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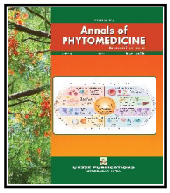

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Ecology, ethnopharmacology and conservation aspects of *Nardostachys jatamansi* (D. Don) DC.: An endangered, invaluable medicinal plant species of the Himalayas

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Abstract

Nardostachys jatamansi (D. Don) DC., commonly referred to as Indian spikenard, is a medicinally important plant species found the Himalayas at high altitudes and is presently considered critically endangered. It is widely used in Tibetan, Chinese, Indian, Japanese, Nepalese, and Bhutanese medicine. High demand for *N. jatamansi* in domestic and international markets, largely for its rhizomes, together with illegal and unsustainable collection practices, has made this species endangered with extinction. Thus, more research incorporating *in vitro* biotechnological methods is needed to support its sustainable utilization and long-term conservation. Nevertheless, more investigation is required to increase our understanding of this herb's chemical makeup, medicinal potential, and state of conservation. This review article presents a comprehensive overview of the existing knowledge on the pharmacology, phytochemistry, trade importance, ethnomedicinal uses, and the potential role of modern plant biotechnology approaches in conserving this valuable plant species.

1. Introduction

The history of *N. jatamansi* is worth reviewing in 1790, renowned orientalist Sir William Jones found that the Greeks' "Nardus," the Bible's "Spidenard," the Persians and Arabians' "Sumbul-e-Hind," and the Indians' "Balchar" were all Jatamansi of Sanskrit. He received a specimen from Bhutan under the name "Jatamansi," the specimen consisted of parts from two different plants: the aerial portion belonged to *Valeriana jatamansi*, while the rootstock originated from *Nardostachys jatamansi*. In 1835, Jones classified this specimen as *Valeriana jatamansi*, and earlier, in 1795, William Roxburgh added to the confusion by publishing an illustration derived from the same specimen. In 1821, D. Don discovered a mistake and obtained a specimen of real Jatamansi, which he re-described as *Valeriana jatamansi* and then as *Patrinia jatamansi*. Subsequently, in 1830, De Candolle described another species, *Nardostachys grandiflora*, and established the new genus Nardostchys, naming it *Nardostachys jatamansi.* Although several authorities have regarded *N. jatamansi* and *N. grandiflora* as two separate species that explain the variations in inflorescences, Weberling and Engel (1975) proposed that not only *Nardostachys jatamansi* but also *Nardostachys chinensis* and *Nardostachys gracilis* Kitamura belong to the range of variability of *Nardostachys grandiflora* and recommended that research should be focused on the environmental factors that affect the genus.

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Weberling and Engel (1975) have provided a detailed description of the morphological traits of *N. jatamansi*. A perennial herb, *N. jatamansi* has a robust, unbranched or sparsely branched woody plant and a fragrant rhizome covered in thick, reddish-brown fiber from the remaining petioles of fallen radical leaves. It has a single long tap root and a rhizome that is 2-7, and occasionally up to 12. Generally found clinging to grassy slopes and steep rocky cliffs, the plant is slightly lithophilous. It has also been reported to occur in moist meadows, along the margins of small streams in high-altitude valleys, and on mountain slopes at elevations ranging from 3000 to 4000 meters. The flowering of the plant between July and August, while fruiting takes place from September to October.

N. jatamansi contains both volatile and non-volatile chemical constituents. The volatile fraction is primarily rich in sesquiterpenes, while the non-volatile components comprise sesquiterpenes along with coumarins, lignans, neolignans, and alkaloids (Pathak and Godela 2024; Chen *et al*., 2017). Due to which it has traditionally been used in ayurvedic and traditional medical systems (Sharma *et al*., 2000; Chen and Mukherji, 2013; Kaur *et al*., 2020). However, the population of *N. jatamansi* has declined by 75-80% in India (Singh *et al*., 2013) and it is categorized as Endangered in the states of Arunachal Pradesh, Sikkim, and Himachal Pradesh, while it is considered critically Endangered in Uttarakhand. Considering its rapid population decline, high trade value, endemic distribution, continuous anthropogenic pressure, and the likelihood of further decline in the future, the species has been categorized as critically Endangered under criterion A2cd (Chauhan, 2021). According to the National Medicinal Plants Board, Government of India, most plants in the market are collected from natural habitats and traded illegally, with limited records of legal rhizome collection (Kaur *et al*., 2020). Therefore, the governments of India and Nepal have prohibited its illegal harvesting and trade of

this valuable medicinal plant. Purohit *et al*. (2012), emphasized that conserving this important high-altitude plant necessitates the establishment of efficient *ex situ* conservation sites, along with the active involvement of forest authorities and local village communities. Researchers are focused on alternative methods for conserving this priceless Himalayan plant in order to guarantee its ongoing supply and investigate its potential for medical use.

It is expected that the gap would open up new study directions and challenges from a conservation standpoint. Additionally, this assessment will give government-funded organizations, researchers, policy makers, botanists, and conservationists valuable information on prospective conservation strategies and ways to support economic potential. Although, many Himalayan biodiversity hotspots have high endemic floral value and potential medicinal value, only a small number of these hotspots have been exploited in the market for herbal medicines and have undergone scientific study. Due to inadequate scientific investigation and ignorance, a number of Himalayan species with great promise have not been employed commercially. The current review covers botanical categorization, taxonomy, ethnobotany, phytochemistry, and pharmacology up until January 2026 and is based on literature that has been published in a number of scientific web directories, such as Google Scholar, Science Direct, Springer, and PubMed. Medicinal usage, botany, ecology and distribution, pharmacological activity, and traditional uses of *N. jatamansi* were the keywords utilized to locate pertinent material.

2. Geographical distribution

The species occurs at elevations ranging from 3,000 to 5,000 m above sea level in the alpine Himalayan regions of Bhutan, China, India, Myanmar, and Nepal (Airi *et al*., 2000). Chauhan and Nautiyal (2005) and Ved *et al*. (2015) reported its presence in the Indian states of Himachal Pradesh, Uttarakhand, Sikkim, and Arunachal Pradesh, as well as in Nepal, Bhutan, Myanmar, and southwestern China. It is also found in the Xizang (Tibet) region and the Chinese provinces of Gansu, Sichuan, and Yunnan (Mulliken and Crofton, 2008).

3. The Ecology and Taxonomy of *N. jatamansi* and its adulterant

The perennial rhizomatous herbaceous plants *N. jatamansi* and *V. jatamansi* are related. There are several colloquial names for *N. jatamansi* in India, including tapaswani, manshi, spikenard, jatamaschi, and jatamansi (Purnima *et al*., 2015).

The species is recognized as synonymous as *Patrinia jatamansi* D. Don, *N. grandiflora* DC, and *N. chinensis* Batalin and *N. gracilis* Kitam are among them (Mabberley and Noltie, 2014). However, Webberling and Engel (1975), regarded the genus *Nardostachys* as monospecific and pointed out that there is a continuous range of variability within *N. jatamansi*, indicating that the variability of many traits is not discontinuous. The five types that Webberling and Engel (1975) identified are the jatamansi, *grandiflora*, *gracilis*, *longiflora*, and *laxiflora* types. Both species (the top portion of the rhizome and the stem base) are marketed for Materia Medica, and *N. jatamansi* is frequently mistaken for *V. jatamansi* (Mabberley and Noltie, 2014). According to Raina and Negi (2015), *V. jatamansi* shares a number of colloquial names, including Indian *Valerian jatamansi*, and manshi, which causes market confusion, misidentification, and adulteration. While *V. jatamansi*'s petioles are hairless, jatamansi's (*N. jatamansi*) rhizomes are typically covered in twisted, tufted, fibrous, completely haired petioles (Dhiman *et al*., 2020).

Table 1 lists the differences between *N. jatamansi* and *V. jatamansi*. Nevertheless, a close examination of the two species' protologues made it evident which was different. The ovary may be tomentose or covered in soft hairs; the stigma may be simple and capitate; the leaves may be lanceolate, acute, entire, hairy, and radical; the flowers may be in fascicles or clusters with four stamens; and the corolla's throat may be bearded or hairy (Lambert 1821).

V. jatamansi, flowers contain radical petiolate leaves, 3 stamens, and cordate leaves grouped in a cluster of 4 (Jones 1790). While *V. jatamansi* grows at levels between 1200 and 4000 meters above sea level (Rather *et al*., 2012; Mukherjee *et al*., 2013; Dhiman *et al*., 2020), *N. jatamansi* is found at high elevations between 3000 and 5200 meters above sea level (Nautiyal *et al*., 2003; Chauhan and Nautiyal, 2005). Alongside other species, including *Bergenia* sp. and *Picrorhiza kurroa* Royle ex Benth., *N. jatamansi* grows on riverbanks and slopes between 40 and 70 degrees (Chauhan and Nautiyal, 2005).

Dhiman and Bhattacharyya (2020) have pointed out chemical variations between the two species in their latest paper. Both generate essential oils with therapeutic value from their subsurface tissues (rhizomes and roots). While the essential oils of *V. jatamansi* are abundant in valepotriates, such as sweet scents with calming effects, the essential oils isolated from *N. jatamansi* contain a variety of therapeutic qualities (Toolika *et al*., 2015). The appropriate use of *N. jatamansi* in pharmaceutical enterprises and traditional medicinal systems thus depends on accurate identification and differentiation.

4. Ethnomedicinal uses

Since ancient times, *N. jatamansi* has served as an important source of traditional medicine for a large proportion of the world's population. Now a days, they are also used to make pharmaceutical medications. The leaves, stems, roots, flowers, and bulbs of plants have all been utilized for ages to treat a variety of illnesses. Ayurvedic classics like Charak Samhita, Nighantus Chikitas Granthas, and Sushruta Samhita have extensive documentation of the medicinal uses of *N. jatamansi*, and traditional records of its use in India in the Vedic era (500-1000 BCE) (Sharma *et al*., 2000; Chen and Mukherji, 2013).

Traditionally, the plant is valued for its sedative, nervine, and rejuvenating properties, and is commonly used to treat epilepsy, hysteria, insomnia, anxiety, and mental disorders (Ganguly *et al*., 2026). Tibetan community uses of *N. jatamansi* to cure high-altitude sickness, fever, headaches, and wounds (Ghimire and Aumeeruddy-Thomas, 2009). People who live in the Western Himalayan states of India use *N. jatamansi* as a paste to treat a variety of illnesses. Many ethnic groups, including Bhotias, Tolchhas, and Garhwalis in Uttarakhand, also use this plant to treat a variety of ailments, including colds, coughs, arthritis, heart illness, urinary issues, and religious rites (Negi *et al*., 2018). In the Eastern Himalayan region of West Kameng, Arunachal Pradesh, the roots of *N. jatamansi* are used as tonics to treat fever, cold, cough, skin issues, and diarrhea (Tiwari *et al*., 2009). Kala *et al*. (2006) state that in northern India, roots are utilized in religious ceremonies. Remarkably, traditional healers in Kerala use stem decoctions for postpartum care, even though the state is far from the Himalayas (Anvar and Haneef, 2015).

Table 1: Comparison of *N. jatamansi* and V. *jatamansi*

	N. jatamansi	***V. jatamansi***
Currently accepted scientific names enlisted in the plant list of Kew Botanical Gardens and the Plant list databases	The currently accepted scientific name of *Nardostachys jatamansi* is *Nardostachys jatamansi* (D.Don) DC.	*Valeriana jatamansi* is recognized as *Valeriana jatamansi* Jones ex Roxb. (also cited as *Valeriana jatamansi* Jones).
Synonymy	*N. jatamansi* has been reported under several synonyms, including *Nardostachys grandiflora* DC., *Patrinia jatamansi* D.Don, *N. chinensis* Batalin, and *N. gracilis* Kitamura.	*V. jatamansi* is also known by the synonym *Valeriana wallichii* DC.
Common names	*N. jatamansi* is commonly referred to as Indian spikenard or jatamansi.	*V. jatamansi* is widely known as Indian valerian or jatamansi.
Conservation status and population trend	*N. jatamansi* is categorized as critically Endangered (A2cd, version 3.1) under the IUCN Red List criteria, with a continuously declining population.	*V. jatamansi* is not listed in the IUCN Red Data List
Geographic coordinates and distribution	*N. jatamansi* between 30°10 N to 31° 06 N latitude and 78°18 E to 79° 70 E longitude. Its distribution extends across Bhutan, China, India (Uttarakhand, Sikkim, Himachal Pradesh, Arunachal Pradesh), Myanmar, and Nepal.	*V. jatamansi* occurs between 29° 4600 N to 30° 24 21 N latitude and 78° 17 21 E to 80° 18 00 E longitude, and is distributed in China (Chongqing, Guizhou, western Hubei, Hunan, Sichuan, Yunnan), Tibet, India, Vietnam, and Afghanistan
Altitudinal range and endemism	*N. jatamansi* grows at higher elevations ranging from 2200-4800 m above mean sea level and is endemic to the higher Himalayan region.	*V. jatamansi* occurs at relatively lower altitudes (1200-3000 m) and is native to lower Himalayan zones.
Morphological features	*N. jatamansi* is an herbaceous plant measuring 10-60 cm in height. Leaves are primarily radical, and the stem appears mainly during flowering; cauline leaves are present only on reproductive shoots. Rhizomes are covered with persistent fibrous leaf bases.	*V. jatamansi* grows up to 50 cm tall, often bearing several stems (15-45 cm long). It possesses both radical and cauline leaves with variable wavy margins that may be entire or sinuate. Its rhizomes lack surface fibers and yield approximately 2.1% oil on a dry weight basis.
Cultivation status	Cultivation attempts of *N. jatamansi* have largely been unsuccessful	*V. jatamansi* can be successfully cultivated, even at comparatively lower altitudes
Commercially utilized parts and propagation	Rhizomes and their essential oils constitute the primary commercial products. Propagation occurs sexuallythrough seeds and vegetatively *via* rhizomes.	
Habitat and soil preference	*N. jatamansi* inhabits alpine grasslands, rocky cliffs, and Himalayan Mountain peaks, preferring well-drained sandy loam soils with sufficient moisture.	Commonly found on north-facing slopes, open hill areas, forested terrains. It tolerates diverse soils but performs best in well-drained, humus-rich, nitrogen-enriched heavy loam soils with adequate moisture.
Seasonal growth pattern	Vegetative growth in *N. jatamansi* occurs from May to June, flowering from June to July, fruiting from August to October, followed by senescence in late October.	*V. jatamansi* shows vegetative growth from January to February, with flowering and fruiting occurring between March and June.
Oil yield	The rhizomes of *N. jatamansi* may yield up to 2.9% essential oil (dry weight basis).	*V. jatamansi* typically yields about 2.1%.
Pharmacological activities	Antiarrhythmic, anxiolytic, sedative, anticonvulsant, antidepressant, hypotensive, nootropic, hair growth-promoting, anti-Alzheimer's, antispasmodic, diuretic, and cardioprotective properties.	Anticancer, anticonvulsant, anti-Parkinson's, anti-Alzheimer's, antidepressant, diuretic, and sedative activities.
Secondary metabolites		
Alkaloids	*N. jatamansi* contains actinidin.	*V. jatamansi* contains actinidin and valeranine.
Phenolic compounds	*N. jatamansi* includes jatamansinol, protocatechuic acid, syringic acid, jatamansin, oroselol, angelicin, and coumarins.	*V. jatamansi* contains jatamansinol, chlorogenic acid, caffeic acid, isoferulic acid, and pinoresinol.

Sterols and fatty acids	β-sitosterol has been reported in both species (less extensively studied in *N. jatamansi*).	Additionally, *V. jatamansi* contains linolenic acid, isovaleric acid, and methyl eicosanoate.
Terpenoids	Both species share several terpenes such as valera-none (jatamansone), valerian-4,7-diene, α-and β-patchoulene, valerenic acid, patchouli alcohol, elemol, β-eudesmol, α-gurjunene, and spirojatamol. However, each species also contains distinct terpenoid constituents, contributing to differences in their pharmacological and aromatic profiles.	

5. Pharmacology based studies

The abundance of data supports the ethnomedical applications of *N. jatamansi* in conventional medicine and substantiates its pharmacological benefits. Several solvent extracts, including those for antioxidant activities, have been made from the leaves, roots, and rhizomes in a number of biological tests due to the long and rich history of *N. jatamansi* in traditional medicine (Table 2).

It is interesting to note that very few studies have examined entire *N. jatamansi* plants, despite the fact that underground tissues are crucial plant sections that many researchers frequently use. The hepatoprotective effects of 50% ethanolic extracts of *N. jatamansi* whole plants on lipid peroxidation were examined by Ali *et al.* (2005); Umanath *et al.* (2025). An aqueous extract of entire plants was also shown to have an antidiabetic impact on pretreatment mice, preventing type 1 diabetes and pancreatic b-cell damage while also improving the survival of cytokine-treated RIN5mF cells (Song *et al.*, 2010).

The roots of *N. jatamansi* are also a good source of biological activity; methanolic root extracts have been shown to have anticancer activity against ER- and MCF-7 breast carcinoma cells (Chaudhary *et al.*, 2015); an ethanolic extract of roots was shown to have antidiabetic and antihyperglycemic effects on alloxan-induced albino rats in a study by Ghaisas *et al.* (2007); Suryavanshi *et al.* (2017) examined the use of an ethanolic root extract and reported low viability of neuroblastoma cell lines (IMR-32 and SK-N-MC), but no effect on HEK-293 cells; interestingly, root extracts also demonstrated neuroprotective activity against Alzheimer's disease (Liu *et al.*, 2015; Umanath *et al.*, 2025) and antidepressant activity toward the middle cerebral artery and acute cerebral ischemia (Prabhu *et al.*, 1994). A study by Ko *et al.* (2018), establishes a clear link between nardosinone-type sesquiterpenes from *N. jatamansi* and anti-neuroinflammatory activity in LPS-stimulated BV2 microglial cells. The compounds suppressed NO and PGE, production by downregulating iNOS and COX-2, while also reducing pro-inflammatory cytokines (IL-1β, IL-6, TNF-α). Mechanistically, their effects were mediated through inhibition of NF-κB activation and MAPK (ERK, JNK, p38) signaling pathways, highlighting their potential as lead molecules for neuroinflammation-targeted drug development.

Table 2: Details of pharmaceutical activities

Activity	Extracting solvent/extract/test system/used against/major outcomes
Antifungal activity	The essential oil tested *in vitro* showed strong antifungal efficacy against molds such as *Aspergillus flavus*, *Fusarium oxysporum*, and *Aspergillus niger* (Mishra *et al.*, 1995). Additionally, it inhibited dermatophytes including *Trichophyton* and *Microsporum* species (Nautiyal, 2013).
Antimicrobial activity	A 50% ethanol extract, evaluated under *in vitro* conditions, demonstrated antibacterial activity against *Escherichia coli* (21 mm inhibition zone), *Klebsiella pneumoniae* (14 mm), *Pseudomonas aeruginosa* (14 mm), *Staphylococcus aureus* (12 mm), and *Salmonella typhimurium* (11 mm) (Sharma *et al.*, 2016).
Anti-inflammatory activity	A methanolic (MeOH) extract evaluated *in vivo* in female C57BL/6 mice demonstrated a protective effect against endotoxin-induced shock, suggesting notable anti-inflammatory potential (Bae *et al.*, 2014).
Hepatoprotective activity	A 50% ethanol extract demonstrated protective effects against alkali-induced liver injury in male Wistar rats exposed to hepatotoxic agents (Ali *et al.*, 2000). Furthermore, studies conducted in Swiss albino mice showed significant chemopreventive effects on the skin (Ali *et al.*, 2005).
Anti-Parkinson activity	Ethanolic extract administered *in vivo* to male Wistar rats showed neuroprotective properties, helping delay neuronal degeneration (Ahmad *et al.*, 2006).
Anticonvulsant activity	re-treatment with an ethanol extract in male albino Wistar rats increased the protective index of phenytoin against induced seizures (Rao *et al.*, 2005)
Neuroprotective activity	A 95% ethanol extract evaluated *in vivo* in male Wistar rats improved glutamate regulation, enhanced catalase enzyme activity, and reduced lipid peroxidation (Salim *et al.*, 2003).
Antidiabetic activity	An 80% ethanol extract tested in alloxan-induced male albino rats exhibited significant antihyperglycemic effects at higher doses (Kumar *et al.*, 2011). Similarly, the aqueous extract (AE) protected pancreatic â-cells from damage in male ICR mice (Song *et al.*, 2010).
Memory-enhancing activity	A 95% ethanol extract studied in Swiss mice models improved learning ability and supported memory restoration (Joshi and Parle, 2006).

Hypoglycemicactivity	Ethanolic extract evaluated in alloxan-induced male albino rats produced a moderate reduction in blood glucose levels (Ghaisas *et al*., 2007).
Insecticidal activity	The essential oil demonstrated insecticidal activity *in vitro* against *Liposcelis bostrychophila* (LC_{50} = 0.74 mg/l), *Sitophilus zeamais* (LC_{50} = 82.13 mg/l), and *Tribolium castaneum* (LC_{50} = 53.29 mg/l) (Liu and Liu, 2014).
Anticancer activity	Ethanol and aqueous extracts evaluated *in vitro* against lung carcinoma (CORL-23) and prostate cancer (PC3) cell lines exhibited moderate cytotoxic activity, with IC_{50} values of 45.7 mg/ml and 22.97 mg/ml, respectively (Saetung*et al*., 2005; Liu *etal*., 2018). The methanolic extract showed notable anticancer activity against breast carcinoma cell lines MCF-7 and ER-MDA-MB-231, with IC_{50} values of 23.83 mg/ml and 58.01 mg/ml (Chaudhary *et al*., 2015). Additionally, the ethanolic extract demonstrated dose-dependent inhibition of growth in human neuroblastoma cell lines IMR-32 (IC_{50} = 61.43 mg/ml) and SK-N-MC (IC_{50} = 63.42 mg/ml) (Suryavanshi *et al*., 2017). Furthermore, a methanol–chloroform (1:1) fraction displayed moderate cytotoxic effects against lung (A-59), prostate (DU-145), breast (MCF-7), and neuroblastoma (SK-N-SH) cancer cell lines, with IC_{50} values around 185.10 mM (Rekha *et al*., 2013).

Abbreviation: ES - Extracting solvent, AE-aqueous extract, EtOHethanol, CF- chloroform.

Crucially, both female mice and mouse peritoneal macrophages demonstrated an anti-inflammatory response to the methanolic root extract (Bae *et al*., 2014). Human cancer cell lines' dose-dependent growth suppression was eliminated by the 95% ethanolic extract and its n-butanol fraction, which also shown powerful anticancer potential (Bhagat *et al*., 2013). Using a 95% ethanolic root extract, Rao *et al*. (2005) examined the neurotoxicity profile of male Wistar rats. The threshold for maximal electroshock syndrome-induced seizures was considerably raised by root extracts. Additionally, root extracts in 50% hydroethanolic acid, n-hexane, n-butanol, 95% ethanol, and chloroform demonstrated strong anticancer activity (Pandita *et al*., 2012; Chaudhary *et al*., 2015; Suryavanshi *et al*., 2017). In addition to having strong pharmacological activity as an antidiabetic drug, the rhizome of *N. jatamansi* is the most physiologically active tissue (Figure.1).

Although, *N. jatamansi* essential oil exhibits notable antioxidant and antimicrobial activities, the study underscores that most reported bioactivities rely on extract-level assays (*e.g*., essential oils analysed by GC-MS) without isolating specific bioactive constituents or defining dose response relationships, highlighting gaps in mechanistic and standardized evaluation (Majeed *et al*., 2023). The neuro-protective effects of jatamansinol in a *Drosophila* Alzheimer's model but is limited to a non-mammalian system without clinical validation (Kizhakke *et al*., 2022). In another study, Li *et al*. (2021) systematically evaluated SERT activity across extracts, fractions, and constituents of *N. jatamansi*, the findings remain largely confined to preclinical *in vitro* and *in vivo* models without pharmacokinetic validation or clinical dose standardization. The coexistence of SERT enhancers and inhibitors also suggests complex bidirectional pharmacodynamics, which may complicate reproducibility and therapeutic predictability.

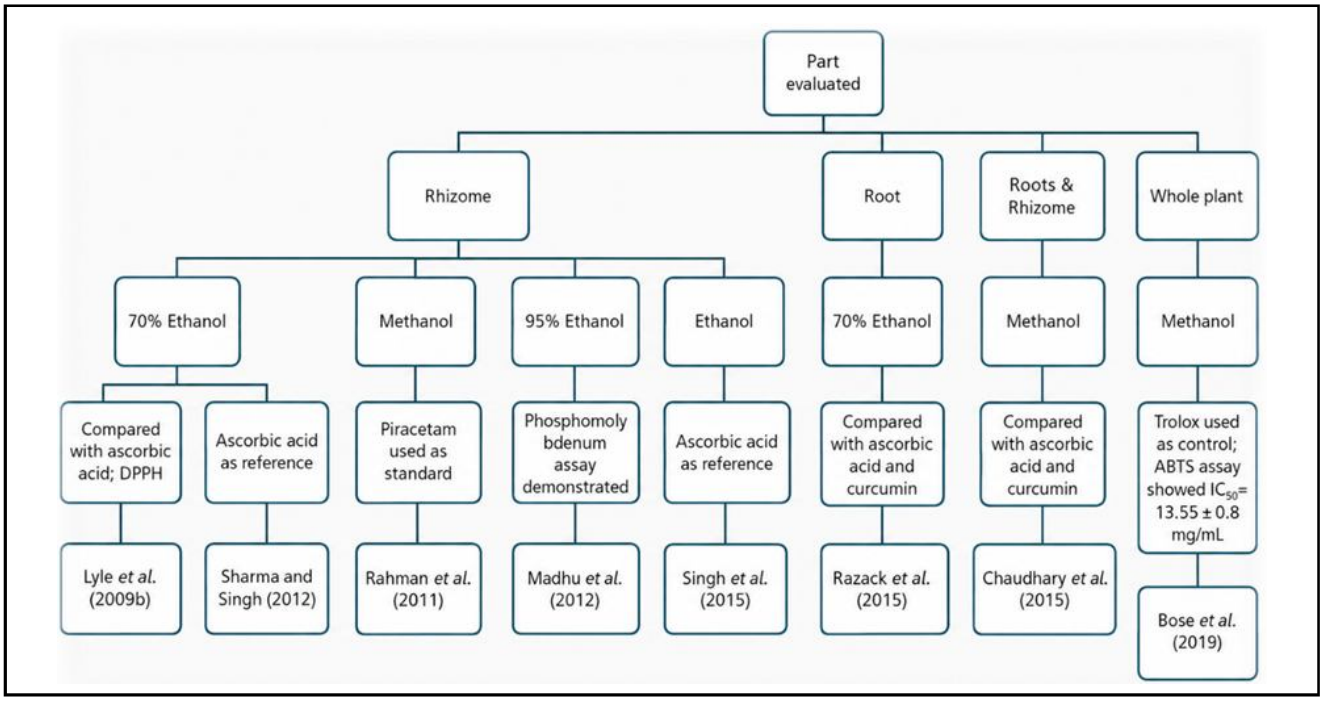

Figure 1: Antioxidant activities of different extracts.

The antioxidant potential of the essential oil was assessed using DPPH radical scavenging, reducing power, and ferric reducing antioxidant power (FRAP) assays (Majeed *et al*., 2023). The essential oil demonstrated notable DPPH radical scavenging activity with an IC_{50} value of 0.95 ± 0.008 mg/ml, while the IC_{50} for reducing power was 1.70 ± 0.082 mg/ml. Additionally, the FRAP value was determined to be 154 ± 6.13 mM Fe^{2+} equivalents per 100 mg of the sample.

Furthermore, Zhang *et al*. (2026) investigated the antioxidant and antimicrobial properties of the essential oil and reported significant free radical scavenging activity, along with antibacterial effects against *Staphylococcus aureus* and *Escherichia coli*. Molecular docking analysis further corroborated these results by demonstrating strong binding interactions between the major constituents of the essential oil and target proteins associated with antioxidant and antibacterial activities.

Pant *et al*. (2024) compared the antioxidant potential and flavonoid (quercetin) content of naturally grown and *in vitro* propagated plants. Methanolic root extracts from both sources were analyzed using the DPPH assay and HPLC. Results indicated comparable antioxidant activity in both samples (IC_{50} : 24.18 µg/ml for natural plants and 29.55 µg/ml for *in vitro* plants), while quercetin content was slightly higher in natural plants (1.95 mg/ml) than in *in vitro* plants (1.83 mg/ml), with similar retention times observed in HPLC analysis. Sandeep *et al*. (2015) highlights the antiandrogenic potential of *N. jatamansi* in the management of polycystic ovary syndrome (PCOS). Using the RIKILT yeast androgen bioassay and an estradiol valerate-induced rat model, the extract demonstrated significant antiandrogenic activity.

6. Phytochemicals and their biological functions

The structure, drug delivery methods, and mode of administration of phytochemicals make them promising sources for new dietary supplements and nutraceuticals (Zhang *et al*., 2017; Bose *et al*., 2019). Because *N. jatamansi* rhizomes contain physiologically active and industrially relevant phytochemicals with a range of biological activities, including coumarins, alkaloids, lignans, neoloignans, sesquiterpenes, and their derivatives, they are widely utilized for drug manufacture (Chatterjee *et al*., 2005; Saroya, 2011; Purnima, 2015; Bagchi *et al*., 1990; 1991a, b).

Actinidine (alkaloid), jatamansin and jatamansinol (coumarin), nardostachone, valeranone, jatamansinone, nardosinone, and jatamol A and B (sesquiterpenoids) are among the other important substances found in subterranean tissues (Zinzius, 1961; Biswas, 1963; Sastry *et al*., 1967; Bagchi *et al*., 1991b; Singh *et al*., 2013; Monga and Kumar, 2013; Bose *et al*., 2019; Dhiman and Bhattacharyya, 2020).

Hnamte *et al*. (2024) studied phytochemicals from *N. jatamansi*, particularly sesquiterpenoids, screened *in silico* for their ability to inhibit the HCV E2 envelope protein responsible for viral entry into hepatocytes. Molecular docking and ADME-toxicity analyses identified nardostachysin and α-gurjunene as promising E2 inhibitors, likely acting through stable hydrophobic interactions with key receptor-binding domains. Study by Yoon *et al*. (2024) showing that *cycloolivil*, a lignan isolated from *N. jatamansi*, significantly inhibits TNF-α/IFN-λ-induced inflammatory signaling in keratinocytes by blocking NF-κB nuclear translocation and suppressing JAK2/STAT1/STAT3 phosphorylation, leading to reduced IL-6 and COX-2 expression. Several novel and known sesquiterpenoids (*e.g.,* 7-methoxydesoxo-narchinol, kanshone N, narchinol A) isolated from *N. jatamansi* inhibited LPS-stimulated nitric oxide (NO) production in BV2 microglial cells (Yoon *et al*., 2018a). They also downregulated pro-inflammatory mediators (PGE, iNOS, COX-2, IL-1β, IL-6, TNF-α) by inhibiting the NF-κB signaling pathway, suppressing IκB-α phosphorylation and NF-κB nuclear translocation. The homoguaiane sesquiterpene *narjata-molide* from *N. jatamansi* exhibited antiproliferative activity against BEL-7402 human hepatocellular carcinoma cells, inducing cell cycle arrest at the G2/M phase, indicating a defined mechanistic effect on cell division regulatory pathways (Chai *et al*., 2021). The pyranocoumarin *jatamansinol*, a coumarin-type phytochemical in *N. jatamansi*, significantly extended lifespan, enhanced locomotor activity and memory, reduced Aβ42 levels, boosted antioxidant enzymes, and inhibited cholinesterase activity in an Alzheimer's fly model (Kizhakke*et al*., 2022) GC-MS and RP-HPLC profiling of *N. jatamansi* extracts showed significant antioxidant and protective activities against biomolecule oxidation (protein and DNA damage, ROS scavenging), which mechanistically supports oxidative stress mitigation, a key pathway for many chronic diseases (Razack *et al*., 2015). Desoxo-narchinol A and narchinol B from *N. jatamansi* exhibit strong anti-neuroinflammatory effects by inhibiting NF-κB signaling and inducing the Nrf2/HO-1 pathway in microglial cells. These effects involve MAPK and PI3K/Akt signaling and are partly reversed by HO-1 inhibition.

Table 3 includes several significant phytochemicals that are obtained from *N. jatamansi*and their biological activities. The major terpenoid ester in rhizomes is nardostachysin, a novel compound (Chatterjee *et al*., 2000). The rhizomes also contained Nardin, a sesquiterpene and pyranocoumarin, whose structure was determined by spectrum analysis (Chatterjee *et al*., 2005). Table 3 is a list of several significant phytochemicals that are obtained from *N. jatamansi*. Rhizomes contain a considerable amount of nardostachysin, a novel terpenoid ester (Chatterjee *et al*., 2000). According to Chatterjee *et al*. (2005), spectral analyses were used to determine the structure of nardin, a sesquiterpene and pyranocoumarin that was also discovered in the rhizomes.

The rhizomes contain nardin, a sesquiterpene and pyranocoumarin, whose structure was elucidated through spectral analysis (Chatterjee *et al*., 2005) and further confirmed by X-ray diffraction studies (Wu *et al*., 2018). Likewise, the subterranean tissues of *N. jatamansi* have been investigated for their phytochemical constituents, leading to the identification of two nardosinone-type sesquiterpenoids, kanshone J and kanshone K, along with several other sesquiter-penoids such as kanshone L, kanshone M, kanshone N, 7-methoxydesoxonarchinol, and nardosdaucanol (Yoon *et al*., 2018a, b).

The products' configurations and absolute structures were verified using 1D and 2D NMR studies as well as by MS. Nardal, a novel sesquiterpene, was extracted from the *N. jatamansi* plant by Rao *et al*. (2008). Essential oils are also considered to be one of the most important phytoconstituents found in subterranean areas (Arora *et al.,* 1962; Rucker *et al*., 1978; Paudyal *et al*., 2012). Thus, the essential oils of *N. jatamansi* are also used to produce angelecin, beta-sitosterol, beta-eudesmol, jatamansinol, alpha-patchoulense, beta-patchoulense, jatamansin, nardostachnol, and two terpenic coumarins (orosenol and jatamansin) (Shanbhag *et al*., 1964; 1965; Purnima *et al*., 2015; Dhiman and Bhattacharyya, 2020). Nonetheless, several of these

phytochemicals have different therapeutic properties and are also found in other plant species. To determine the precise phytochemicals of *N. jatamansi*, new techniques for separation, characterization, and purification must be created for full metabolic profiling. The biological functions of a small number of chemicals have been studied. As an illustration, nardosinone that was isolated from roots shown neurodegenerative properties (Li *et al*., 2014). Additionally, it was demonstrated that this chemical has an anti-inflammatory impact on lipopolysaccharide-induced murine peritoneal macrophages and murine endotoxin shock models (Shin *et al*., 2015). While the dinardokanshones C-E and isonardoeudesmols BC showed the greatest SERT activity, the new compounds isonardoeudesmols D and nardoeudesmol considerably decreased serotonin (SERT) activity (Wu *et al*., 2018). Interestingly, by preventing the synthesis of proinflammatory mediators, desoxonarchinol A and narchinol B demonstrated anti-inflammatory effects (Yoon *et al*., 2018 b). Some important phytochemicals derived from *N. jatamansi* are listed in Figure 2.

Table 3: Phytochemicals and their biological activities

Class	Compound Name	Plant art investigated	Reported biological activity	References
Furanocoumarin	Oroselol		Demonstrates antibacterial activity	Shanbhag *et al*., 1964
Furocoumarin	Angelicin	Roots and rhizomes	Exhibits anti-influenza, antiproliferative, anti-inflammatory, antiviral, and antimicrobial properties	Chatterjee *et al*., 2007
Phytosterol	Beta-sitosterol		Shows anthelmintic, antimutagenic, anti-microbial, and anti-inflammatory effects	Bose *et al*., 1957; Shanbhag *et al*., 1965
Bicyclic ses-quiterpene	Calarene (Aristolene)		Possesses antifungal and attractive (seductive) properties	Chatterjee *et al*., 2000; Purnima *et al*., 2015
Nardosinone-type sesquiterpenoid	Desoxonarchinol		Displays anti-neuroinflammatory activity	Yoon *et al*., 2018a
	Jatamol B		Biological activity not specified	Bose *et al*., 1957; Shanbhag *et al*., 1965; Bagchi *et al*., 1991b
	Beta-selinen-2-alpha -ol (Jatamol A)		Exhibits antimicrobial and anti-inflam-matory activities	Shanbhag *et al*., 1965; Bagchi *et al*., 1991a; Chatterjee *et al*., 2007
	Dinardokansshones C–E; Isonardoeudesmols A–D; Nardoeudesmol D		Shows antimicrobial and anti-inflammatory effects	Wu *et al*., 2018
	Jatamanshic acid		Promotes hair growth	Chaudhry *et al*., 1957
	Kanshone D, N, M	Roots	Activity not specified	Yoon *et al*., 2018a, b
Sesquiterpenoid	Maaliol		Produces antinociceptive effects	Naves, 1963
	7-Methoxydesoxo-narchinol	Roots and rhizomes	Demonstrates anti-neuroinflammatory activity	Yoon *et al*., 2018a, b
	Narchinol A		Exhibits anti-neuroinflammatory properties	Yoon *et al*., 2018b
	Jatamansone		Shows anti-estrogenic, hypotensive, anti-arrhythmic, anticonvulsant, tranquilizing, sedative, and behavioral corrective effects	Bose *et al*., 1957; Govindachari *et al*., 1959; Singh *et al*., 2009; Purnima *et al*., 2015
	Spirojatomol		Possesses antibacterial and anti-inflam-matory properties	Huang and Forsyth, 1995; Bagchi *et al*., 1990
Sesquiterpenoid ketone	Nardostachone	Roots	Demonstrates antimicrobial and anti-inflammatory activities	Sastry *et al*., 1967; Purnima *et al*., 2015
Alkaloid	Actinidine		Acts as a pheromonal compound	Shanbhag *et al*., 1965; Bose *et al*., 1957; Bagchi *et al*., 1991a
Sesquiterpene aldehyde	Nardin	Rhizomes	Promotes hair growth	Rao *et al*., 2008
Terpenic coumarin	Jatamansinol	Rhizome	Shows antimicrobial and anti-inflammatory activities	Shanbhag *et al*., 1965; Satyal *et al*., 2015

Terpenoid ester	Nardostachysin		Displays nootropic activity	Chatterjee *et al*., 2000
Terpenic coumarin	Jatamansin	Roots and rhizomes	Exhibits anti-inflammatory properties	Shanbhag *et al*., 1965; Bagchi *et al*., 1991; Singh *et al*., 2009
Tricyclic sesquiterpene	Patchouli alcohol (Patchoulol)		Exhibits antibacterial, anti-inflam matory, immunomodulatory, and antinociceptive activities	Bagchi *et al*., 1991a; Chauhan *et al*., 2017
Tricyclic sesquiterpene	Patchouli oil (Beta-patchoulene)		Demonstrates anti-inflammatory activity	Bose *et al*., 1957; Purnima *et al*., 2015

7. Commercial prospects

The medicinal herb *N. jatamansi* is traded extensively on a local, regional, and global scale. But in many nations, there is a dearth of thorough information about its trading. According to Dhiman and Bhattacharyya (2020), the dry powder and extracts of *N. jatamansi* were sold for about 2972 US dollars per kilogram in a number of medical markets, including Canada, Ireland, the Netherlands, Singapore, Turkmenistan, and the USA. Cosmetic companies sold "Spikenard oil" in North America and Europe for about $70 per kilogram (Mulliken and Crofton, 2008). The species is one of the top 20 most trafficked and extensively exploited medicinal herbs in India. According to Ved and Goroya (2008), the yearly domestic trade of *N. jatamansi* rhizomes is expected to be over 200 metric tons. The majority of the material on the market, according to the National Medicinal Plants Board (NMPB), is gathered from wild populations and frequently handled illegally. Additionally, there is still a lack of official documentation about rhizome harvesting that is permitted. As a result, the governments of Nepal and India have outlawed the illicit sale and collecting of this valuable species. Research on commercialization aspects is still scarce despite its widespread use worldwide, underscoring the necessity for more thorough studies in this field.

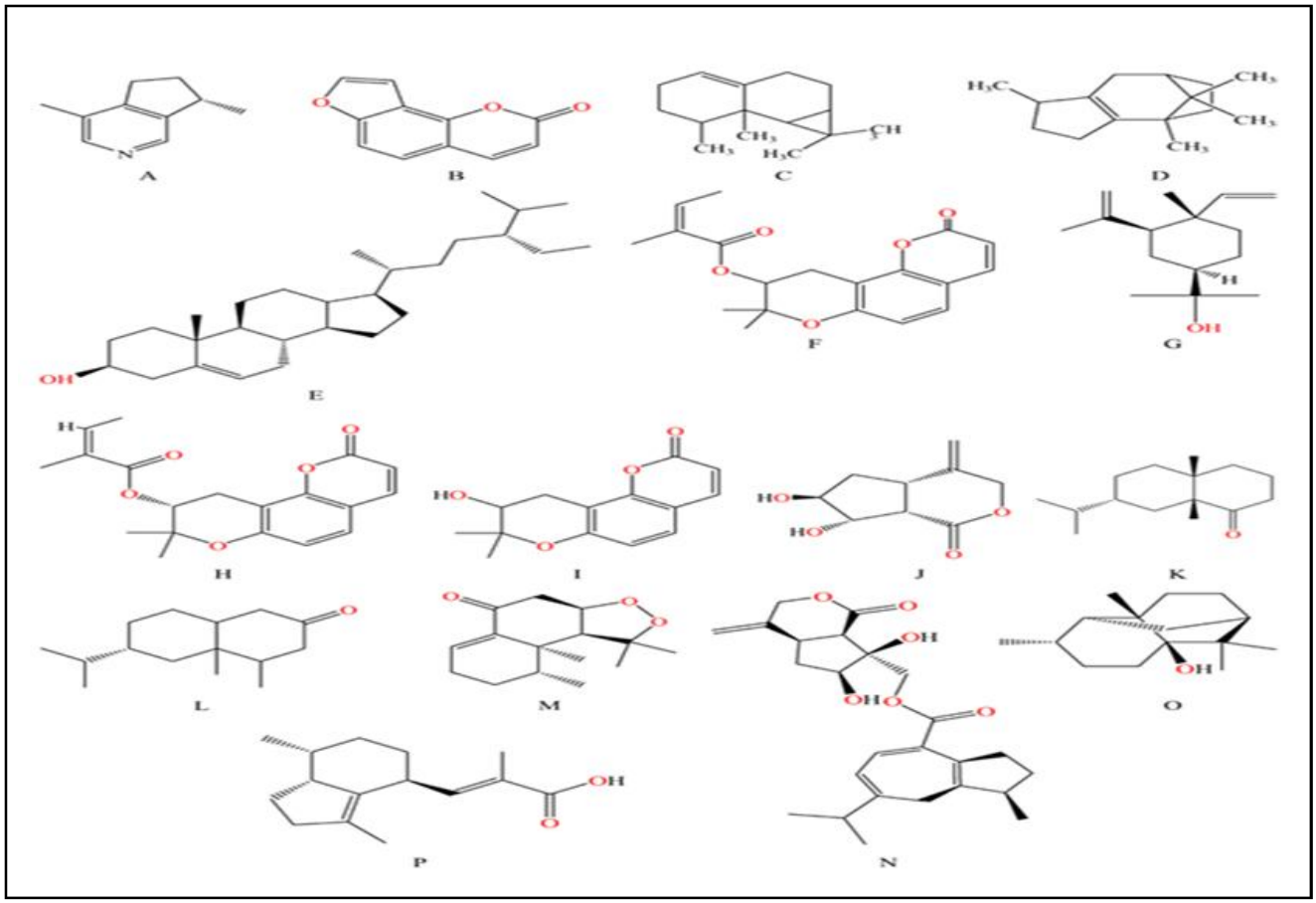

Figure 2: Chemical Structure of some important phytochemicals (A): Actinidine,(B): Angelecine, (C): Aristolene, (D): Beta-patchoulene, (E): Beta-sitosterol, (F): Dihydrojatamansin, (G): Elemol, (H): Jatamansin, (I): Jatamansinol (J): Jatamanin A, (L): Nardostachone, (M): Nardosinone, (N) Nardostachysin, (O): Patchouli alchohol and, (P) Valerenic acid.

8. Biotechnological strategies for conservation

The potential benefits of medicinal plants for primary healthcare, cultural identity, financial revenue, and livelihood security make them extremely important (Hamilton, 2004; Moyo *et al*., 2015). The primary means of obtaining raw materials and engaging in trade is still the collecting of medicinal plants from the nature (Canter *et al*., 2005). However, these medicinal species are mostly collected by unskilled and untrained laborers *via* extraction of the bulb, root, rhizome and whole plant before seed set, resulting in limited re-establishment in the natural habitat (Rai *et al*., 2000). The conservation of natural resources, especially medicinal plant species, remains a global challenge (Hamilton, 2004; Affolter and Pengelly, 2007; Moyo *et al*., 2015). Conservation measures include protecting the environment and natural resources to prevent over exploitation and habitat degradation (Okigbo *et al*., 2008; Aremu *et al*., 2011). Due to high demand, population urbanization, and other anthropogenic activities, many plant species with enormous medicinal value are currently under stress (threatened, critically endangered, vulnerable, and dwindling) in the natural population worldwide and are frequently hard to locate outside of protected areas (Zschocke *et al*., 2000; Okigbo *et al*., 2008; Moyo *et al*., 2015).

The natural habitat has been altered by over exploitation, careless harvesting, and trampling during the collection of these species, which has led to the extinction of other related species (Cunningham, 1997; Rai *et al*., 2000; Aremu *et al*., 2011). Demand will surely rise due to *N. jatamansi's* well-known significance in traditional medical systems and the herbal preparations that are currently on the market. As a result, limited groups may engage in illicit or unsustainable harvesting from natural populations, thereby jeopardizing its conservation. *N. jatamansi* is designated as severely endangered because of the ongoing decline in natural populations caused by destructive and illegal harvesting (Ved *et al*., 2015).

Therefore, in order to ensure its survival in natural environments, *N. jatamansi* requires immediate conservation actions. For translation studies on this species, a significant quantity of real plants must be available. Some plant species are difficult to regenerate because of a low germination rate and lengthy regeneration timeframes, making established conventional propagation methods unappealing and ineffectual. In order to overcome these challenges and enable the standardization and scale-up of useful phytochemicals, novel plant biotechnology methods are required (Gandhi *et al*., 2014). By guaranteeing a plentiful supply of genuine plant material and preventing the extinction of several important species, recent advancements in the field of plant tissue culture (PTC) techniques have revolutionized the conservation scenario of natural genetic resources (Moyo *et al*., 2011; Bose *et al*., 2016; Kumar 2015, 2017). These methods include *in vitro* cryobanking, *in vitro* generation of secondary metabolites, *in vitro* micropropagation/somatic embryogenesis, and gene transfer experiments to reintroduce endangered or critically endangered species and ease the strain on natural ecosystems. However, only a few protocols have been devised to evaluate the viability and use of *in vitro* regeneration in *N. jatamansi* utilizing various explants (leaves, shoot tips, and petioles) to maximize the propagation of true-to-type clones. Early work on *in vitro* root morphogenesis using callus-derived tissues demonstrated successful shoot regeneration when cultured on medium supplemented with 3.0 mg/l NAA and 0.25 mg/l Kn, although genetic fidelity was not assessed (Mathur, 1992). Subsequently, somatic embryogenesis was achieved from petiole segments using 16.1 µM NAA and 1.16 µM Kn, resulting in the induction of somatic embryos (Mathur, 1993). Further advances in micropropagation using shoot tip and petiole explants showed efficient shoot regeneration with 1.0 mg/l mT, and genetic stability of the regenerated plants was evaluated using SCoT markers, which produced mostly monomorphic bands with only a few polymorphic bands (Bose *et al*., 2016). In another study, *in vitro* plant regeneration from leaf explants was achieved through callus formation on 5 µM BA, followed by complete plant regeneration, and RAPD marker analysis confirmed high genetic fidelity with predominantly monomorphic bands (Rawat *et al*., 2018b).

Advanced biotechnological techniques such as micropropagation and somatic embryogenesis, which involve the regulation of various plant growth regulators (PGRs) and controlled environmental conditions, offer promising strategies for the conservation of *N. jatamansi*. Furthermore, approaches like *in vitro* cryobanking, synthetic seed technology, and large-scale propagation through bioreactors can support both the preservation and commercial production of valuable phytochemicals from this species. For broader acceptance within the pharmaceutical sector, *N. jatamansi* should be evaluated not only from a cultivation perspective but also for its diverse biological activities. Biotechnological interventions, including optimization of explant sources, culture conditions, and nutrient media, can significantly improve biomass production and stimulate the synthesis of important secondary metabolites in cultured cells of *N. jatamansi*. Moreover, plant growth regulators particularly auxins and cytokinins are known to influence the biosynthesis of various bioactive compounds in several medicinal plants, including those native to the Himalayan region (Amoo *et al*., 2014; Aremu *et al*., 2013; Moyo *et al*., 2014; Bose *et al*., 2016; Bhardwaj *et al*., 2018; Rawat *et al*., 2018a; Kumar *et al*., 2019).

In addition to scientific efforts, effective conservation requires the implementation of strict governmental policies. The development of suitable agrotechniques practices for domestication from wild populations and the establishment of germplasm repository centres are essential for safeguarding this species. Community-based development programs can also help raise awareness about the ecological and medicinal importance of this plant species and promote its conservation. Given the alarming decline of *N. jatamansi* populations in the Himalayan region, its systematic cultivation and regeneration are crucial for ensuring long-term survival and sustainable utilization. Overall, increased public awareness and education regarding conservation initiatives, along with the pharmacological importance and biological value of *N. jatamansi*, are urgently needed among local communities and traditional practitioners.

9. Conclusion

The extensive ethnomedicinal importance and diverse biological activities of *N. jatamansi* have established it as a highly valued medicinal plant species of the Himalayan region. Its rhizomes and roots are widely utilized in numerous traditional remedies, and the availability of multiple herbal formulations in the market further reflects its significant role in indigenous healthcare systems. However, considerable morphological similarity and frequent confusion with *V. jatamansi* highlight the urgent need for a clearer understanding of its geographical distribution along with comprehensive

phytochemical investigations to avoid misidentification and adulteration. In addition to the published regeneration protocols for *N. jatamansi*, the application of innovative plant biotechnological approaches and the optimization and development of low-cost production methods could aid in efficient and robust sustainability and conservation in the future. In this regard, the selection of explants and the introduction and manipulation of the type and concentration of different PGRs will play inevitable roles in mass clonal propagation as well as the upregulation of phytochemical content. *In vitro* based cryopreservation techniques will certainly facilitate germplasm conservation in cryobanks. Furthermore, advanced molecular research along with conventional breeding techniques can enhance biomass production and develop improved varieties of this valuable Himalayan plant. It is also important that the protocols developed for cultivation and regeneration are both efficient and economically feasible. In this context, crop-ecology and agrotechnique practices could support large-scale propagation in regions and countries associated with the Himalayan regions. Without timely and practical conservation strategies, the population of *N. jatamansi* in the Himalayas may decline drastically; therefore, immediate efforts are required to promote awareness and encourage its conservation.

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Anand Singh Bisht: Conceptualization, writing-reviewand editing, **Shweta B Kukreti** and **T.S. Mehra:** Methodology and editing, **Bijendra Lal** and **Uday Bhanu Pratap:** Review and editing.

Conflict of interest

The authors declare no conflicts of interest relevant to this article

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