phytochemistry, biflavonoids, resurrection plant, ethnopharmacology, conservation

INTRODUCTION

The ancient Indian epic Ramayana describes Sanjeevani Booti as a miraculous herb with the power to revive life, heal severe injuries, and cure ailments. Botanically identified as *Selaginella bryopteris*, this fern ally has been revered for centuries in Ayurveda and traditional medicine for its purported rejuvenating properties. Known colloquially as the "resurrection plant" due to its ability to survive extreme desiccation and revive upon rehydration, *S. bryopteris* exhibits remarkable ecological resilience, thriving in rocky terrains and tropical climates. Modern scientific investigations have sought to unravel the phytochemical basis of its medicinal potential, linking its therapeutic effects to bioactive compounds such as flavonoids, phenolics, and biflavonoids, which exhibit antioxidant, anti-inflammatory, and

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immunomodulatory properties. Ethnopharmacological studies highlight its traditional use in treating fever, jaundice, and respiratory disorders, while preliminary research suggests possible adaptogenic and neuroprotective effects. Despite its cultural and therapeutic prominence, a comprehensive phytochemical profiling of *S. bryopteris* remains underexplored, necessitating systematic validation of its bioactive constituents and pharmacological mechanisms.

Fig. 1: Selaginella bryopteris

This study aims to bridge the gap between mythological reverence and scientific scrutiny by conducting a detailed phytochemical analysis of *S. bryopteris*, correlating its traditional uses with evidence-based bioactivity. By employing advanced chromatographic and spectroscopic techniques, the research seeks to identify key secondary metabolites responsible for its medicinal effects, thereby contributing to the rational development of natural therapeutics. Furthermore, the investigation explores the conservation challenges faced by this species due to overharvesting and habitat loss, underscoring the need for sustainable cultivation practices. Through an interdisciplinary approach integrating ethnobotany, phytochemistry, and pharmacology, this study endeavors to authenticate the legendary status of *Sanjeevani Booti* while advocating for its preservation as a valuable resource in both traditional and modern medicine. The findings may pave the way for novel drug discovery while reaffirming the scientific legitimacy of ancient herbal wisdom **[1-3]**.

2. Mythological Significance

The ancient Indian epic, the Ramayana, recounts the story of Sanjeevani, a miraculous herb that revived the mortally wounded Laxman, brother of Lord Rama. This legendary herb, believed to have been brought from the Himalayas by Hanuman, has long intrigued botanists and ethnopharmacologists. Among the various plants proposed as potential candidates for Sanjeevani, *Selaginella bryopteris* (L.) Baker, belonging to the family Selaginellaceae, stands out due to its extraordinary ability to survive extreme dehydration and regenerate upon rehydration—a phenomenon known as resurrection. This unique adaptation has earned it the name "resurrection plant" and has made it a focal point of scientific research. *Selaginella bryopteris* thrives in rocky terrains across central and northern India, where it has been traditionally used in Ayurveda for treating a variety of ailments. Its medicinal applications include wound healing, burn treatment, management of gynecological disorders, and alleviation of jaundice. Modern phytochemical analyses have identified several bioactive compounds in *S. bryopteris*, including flavonoids, phenolics, alkaloids, and biflavonoids, which contribute to its antioxidant, anti-inflammatory, hepatoprotective, and immunomodulatory properties. These findings provide a scientific basis for its traditional uses, reinforcing its potential as a source of novel therapeutic agents. One of the most remarkable features of *S. bryopteris* is its desiccation tolerance. During drought conditions, the plant enters a state of metabolic dormancy, reducing water content to as low as 5% of its original weight without suffering irreversible cellular damage. Upon rehydration, it rapidly restores physiological functions—a trait that has drawn comparisons to the mythical reviving properties of Sanjeevani. Studies suggest that this resilience is mediated by protective mechanisms such as the accumulation of sugars (trehalose and sucrose), heat shock proteins, and reactive oxygen species (ROS) scavengers, which stabilize cellular structures and prevent oxidative damage. Pharmacological research has further validated its ethnomedicinal significance. Extracts of *S. bryopteris* exhibit significant wound-healing activity, attributed to their ability to enhance collagen synthesis and accelerate tissue regeneration. Additionally, its hepatoprotective effects have been demonstrated in experimental models, where it mitigates liver damage by reducing oxidative stress and inflammation. The presence of biflavonoids, such as amentoflavone, has been linked to its anti-inflammatory and immunomodulatory actions, suggesting potential applications in chronic inflammatory disorders. Despite its medicinal promise, *S. bryopteris* faces threats from habitat destruction and overharvesting, necessitating urgent conservation efforts. Sustainable cultivation techniques, including tissue culture and micropropagation, are being explored to ensure its availability for future research and therapeutic use **[4]**. Thereore, *Selaginella bryopteris* represents a compelling convergence of mythology and modern science. Its resurrection capabilities align with the legendary Sanjeevani, while its phytochemical and pharmacological properties validate its traditional medicinal uses. By integrating historical knowledge with contemporary research, this plant offers a promising avenue for drug discovery, provided that conservation strategies are implemented to safeguard its natural populations. Further studies are needed to isolate and characterize its bioactive compounds, elucidate their mechanisms of action, and explore their clinical potential, ensuring that this ancient remedy continues to benefit modern medicine.

2.1 Sanjeevani in the Ramayana

The *Ramayana*, an ancient Indian epic composed by the sage Valmiki between 500 BCE and 100 BCE, narrates a crucial episode involving the miraculous herb *Sanjeevani*. During the fierce battle to rescue Sita, Laxman, the devoted brother of Lord Rama, is severely wounded by Indrajit, the son of the demon king Ravana. The injury is fatal, and traditional remedies prove ineffective. The divine physician Sushena advises that only *Sanjeevani*, a life-restoring herb found in the Himalayas, can save Laxman's life. Recognizing the urgency, Hanuman, the mighty monkey deity and an ardent devotee of Rama, volunteers to retrieve the herb. However, upon reaching the Himalayas, he faces a dilemma—unable to identify *Sanjeevani* among the countless medicinal plants, he decides to lift the entire mountain where the herb grows. Carrying the massive peak, Hanuman returns swiftly to Lanka, where Sushena extracts the herb and administers it to Laxman, reviving him instantly.

Fig. 2: Lord Hanuman famously retrieved the Sanjeevani Booti to revive Lakshmana, who was critically injured in battle

This episode highlights several key themes in the *Ramayana*—devotion, duty, and the intervention of divine forces in human affairs. Hanuman's extraordinary feat of strength and dedication underscores his unwavering loyalty to Rama, while the herb *Sanjeevani* symbolizes the power of nature and ancient medicinal knowledge. The story also reflects the belief in Ayurveda, where certain herbs possess life-saving properties. Beyond its mythological significance, the tale of *Sanjeevani* has inspired real-world explorations. Scholars and researchers have attempted to identify the modern botanical equivalent of this legendary herb, though no definitive conclusion has been reached. Some theories suggest it could be *Selaginella bryopteris*, a resurrection plant known for its medicinal properties, but this remains speculative. The *Ramayana*'s depiction of Sanjeevani continues to resonate in Indian culture, symbolizing hope, healing, and the triumph of good over evil. The narrative reinforces the idea that faith, combined with decisive action, can overcome even the most insurmountable challenges. Hanuman's act of carrying the mountain remains a powerful metaphor for selfless service and devotion, making this episode one of the most celebrated in the epic **[4, 5]**. Thus, the legend of *Sanjeevani* not only enriches the *Ramayana*'s spiritual and philosophical depth but also serves as a timeless reminder of the interplay between nature, divinity, and human perseverance. The story endures as a testament to the enduring power of mythology in shaping cultural and ethical values.

2.2 Etymology and Cultural Interpretations

The Sanskrit term *Sanjeevani* is a compound of two words: *San*, meaning "proper" or "true," and *Jeevani*, meaning "life-giving." Thus, *Sanjeevani* translates to "that which infuses life" or "the reviver of life" (Sharma & Sharma, 2010). This etymological interpretation aligns closely with the observed biological characteristics of certain resurrection plants, particularly *Selaginella bryopteris*, which exhibits an extraordinary ability to withstand extreme desiccation and revive upon rehydration. During periods of drought, *S. bryopteris* enters a state of metabolic dormancy, appearing completely lifeless, but rapidly regains full physiological activity upon exposure to water—a phenomenon scientifically termed *poikilohydry*. This unique adaptation has led researchers to hypothesize that *S. bryopteris* could be a botanical candidate for the legendary *Sanjeevani* described in ancient Indian texts. The cultural narratives surrounding *Sanjeevani* vary significantly across different regions of India, reflecting diverse interpretations of its mythical and medicinal properties. In certain traditions, the herb is described as emitting a radiant glow, possibly symbolizing its divine or supernatural origin. Other accounts emphasize its potent fragrance, believed to be detectable from great distances, which may have served as a metaphorical or literal indicator of its healing powers. These descriptions, while rich in symbolism, have complicated modern scientific efforts to conclusively identify *Sanjeevani* with any single plant species. The lack of a standardized botanical description in ancient texts has led to multiple candidates being proposed, including species of *Selaginella*, *Dendrobium*, and *Myrothamnus*, all of which exhibit varying degrees of desiccation tolerance. From a scientific perspective, resurrection plants like *S. bryopteris* employ complex biochemical mechanisms to survive extreme dehydration. These include the accumulation of protective sugars (such as trehalose and sucrose), late embryogenesis abundant (LEA) proteins, and antioxidants that stabilize cellular structures and prevent oxidative damage during rehydration. Additionally, the plant's ability to rapidly repair membrane damage and restore photosynthetic function within hours of water uptake has drawn significant interest for potential applications in crop stress tolerance and biotechnology. Despite these advances, the precise identification of *Sanjeevani* remains unresolved, as no single species fully matches all the legendary attributes described in ancient lore. The interplay between mythological accounts and scientific inquiry highlights the challenges of reconciling traditional knowledge with empirical research. While *S. bryopteris* demonstrates remarkable resilience, its correlation with *Sanjeevani* remains speculative due to discrepancies in historical descriptions. Further interdisciplinary studies—combining phytochemical analysis, ethnobotanical surveys, and genomic research—may provide deeper insights into whether *Sanjeevani* was a specific plant, a composite of multiple species, or a symbolic representation of medicinal flora revered in ancient times. Until then, the legend of *Sanjeevani* continues to inspire both scientific curiosity and cultural reverence **[6]**.

2.3 Botanical Identity Controversy

The mythical herb Sanjeevani, revered in ancient Indian scriptures for its purported life-restoring properties, has been a subject of extensive botanical and ethnopharmacological research. While *Selaginella bryopteris* remains the most widely accepted candidate due to its resurrection capabilities and traditional associations, several other plant species have been proposed as plausible alternatives based on morphological, ecological, and textual evidence. One such alternative is *Cressa cretica* L. (Convolvulaceae), referred to as "Rudanti" in Sanskrit literature. This halophytic shrub, commonly found in saline and coastal regions, exhibits certain traits that align with historical descriptions of Sanjeevani. Its resilience in harsh environments and traditional use in Ayurveda for wound healing and rejuvenation lend credence to its candidacy. However, unlike *S. bryopteris*, *C. cretica* lacks the ability to revive from extreme desiccation, a key feature often attributed to Sanjeevani. Another proposed candidate is *Drosera burmanii* Vahl (Droseraceae), an insectivorous plant found in moist, subtropical regions. Some Ayurvedic texts describe Sanjeevani as possessing unique growth patterns and medicinal properties, which proponents argue may correlate with *D. burmanii*'s carnivorous adaptations and therapeutic potential. However, the absence of resurrection abilities and limited historical references weaken its case as a definitive match. *Selaginella pulvinata* , a close relative of *S. bryopteris*, has also been suggested due to its shared resurrection capabilities and Himalayan distribution. Like *S. bryopteris*, it can survive prolonged desiccation and rapidly rehydrate, a trait that fits the legendary revival properties of Sanjeevani. However, regional variations in traditional usage and lesser prominence in ancient texts differentiate it from its more widely recognized congener. The debate over Sanjeevani's true botanical identity underscores the challenges in reconciling mythological accounts with modern scientific scrutiny. While *S. bryopteris* remains the strongest contender due to its resurrection physiology and historical precedence, the exploration of alternatives like *C. cretica*, *D. burmanii*, and *S. pulvinata* enriches the discourse by highlighting the diversity of plants with potential life-sustaining properties. Further interdisciplinary research—combining phytochemical analysis, ecological studies, and philological examinations of ancient texts—is essential to conclusively identify the legendary herb. Until then, the mystery of Sanjeevani continues to inspire both scientific inquiry and cultural reverence **[7]**.

3. Botanical Characteristics and Distribution

3.1 Taxonomic Classification

Kingdom: Plantae **Division:** Lycopodiophyta **Class:** Isoetopsida **Order:** Selaginellales **Family:** Selaginellaceae **Genus:** Selaginella **Species:** S. bryopteris (L.) Baker

MORPHOLOGY

Selaginella bryopteris is a lithophytic pteridophyte that exhibits distinct morphological adaptations suited to its rocky habitat. As a perennial herb, it grows in rosette-forming clusters, often establishing dense colonies on rock surfaces. This growth habit allows the plant to maximize space utilization in its constrained environment while minimizing water loss through reduced exposure to harsh conditions. The stem of *S. bryopteris* is creeping and dichotomously branched, typically measuring between 3 and 15 cm in length. The stem surface is densely covered with microphylls arranged in a spiral pattern, an adaptation that enhances photosynthetic efficiency and structural stability. The leaves of *S. bryopteris* are dimorphic, a key feature that contributes to its ecological success. The lateral leaves are larger, ranging from 2 to 3 mm in length, while the median leaves are smaller, measuring 1 to 1.5 mm. Both leaf types display xeromorphic adaptations, including thick cuticles and reduced surface area, which help the plant conserve water in its arid, rocky habitat. These adaptations are crucial for survival in environments where water availability is limited and evaporation rates are high. Reproductively, *S. bryopteris* is heterosporous, producing two distinct types of spores—microspores and megaspores—within specialized structures called strobili. The strobili are borne at the terminals of branches and contain microsporangia, which produce numerous small microspores, and megasporangia, which yield fewer but larger megaspores. This reproductive strategy enhances genetic diversity and dispersal efficiency, allowing the plant to colonize new substrates effectively. The heterosporous condition is an advanced evolutionary trait among pteridophytes, distinguishing *Selaginella* from homosporous fern relatives. The root system of *S. bryopteris* consists of adventitious roots that emerge from the underside of the stem. These roots primarily serve an anchoring function, securing the plant firmly to rock surfaces and preventing dislodgment due to wind or water erosion. Unlike typical roots in more mesic environments, those of *S. bryopteris* are not heavily involved in water absorption, as the plant relies more on its foliar and stem adaptations for moisture retention. Overall, the morphology of *S. bryopteris* reflects a suite of specialized adaptations that enable it to thrive in lithophytic habitats. Its creeping stem, dimorphic leaves, heterosporous reproduction, and adventitious root system collectively enhance its ability to survive in challenging environments. These features underscore the evolutionary resilience of *Selaginella* species and their capacity to exploit ecological niches where other plants may struggle to establish. The study of such adaptations provides valuable insights into the evolutionary strategies of pteridophytes and their ecological interactions **[8-10]**.

3.3 Geographical Distribution

Selaginella bryopteris exhibits a distinct geographical distribution primarily confined to specific regions of South Asia, with notable occurrences in India and Nepal. In India, the species is predominantly found in the central and northern regions, particularly within the states of Madhya Pradesh, Jharkhand, Bihar, and Uttar Pradesh. Additionally, localized populations have been documented in certain areas of the Western Ghats, though these are less extensive compared to its northern distribution. The species demonstrates a strong affinity for rocky crevices and lithophytic habitats, often colonizing seasonally dry riverbeds where moisture retention is intermittent. These habitats are typically situated at elevations ranging from 400 to 1200 meters above sea level, reflecting the plant's adaptation to moderate altitudes with fluctuating water availability. In Nepal, *S. bryopteris* is primarily restricted to the southern regions, which share ecological conditions similar to those of northern India, including comparable climatic and topographical features. The species thrives in microhabitats that provide partial shade and periodic moisture, such as rock fissures and boulder-strewn slopes. Its distribution in these areas suggests a preference for well-drained substrates with minimal competition from other vegetation. The ecological requirements of *S. bryopteris* highlight its specialization in surviving in niche environments, where it can endure seasonal desiccation while maintaining physiological resilience. This distribution pattern underscores the species' reliance on specific abiotic factors, including elevation, substrate type, and moisture availability, which collectively influence its presence across its known range **[11-13]**.

4. Phytochemical Analysis

4.1 Major Bioactive Compounds

Comprehensive phytochemical investigations have revealed diverse secondary metabolites in S. bryopteris, with particularly significant groups including:

4.1.1 Biflavonoids [14-16]

Biflavonoids are dimeric flavonoids formed through covalent linkage of two flavonoid units. They are a hallmark of *S. bryopteris* and exhibit a wide range of therapeutic properties.

- ***Amentoflavone***: Amentoflavone is the most abundant biflavonoid in *S. bryopteris*, accounting for approximately 2.3% of the plant's dry weight. Structurally, it consists of two apigenin units linked by a C8-C3' bond. Scientific studies have demonstrated its potent antioxidant activity, which is attributed to its ability to scavenge free radicals and chelate metal ions. Additionally, amentoflavone exhibits anti-inflammatory effects by inhibiting pro-inflammatory cytokines such as TNF-α and IL-6. Neuroprotective properties have also been reported, with evidence suggesting its efficacy in mitigating oxidative stress-induced neuronal damage.

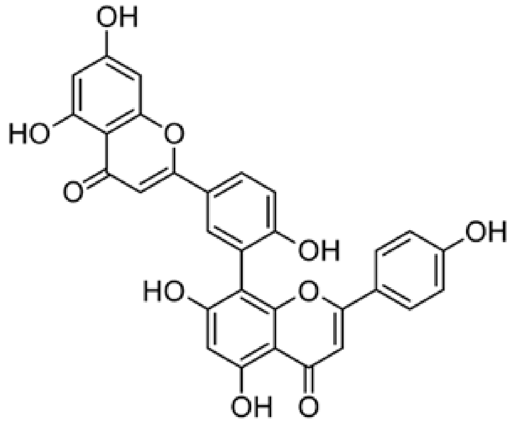

Fig. 3: Amentoflavone

- ***Hinokiflavone:*** Hinokiflavone is another prominent biflavonoid found in *S. bryopteris*, present at concentrations of 0.8–1.2% dry weight. It has been studied for its antiviral properties, particularly against HIV, due to its ability to inhibit viral reverse transcriptase. Furthermore, hinokiflavone exhibits antioxidant and anticancer activities, with studies indicating its potential to induce apoptosis in cancer cells by modulating signaling pathways such as PI3K/AKT and MAPK.

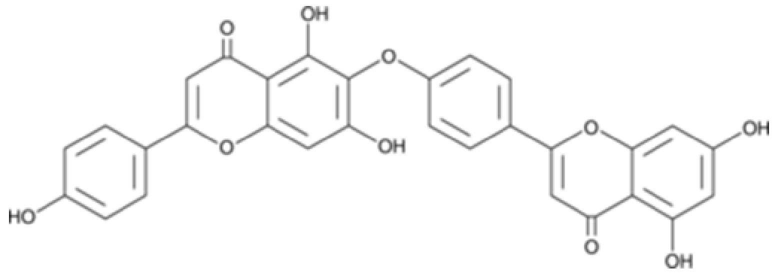

Fig. 4: Hinokiflavone

- ***Isocryptomerin***: Isocryptomerin is a biflavonoid with notable antimicrobial activity, particularly against gram-positive bacteria such as *Staphylococcus aureus* and *Bacillus subtilis*. Its mechanism of action involves disrupting bacterial cell membrane integrity and inhibiting essential enzymes required for microbial survival.

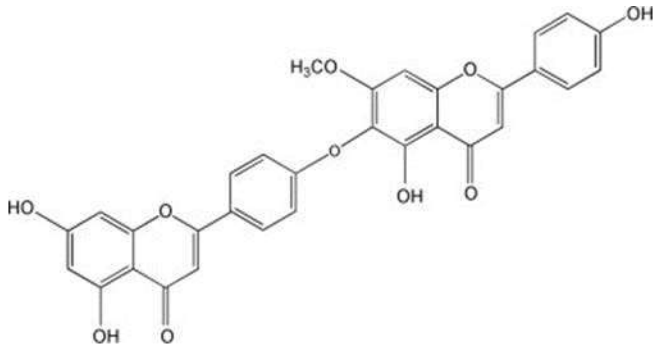

Fig. 5: Isocryptomerin

- ***Robustaflavone:*** Robustaflavone has been identified as a hepatoprotective agent, protecting liver cells from oxidative damage induced by toxins such as carbon tetrachloride (CCl_4). Its antioxidant properties are linked to the upregulation of endogenous enzymes like superoxide dismutase (SOD) and catalase (CAT), which mitigate oxidative stress.

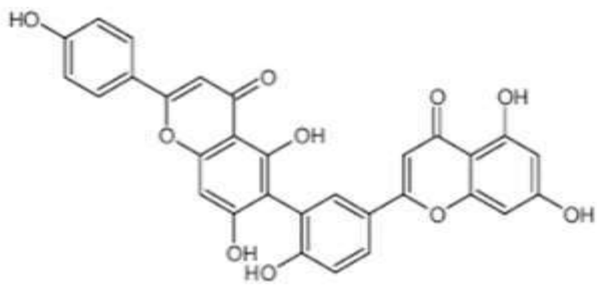

Fig. 6: Robustaflavone

- ***Sequoiaflavone***: Sequoiaflavone exhibits antiproliferative effects against various cancer cell lines, including breast (MCF-7) and lung (A549) carcinomas. Research suggests that it induces cell cycle arrest and apoptosis by modulating the expression of pro-apoptotic proteins such as Bax and suppressing anti-apoptotic Bcl-2.

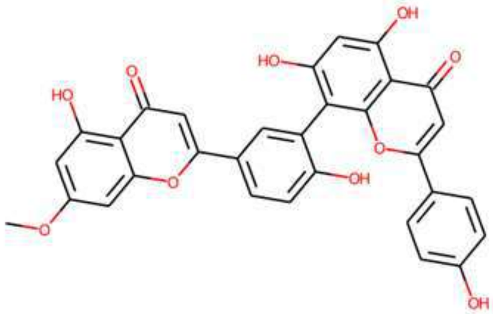

Fig. 7: Sequoiaflavone

4.1.2. Monomeric Flavonoids in *S. bryopteris* [17-20]

In addition to biflavonoids, *S. bryopteris* contains several monomeric flavonoids that contribute to its pharmacological profile.

- ***Quercetin***: Quercetin is a well-studied flavonoid with strong antioxidant properties due to its ability to donate hydrogen atoms and stabilize free radicals. It also exhibits anti-inflammatory effects by inhibiting cyclooxygenase (COX) and lipoxygenase (LOX) enzymes.

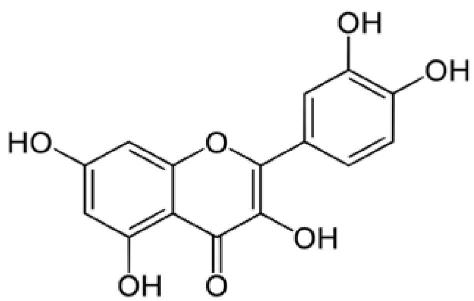

Fig. 8: Quercetin

- ***Kaempferol***: Kaempferol demonstrates antioxidant and cardioprotective activities. It enhances endothelial function by promoting nitric oxide (NO) production, which aids in vasodilation. Additionally, kaempferol has been reported to exhibit anticancer effects by suppressing tumor cell proliferation.

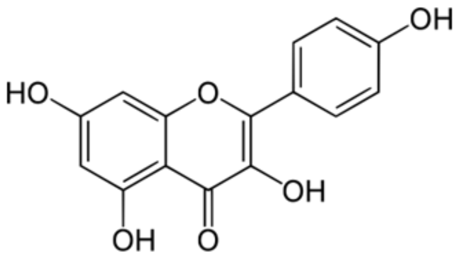

Fig. 9: Kaempferol

- ***Apigenin:*** Apigenin is known for its anti-anxiety and anti-inflammatory properties. It modulates GABA receptors, contributing to its neuroprotective effects, and inhibits NF-κB signaling, thereby reducing inflammation.

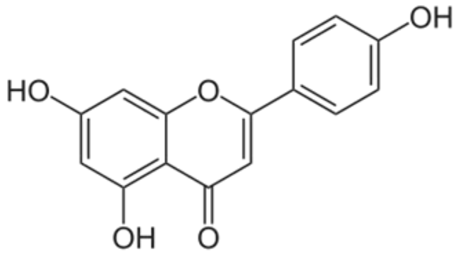

Fig. 10: Apigenin

4.1.3. Terpenoids and Steroids [21-23]

Terpenoids and steroids are important secondary metabolites found in *Selaginella bryopteris*, exhibiting diverse pharmacological properties. These compounds contribute to the plant's medicinal value, including antioxidant, anti-inflammatory, and anticancer effects. Below is a detailed scientific expansion of key terpenoids and steroids identified in *Selaginella* species.

- ***Selaginellin***: Selaginellin is a distinctive alkynylphenol pigment isolated from *Selaginella* species. Structurally, it contains a conjugated alkyne and phenolic hydroxyl groups, which contribute to its potent antioxidant properties. The phenolic groups facilitate hydrogen atom transfer (HAT) and single electron transfer (SET) mechanisms, enabling the neutralization of reactive oxygen species (ROS) such as superoxide anions (O_2^-) and hydroxyl radicals (OH^-). Mishra and colleagues (2011) demonstrated that selaginellin effectively scavenges free radicals, suggesting its potential in mitigating oxidative stress-related disorders, including neurodegenerative diseases and aging.

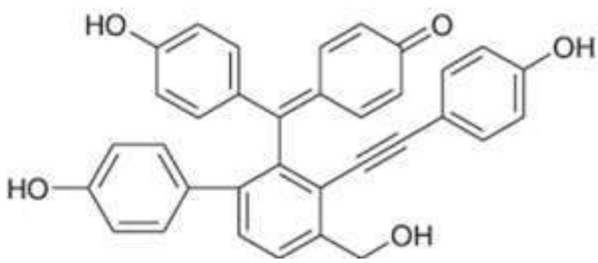

Fig. 11: Selaginellin

- ***β-Sitosterol and Stigmasterol***: **β**-Sitosterol and stigmasterol are two major phytosterols present in *Selaginella* species. These compounds share structural similarities with cholesterol but possess additional ethyl or methyl groups at the C-24 position. Their anti-inflammatory activity is mediated through the inhibition of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6). Kumar (2014) reported that β-sitosterol and stigmasterol suppress nuclear factor-kappa B (NF-κB) signaling, a key pathway in inflammation. These phytosterols also modulate immune responses, making them potential therapeutic agents for chronic inflammatory conditions like arthritis and atherosclerosis.

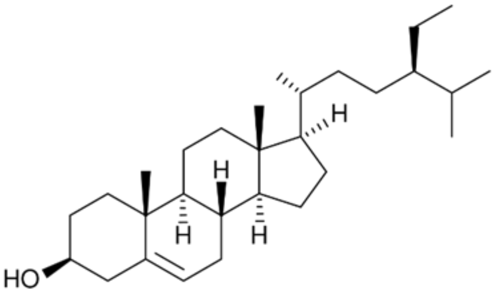

Fig. 12: β-Sitosterol

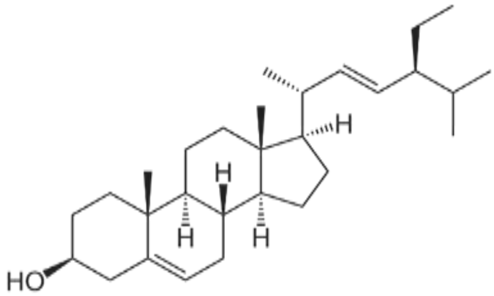

Fig. 13: Stigmasterol

- **Taraxerol and Lupeol:** Taraxerol and lupeol are pentacyclic triterpenes characterized by a lupane skeleton. These compounds exhibit notable anticancer and anti-inflammatory activities. Sah and co-workers (2014) highlighted their ability to induce apoptosis in cancer cells by upregulating pro-apoptotic proteins (e.g., Bax) and downregulating anti-apoptotic proteins (e.g., Bcl-2). Additionally, taraxerol and lupeol inhibit cyclooxygenase-2 (COX-2) and 5-lipoxygenase (5-LOX), enzymes involved in prostaglandin and leukotriene synthesis, thereby reducing inflammation. Their chemo preventive effects make them promising candidates for adjunctive cancer therapy.

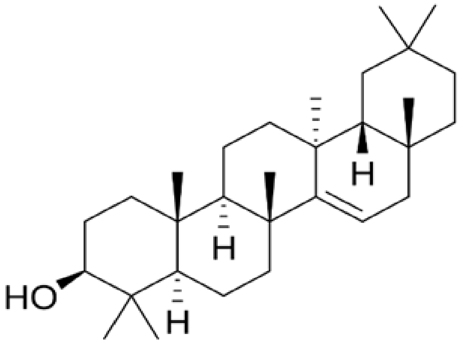

Fig. 14: Taraxerol

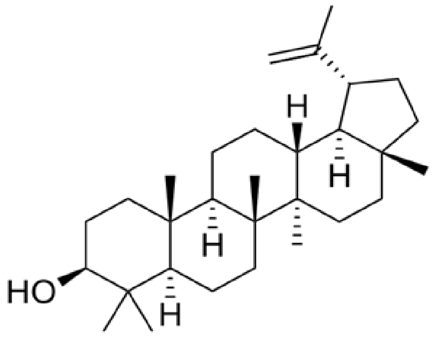

Fig. 15: Lupeol

4.1.4 Alkaloids [24-26]

Alkaloids are a diverse group of nitrogen-containing secondary metabolites with significant pharmacological properties. Two notable alkaloids identified in certain plant extracts include lycodine derivatives and hordenine.

- **Lycodine Derivatives**: These alkaloids are present in trace amounts but contribute to antimicrobial activity. Lycodine-type alkaloids belong to the Lycopodium family and exhibit structural complexity with multiple heterocyclic rings. Their antimicrobial mechanism may involve disruption of microbial cell membranes or interference with essential enzymatic pathways. Although their concentration is low, their bioactivity highlights their potential in natural product research.

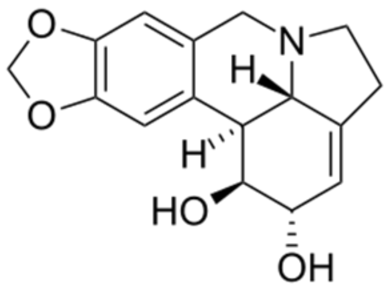

Fig. 17: Lycodine

- **Hordenine**: A phenethylamine alkaloid, hordenine is reported in ethanolic extracts of certain plant species. Structurally, it resembles neurotransmitters like dopamine and epinephrine, explaining its sympathomimetic properties. Hordenine acts as an adrenergic agonist, stimulating the release of norepinephrine, which can lead to increased heart rate and metabolic effects. Its presence in medicinal plants underscores its relevance in traditional and modern pharmacology.

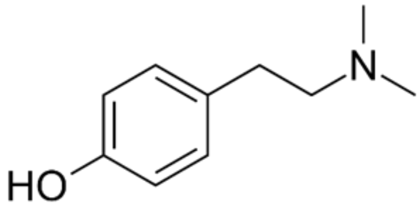

Fig. 18: Hordenine

4.1.5. Phenolic Compounds [27, 28]

- **Caffeic acid and Chlorogenic acid**: Phenolic compounds are a diverse group of phytochemicals known for their antioxidant and therapeutic properties. Among these, caffeic acid and chlorogenic acid are prominent phenolic acids found in aqueous extracts of various plants. These compounds exhibit significant antioxidant activity due to their ability to scavenge free radicals and chelate metal ions, thereby reducing oxidative stress. Chlorogenic acid, an ester of caffeic acid and quinic acid, is particularly effective in neutralizing reactive oxygen species (ROS) and has been associated with anti-inflammatory and cardioprotective effects.

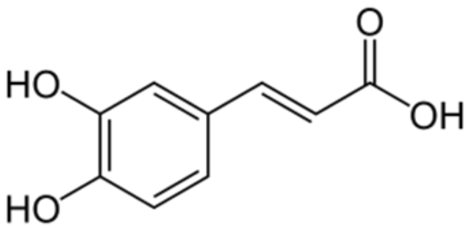

Fig. 19: Caffeic acid

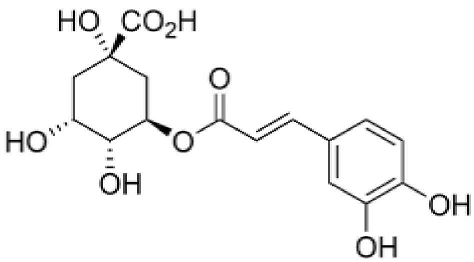

Fig. 20: Chlorogenic acid

- **Tannic Acid and Gallic Acid**: Tannic acid and gallic acid are hydrolyzable tannins that contribute to the astringent properties of plant extracts. These compounds interact with proteins and cellular membranes, leading to tissue contraction and reduced secretion, which is beneficial in traditional wound-healing applications. Gallic acid, a trihydroxy benzoic acid derivative, demonstrates strong radical-scavenging activity, while tannic acid forms complexes with biomolecules, aiding in wound contraction and microbial inhibition.

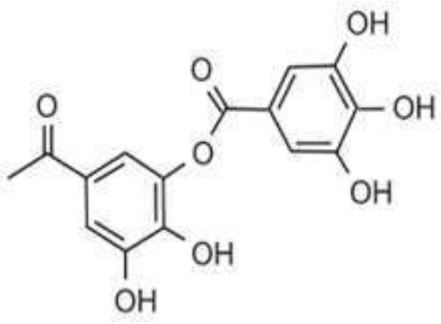

Fig. 21: Tannic Acid

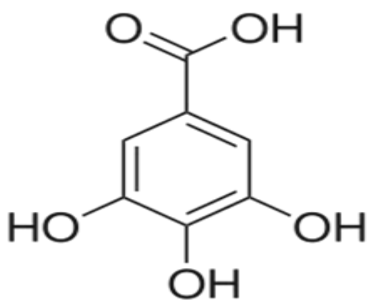

Fig. 22: Gallic Acid

The structural features of these phenolic compounds, including hydroxyl groups and conjugated double bonds, enhance their redox potential, making them effective in mitigating oxidative damage. Their mechanisms include hydrogen atom transfer, single electron transfer, and metal ion chelation, which collectively contribute to their biological activity. Further research is needed to explore their pharmacokinetics and clinical efficacy in therapeutic applications.

4.2. Chemotaxonomic Significance [29, 30]

The phytochemical profile of *S. bryopteris*, particularly its distinctive biflavonoid composition, serves as a valuable chemotaxonomic marker differentiating it from other Selaginella species. The presence of amentoflavone, hinokiflavone, and selaginellin in specific ratios provides a chemical fingerprint that can aid in species authentication, especially when morphological characteristics prove insufficient for definitive identification. Moreover, ecological factors significantly influence the plant's phytochemical composition, with specimens from higher altitudes generally exhibiting elevated biflavonoid concentrations, likely as an adaptive response to increased UV exposure and oxidative stress.

5. Medicinal Properties

5.1 Traditional Medicinal Applications [31]

Selaginella bryopteris has been widely recognized in traditional medicinal systems, particularly within Ayurveda, for its therapeutic potential in treating various health conditions. The plant is frequently employed for wound healing, where fresh fronds are crushed and applied topically to promote tissue repair and reduce the risk of infections. This application is attributed to the presence of bioactive compounds that may enhance cellular regeneration and possess antimicrobial properties. In gynecological care, *S. bryopteris* is utilized in the form of decoctions to address menstrual irregularities, leucorrhea, and post-partum complications. Traditional practitioners suggest that its bioactive constituents help regulate hormonal imbalances and exert anti-inflammatory effects, contributing to its efficacy in managing these conditions. Additionally, the plant is used in the treatment of urinary disorders, including urolithiasis, urinary tract infections, and renal insufficiency. Aqueous preparations of *S. bryopteris* are believed to exhibit diuretic and litholytic properties, facilitating the elimination of renal calculi and alleviating urinary discomfort. The hepatoprotective potential of *S. bryopteris* has also been documented in traditional medicine, where it is prescribed for jaundice and other liver-related ailments. Its extracts, often combined with other hepatoprotective herbs, are thought to enhance liver function by mitigating oxidative stress and promoting detoxification processes. Furthermore, the plant is employed in respiratory care, particularly for bronchial asthma and chronic cough. Inhalation of vapors from heated fronds is traditionally recommended, possibly due to bronchodilatory and expectorant effects that help alleviate respiratory distress. Neurological applications of *S. bryopteris* include its use in epilepsy, memory enhancement, and anxiety disorders. Traditional formulations containing this plant are believed to modulate neurotransmitter activity, exerting neuroprotective and anxiolytic effects. Indigenous communities also associate the plant's ability to revive after desiccation—a phenomenon known as resurrection—with its purported capacity to restore vitality. As such, it is often administered as a general tonic for convalescence and age-related debilities, reinforcing its reputation as a rejuvenating agent in traditional medicine. The therapeutic uses of *S. bryopteris* are deeply rooted in empirical knowledge passed down through generations. While modern scientific research continues to explore its pharmacological mechanisms, traditional applications highlight its significance as a versatile medicinal plant in Ayurveda and other indigenous healing systems. Further studies are necessary to validate these traditional claims through rigorous pharmacological and clinical investigations.

5.2 Pharmacological Activities

Contemporary scientific investigations have substantiated many traditional claims and uncovered additional therapeutic potentials:

5.2.1 Antioxidant Activity [32, 33]

Multiple studies have demonstrated the robust antioxidant capacity of S. bryopteris extracts:

- **Free Radical Scavenging:** Methanolic extracts have shown significant DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging activity with IC50 values ranging from 28-45 μg/ml, comparable to standard antioxidants like ascorbic.
- **Lipid Peroxidation Inhibition:** Aqueous extracts significantly reduce malondialdehyde formation in experimental models, indicating protection against membrane damage.
- **Cellular Protection:** Pre-treatment with S. bryopteris extracts enhances cellular tolerance to oxidative stressors like hydrogen peroxide and UV radiation in fibroblast cultures.

The antioxidant properties are primarily attributed to biflavonoids, particularly amentoflavone, and phenolic constituents that act through both direct radical scavenging and enhancement of endogenous antioxidant systems.

5.2.2 Anti-inflammatory Effects [34-36]

Several studies have documented notable anti-inflammatory properties:

- **Prostaglandin Synthesis Inhibition:** Ethanolic extracts (100-300 mg/kg) demonstrate significant reduction in carrageenan-induced paw edema in rodent models, comparable to diclofenac sodium.
- **Pro-inflammatory Cytokine Modulation:** Treatment with amentoflavone-rich fractions reduces TNF-α, IL-1β, and IL-6 levels in lipopolysaccharide-stimulated macrophages.
- **NF-κB Pathway Suppression:** Biflavonoids from *S. bryopteris* inhibit the nuclear factor-kappa B signaling pathway, a key regulator of inflammatory responses.

5.2.3 Antimicrobial Activity [37, 38]

The plant exhibits broad-spectrum antimicrobial properties:

- **Antibacterial Effects:** Ethyl acetate fractions demonstrate significant inhibitory activity against Staphylococcus aureus, Bacillus subtilis, and Escherichia coli with minimum inhibitory concentrations (MICs) ranging from 125-250 μg/ml.
- **Antifungal Properties:** Methanolic extracts inhibit the growth of Candida albicans, Aspergillus niger, and Trichophyton rubrum with MICs between 250-500 μg/ml.
- **Antiviral Activity:** Hinokiflavone and amentoflavone have shown promising activity against Herpes Simplex Virus (HSV) and Human Immunodeficiency Virus (HIV) in preliminary in vitro studies.

5.2.4 Adaptogenic and Stress-Protective Effects [39, 40]

The plant's remarkable resurrection capability correlates with its adaptogenic properties:

- **Enhanced Stress Tolerance:** Pre-treatment with aqueous extracts improves survival rates in rodents subjected to various stressors including hypoxia, hypothermia, and physical exertion.
- **Neuroprotection:** Biflavonoid-rich fractions demonstrate significant protection against glutamate-induced neurotoxicity in cortical

neuronal cultures, suggesting potential applications in neurodegenerative disorders.

- **Heat Shock Protein Modulation:** Extracts upregulate heat shock proteins (particularly Hsp70), enhancing cellular resilience against environmental stress.

6. Resurrection Biology and Molecular Mechanisms

6.1 Desiccation Tolerance Mechanisms [41-43]

The extraordinary resurrection capability of *S. bryopteris* involves sophisticated physiological and molecular adaptations:

- **Cellular Protection:** Accumulation of protective sugars (particularly trehalose and sucrose) stabilizes membrane structures and prevents protein denaturation during dehydration.
- **Antioxidant Defenses:** Enhanced expression of antioxidant enzymes including superoxide dismutase, catalase, and glutathione peroxidase mitigates oxidative damage during desiccation and subsequent rehydration.
- **LEA Protein Expression:** Late Embryogenesis Abundant (LEA) proteins increase dramatically during dehydration, providing protection to cellular components.
- **Metabolic Reprogramming:** Controlled downregulation of metabolic processes during dehydration and their coordinated restoration upon rehydration prevents metabolic dysfunction.

6.2 Gene Expression and Proteomics [44-46]

Transcriptomic and proteomic analyses have revealed significant molecular insights:

- **Dehydration-Responsive Gene Network:** Upregulation of genes involved in osmoprotection, antioxidant defense, and protein stabilization during progressive dehydration.
- **Transcription Factor Dynamics:** Increased expression of specific transcription factors, particularly those belonging to the NAC, bZIP, and HSF families, orchestrating the desiccation response.
- **Small RNA Regulation:** MicroRNAs play crucial roles in post-transcriptional regulation during dehydration and rehydration cycles.

The molecular mechanisms underlying *S. bryopteris's* resurrection capability not only explain its legendary status but also provide valuable insights for developing stress-tolerant crops and novel therapeutic approaches for conditions involving oxidative damage.

7. Conservation and Sustainability [47-54]

7.1 Conservation Status

S. bryopteris faces significant conservation challenges:

- **Population Decline:** Unsustainable harvesting for medicinal purposes has led to substantial population reductions, particularly in accessible regions of central India.
- **Habitat Destruction:** Mining activities, deforestation, and agricultural expansion in rocky outcrops have diminished available habitats.
- **Climate Change Impact:** Altered precipitation patterns affect the plant's natural dehydration-rehydration cycles, potentially compromising reproduction and establishment.
- **Slow Regeneration:** The species exhibits relatively slow growth rates and specific habitat requirements, limiting natural recovery from population depletion.

While not currently listed in the IUCN Red List, regional assessments indicate vulnerability, with some populations facing local extinction risks.

7.2 Sustainable Harvesting Practices

Implementing sustainable harvesting approaches is crucial for balancing utilization and conservation:

- **Collection Guidelines:** Harvesting limited to 30% of mature fronds per colony, allowing sufficient regeneration capacity.
- **Seasonal Considerations:** Optimal collection during post-monsoon periods (October-November) when the plant has completed its reproductive cycle.
- **Community-Based Management:** Engaging local communities in conservation through education and establishment of sustainable harvesting protocols.
- **Certification Systems:** Developing certification mechanisms for sustainably harvested material to create market incentives for conservation.

7.3 Cultivation and Propagation

Cultivation offers a promising alternative to wild collection:

- **Spore-Based Propagation:** Collection and germination of spores under controlled conditions, followed by establishment in suitable substrates.
- **Vegetative Reproduction:** Division of established colonies and rhizome propagation have shown moderate success rates.
- **In Vitro Techniques:** Development of tissue culture protocols, particularly using spore culture and prothallial multiplication, has demonstrated promising results for mass propagation.
- **Habitat Mimicry:** Creating cultivation environments that replicate natural rocky habitats, including proper drainage and seasonal moisture fluctuations.

Despite these advances, commercial-scale cultivation remains challenging due to the plant's specific ecological requirements and relatively slow growth. Nevertheless, community-based cultivation initiatives in central India have demonstrated viability at a modest scale, offering both conservation benefits and sustainable livelihoods.

8. Future Research Directions [55-60]

8.1 Phytopharmacological Research Priorities

- **Bioactive Compound Isolation:** Further isolation and characterization of novel compounds, particularly selaginellins and related structures with distinctive pharmacological profiles.
- **Structure-Activity Relationships:** Systematic investigation of structure-activity relationships among biflavonoids to identify potential lead compounds for drug development.
- **Pharmacokinetic Studies:** Determination of absorption, distribution, metabolism, and excretion profiles of key bioactive compounds to assess bioavailability and potential delivery systems.
- **Synergistic Interactions:** Exploration of potential synergistic effects among *S. bryopteris* constituents and with conventional therapeutics.

8.2 Clinical Research Opportunities

- **Standardized Clinical Trials:** Conducting robust randomized controlled trials for specific applications, particularly in wound healing, hepatoprotection, and stress-related disorders.
- **Biomarker Development:** Identification of reliable biomarkers for monitoring therapeutic efficacy in clinical applications.
- **Safety Profiles:** Comprehensive assessment of long-term safety, potential herb-drug interactions, and appropriate dosage guidelines.

8.3 Conservation Biology Research

- **Population Genetics:** Investigation of genetic diversity and population structure to inform conservation strategies and identify priority populations for protection.
- **Ecological Requirements:** Detailed characterization of microhabitat requirements for optimizing ex situ conservation and cultivation efforts.

- **Climate Change Impact Models:** Development of predictive models for climate change impacts on natural populations to guide proactive conservation measures.

CONCLUSION

Selaginella bryopteris represents a fascinating convergence of ancient mythology and modern pharmacological potential. Its identification as the legendary Sanjeevani booti from the Ramayana finds scientific credibility in its remarkable resurrection capabilities and diverse medicinal properties. Contemporary research has substantiated many traditional applications through the identification of bioactive compounds, particularly biflavonoids with significant antioxidant, anti-inflammatory, and adaptogenic activities. The phytochemical diversity of S. bryopteris provides promising avenues for novel drug development, especially for conditions involving oxidative stress, inflammation, and microbial infections. However, realizing this potential requires balanced approaches that address both scientific development and conservation concerns. The integration of sustainable harvesting practices, cultivation initiatives, and habitat protection is essential for ensuring the continued availability of this valuable pteridophyte for both traditional and modern medicinal applications. As research progresses, the mythological Sanjeevani narrative continues to inspire scientific exploration, demonstrating how ancient traditional knowledge can guide contemporary pharmaceutical discovery. The ongoing elucidation of S. bryopteris's molecular mechanisms and bioactive constituents not only enhances our understanding of resurrection biology but also expands the frontiers of natural product-based therapeutics, potentially yielding innovative treatments for challenging medical conditions.

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