CENTELLA ASIATICA (URB.) L.: THE HERBAL ELIXIR OF EASTERN MEDICINE

Abstract

Centella asiatica (Urb.) L., commonly known as gotukola or mandookparni is a valuable herb of importance known and mentioned in Ayurveda as well as traditional Chinese medicine literature. It belongs to the family Apiaceae with widespread distribution around the world. Tribals or forest dwellers collect it from the wild and sell in the market as vegetable and medicinal herb that bring them a regular income with no investment. But as herb reproduces by vegetative reproduction primarily it could be a threat in the form of overexploitation in absence of awareness among collectors who are usually from rural background. There is a high demand of this herb in national as well as international markets due to its ethnobotanical uses as well as for its products used for pharmaceutical as well as food industry purposes besides other commercial uses of wider applications. Active biochemicals present in this herb are triterpenoids as Asiaticoside, Madecassocide, Asiatic acid, flavanoids, alkaloids and essential oils etc that provide it dermatological, neuroprotective, antioxidant, anti-inflammatory, anti-cancer, antimicrobial and hepatoprotective etc. properties. Many advancements are going to develop techniques for enhancement and extraction of these secondary metabolites *in vitro* culture with the help of various biotechnological tools that are required for conservation of this valuable herb.

Systematic position

Kingdom: Plantae
Phylum: Tracheophyta
Class: Magnoliopsida
Order: Apiales
Family: Apiaceae
Genus: Centella L.
Species: *Centella asiatica* (L.) Urb

Fig. 1 Morphological features of *C. asiatica*

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Keywords: Asiaticoside, Gotukola,Madecassoside, Mandookaparni, Medhya Rasayana,Neuroprotective,Wound healing

Common/Vernacular Name:

Gotu kola (Hindi), Asiatic pennywort, Indian pennywort (English), *Chokiora* (Bihar), *Thankuni* (Bengali), *Barmi* (Gujarati), *Mandookaparni* (Hindi), *Supriya*, *Mutthil* (Sanskrit), *B rahmi* (Urdu), *Babassa*, *Saraswataku* (Telegu), *Batsyiar/Khliengsyiar* (Khasi,Meghalaya), *Peruk* (Manipuri), *La mbak* (Mizoram) and *Manimun* (Assam)

Geographic Distribution and Habitat:

This herb is widespread across Eastern Asia, including India, China, Japan, and Australia. *Centella asiatica* thrives in a wide range of ecological environments but is especially common in moist, shaded, and fertile regions such as stream banks and damp pathways in temperate areas across India.

Morphological features

A small slender creeping herb. Stems are with stolons, green to reddish green in colour. Leaves are long-stalked, reniform with rounded apex. Flowers are pinkish to red in colour, borne in small, rounded bunches (umbels). Each flower is partly enclosed in two green bracts. It is a creeper that roots at the nodes.

PropagationMethods:

The plant primarily reproduces vegetatively via stem cuttings, with sexual reproduction being less frequent. Recent advances in tissue culture have enabled more efficient propagation, germplasmpreservation, and cost-effective cultivation(Sharma & Vimala, 2010).

Soil and Climate Requirements:

It can grow in sandy, loamy, or clay soils and tolerates acidic, neutral, or alkaline conditions. The plant is adaptable to partial or full sunlight and prefers moist or wet soil for optimal growth.

Nutritional Profile

Proximate analysis of nutritional analysis by Ogunka-Nnoka*et al.*, 2020 and Chandrika *et al.*, 2015 for leaves of *C asiatica*showed it containedmoisture (13.10 ± 1.07%), ash (16.5 ± 0.45%), protein (8.35 ± 1.28%), lipid (1.20 ± 0.10%), fiber (17.00 ± 1.87%), and carbohydrate (43.81 ± 0.70%). Fatty acid profiling indicated a predominance of palmitic acid (55.70%) among the saturated fatty acids and linoleic acid (17.50%) among the unsaturated fatty acids. Amino acid analysis revealed high levels of glutamate (13.389 g/100 g) as the major nonessential amino acid and histidine (11.64 g/100 g) as the major essential amino acid.Phytochemical screening identified several bioactive compounds, including proanthocyanin (11.964 µg/g), rutin (11.8883 µg/g), naringenin (3.0122 µg/g), quinine (10.4490 µg/g), flav-3-ol (2.5900 µg/g), sparteine (3.0122 µg/g), phenol (18.8713 µg/g), flavonones (2.1836 µg/g), steroids (18.8974 µg/g), kaempferol (0.7273 µg/g), phytate (1.6851 µg/g), naringenin (2.7523 µg/g), resveratrol (10.8596 µg/g), tannin (4.4377 µg/g), and ribalinidine (3.0500 µg/g).

The abundance of these nutrients and bioactive phytochemicals in *Centella asiatica* leaves highlights their potential applications in the pharmaceutical and food industries.

Edible and Culinary Applications

Edibility:

The leaves are consumed raw or cooked and are considered a leafy vegetable in countries like India, China, Sri Lanka, and Indonesia. Due to its strong aromatic flavor, it is typically used in moderation when added to salads.

Traditional Culinary Uses:

The plant, commonly referred to as **Beng Saag**, is not consumed raw due to its bitterness. Instead, it is thoroughly washed, boiled or sautéed to reduce bitterness, cooked with digestive and aromatic spices

Popular Dishes Include:

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- Beng Saag Bhaji – Stir-fried with garlic, onions, mustard oil, and chilies
- Mixed Saag Curry – Cooked with other leafy greens
- Beng Saag Dal – Lentil-based curry
- Side Dish for Pakhala – Served with fermented rice water (popular in Odisha)

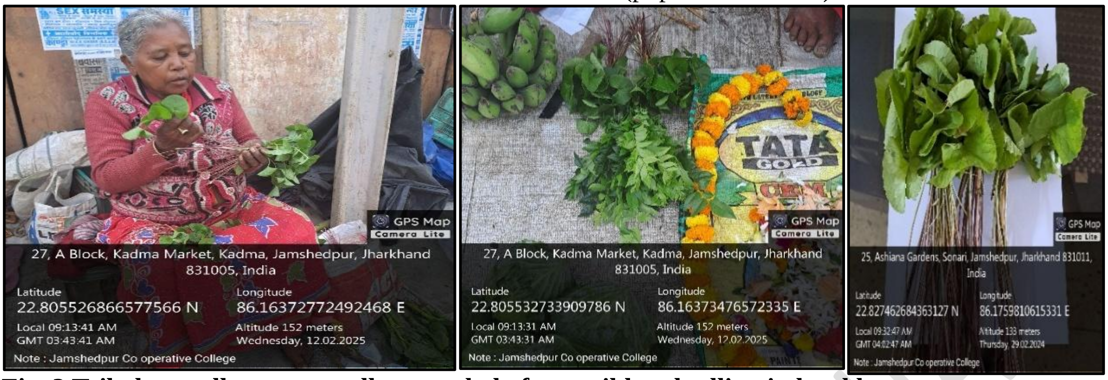

Fig. 2 Tribals usually women collect gotukola from wild and selling in local haats

Gotu Kola/Thankuni plays a significant role in the economy of tribal forest dwellers, particularly in regions like India (Odisha, Tripura, Jharkhand) and Madagascar, by serving as both a cash-generating Non-Timber Forest Product (NTFP) and a source of nutrition. It is collected manually from the wild mostly by rural women and sold in local haatsso playing crucial socio- economy roleguaranteeing future income. Due to its traditional medicinal usage in Ayurvedic and Chinese medicineit is in high demand in both local and international markets so that makes it a valuableherb with almost zero investment and contributes to the poverty alleviation of rural and forest-dwelling populations.

Significance in Ayurveda:

Centella asiatica, known in Ayurveda as *Mandukparni* or *Brahmi*, and referred to internationally as *Gotu Kola*, is a highly valued medicinal plant in both traditional and modern healthcare systems(Chopra *et al.,* 1969, Chopra and Nayar 1956. It holds an important position in the Indian Pharmacopoeia and is recognized for its therapeutic benefitsparticularly in enhancing memory and healing wounds. Its medicinal properties are also documented in international pharmacopoeias, including the European Pharmacopoeia, German Commission E, and the World Health Organization(Howes & Houghton, 2003).

Phytochemical Composition

Phytochemicals of *Centella asiatica* can be extracted by conventional or novel extraction techniques.

1. Conventional extraction methods like Soxhlet and cold methods can be used for extraction purposes but due to prolonged extraction time, less efficiency and requirement ofexcess amounts of solvent and compound degradation these are not considered as efficient ones in comparison to novel techniques.(Savic *et al.,* 2023 and Belwal*et al.,* 2020).
2. Novel extraction methods like supercritical fluid extraction ultrasonic extraction, radio frequency and enzyme-assisted extraction techniques microwave, advance metabolomics techniques, ultra-performance liquid chromatography (UPLC), NMR, and MS, e.g., liquid chromatography-MS (LC-MS/MS) and gas chromatography-MS (GC-MS) provides efficient yieldswith lesser extraction time(Songvut*et al.,* 2021, Yuan *et al.,* 2023, Zakaria *et al.,* 2023 and Ondeko*et al.,* 2020).
3. Similarly cold plasma as a water pretreatment alsoextractsefficiently by retaining the herb's bioactive properties with lesser requirement of energy and extraction time(Tripathy *et al.,* 2023).
4. Likewise, usage of green solvents liketriethylammonium sulfateeffectively extract asiaticoside from *Centella asiatica* in comparison to other solvents(Othman *et al.,* 2023).

Presence of broad spectrum of **bioactive compounds** by scientific investigations done by(Tan *et al.,* 2021Schaneberg*et al.,* 2003 Srivastava*et al.,* 1997)validate the claims of traditional Indian medicine regarding the plant's medicinal potential.

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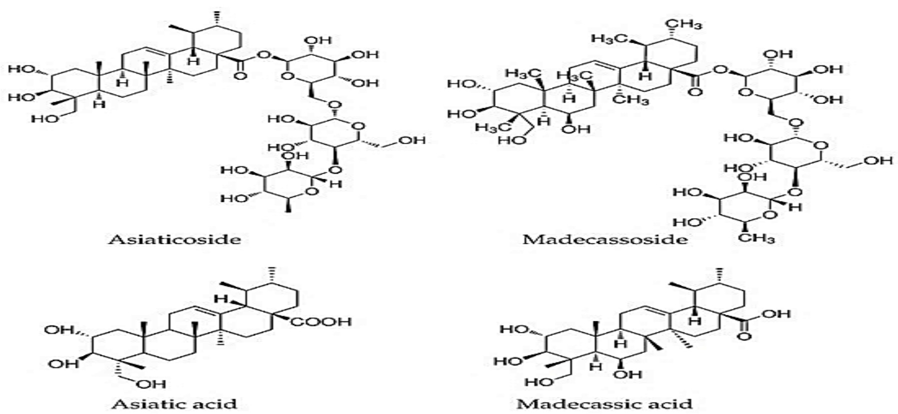

Figure 3 Chemical structures of triterpenoid compounds isolated from Gotukola(Hein*et al.*, 2025)

Table 1 Metabolite spectrum of ***c asiatica*** **and its therapeutic properties**

S No	**Phytochemical**	Biological activity	Application	Reference no
I.	**Triterpenoids** *Signature Phytochemicals*	Research suggests that formulations containing a full spectrum of triterpenoids are more effective than single isolated compounds, indicating a synergistic influence on inflammatory responses and oxidative stress pathways(Shukla *et al.*, 1999).		
a)	**Asiaticoside**	promotes collagen production by increasing the expression of transforming growth factor beta-1 (TGF-β1) and fibronectin. It also supports angiogenesis, facilitating the development of new blood vessels, which plays a crucial role in tissue regeneration.	These properties make it beneficial in the management of skin injuries such as wounds, burns, and scar formation.	(Hashim *et al.*, 2011, Lokanathan*et al.*, 2016 Rashid *et al.*,2023)
		supports in promoting neurogenesis via by increasing the expression of brain-derived neurotrophic factor (BDNF), brain-derived neurotrophic factor	possible therapeutic value for neurodegenerative disorders.	He *et al.*, 2023
b)	**Madecassoside**	Madecassoside plays an important role in suppressing the activation of nuclear factor kappa B (NF-κB), thereby decreasing inflammation triggered by pro-inflammatory cytokines	It also provides protection against ultraviolet (UV)-induced skin aging and contributes to the wound healing process.	(Won *et al.*, 2010, Jung *etal.*, 2013)
		Its anti-inflammatory effects, combined with its capacity to enhance collagen synthesis, make it valuable for skin repair.	Furthermore, incorporating madecassoside into nanoparticle-based delivery systems has been shown to	Lu, *et al.*,**2023s**

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			improve its stability and enhance transdermal penetration for dermatological use.	
c)	**Asiatic acid ($C_{30}H_{48}O_5$) and Madecassic acid ($C_{30}H_{48}O_6$**	demonstrate a wide range of biological activities, including anti-inflammatory, anticancer, hepatoprotective, and neuroprotective effects. These actions are mediated through the regulation of key signaling pathways such as mitogen-activated protein kinases (MAPK), nuclear factor erythroid 2–related factor 2 (Nrf2), and phosphatidylinositol 3-kinase/protein kinase B (PI3K/Akt). signaling pathways	Derivatives of Asiatic acid have attracted attention as potential frameworks for anticancer drug design because of their cytotoxic effects on glioblastoma and melanoma cells. Similarly, Madecassic acid helps in wound healing due to its anti-inflammatory and antioxidant properties.	Tan *et al.*, 2021
d)	**Brahmoside**	potential anxiolytic and adaptogenic effects		Ganie *et al.*, 2022
II.	**Flavonoids and other Polyphenols**	exhibit antioxidant, anti-inflammatory, neuroprotective, and vasoprotective properties. These are also reported to reduce β-amyloid plaque formation and improve synaptic plasticity ‚	indicating potential benefits in addressing neurodegenerative disorders, cognitive impairment, and overall brain health.	Gray *et al.*, 2018
a)	**Quercetin**	Quercetin is known for its strong antioxidant capacity, neutralizing reactive oxygen species (ROS) and by regulating important inflammatory mediators such as cyclooxygenase-2 (COX-2) and tumor necrosis factor-alpha (TNF-α).		Sul, 2021 Domitrovi´c 2012
		It has also shown neuroprotective effects in Alzheimer’s disease	highlighting its potential significance in the prevention and management of cognitive decline and age-associated neurological disorders.	Khan *et al.*, 2020
b)	**Kaempferol**	demonstrates strong		Chatterjee *et*

		anti-inflammatory activity, largely through suppression of the NF-κBsignaling pathway and stimulation of Nrf2-driven antioxidant defense mechanisms.		*al.*, 2024
c)	**Rutin**	enhancing capillary strength and stability, while also contributing to antioxidant and protection against UV-induced damage.	These properties make it especially beneficial in skin care and vascular health applications.	Michalak *et al.*, 2022, Peres *et al.*, 2016
d)	**Apigenin, Luteolin, and Hesperidin**	further expand the therapeutic profile of the herb, providing additional benefits such as anti-aging effects, anxiety-reducing potential, and antimicrobial activity.		Ullah *et al.*, 2020
II.	**Alkaloids**			
a)	**Hydrocotyline and Thankuniside**	associated with neuroprotective and cognitive-enhancing properties. These compounds may also function as cholinesterase inhibitors	potentially supporting memory and overall cognitive performance.	
III.	**Essential Oils and Volatile Compounds (0.1% to 0.2% w/w)**	produce gentle calming, stress-reducing, and skin-soothing effects, consistent with the traditional use of C. asiatica in holistic healing systems. In addition to improving the sensory (organoleptic) qualities of formulations containing C. asiatica, these volatile compounds may act synergistically to enhance the overall therapeutic effect	Although their pharmacological mechanisms have not been studied as extensively as the plant's other metabolites the possible anxiolytic and mood-balancing properties of these volatile components are supported by observations from aromatherapy practices and traditional medicinal preparations.	Kunjumon *et al.*, 2022 Murray *et al.*, 2013
IV.	**Monoterpenes and Sesquiterpenes**	(**Caryophyllene, α-Humulene, and β-Pinene**)	antimicrobial, anxiolytic, and dermal applications	Joshi *et al.*, 2007
V.	**Phytosterols**	[Phytosterols as **β-sitosterol, campesterol, and stigmasterol** are predominantly concentrated in the leaves than other parts35.		
		These plant sterols are known to influence lipid metabolism by competing with dietary	Through this competitive interaction, they help reduce	Miszczuk*et al.*, 2024

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		cholesterol for absorption within the gastrointestinal tract.	circulating cholesterol levels, thereby supporting cardiovascular health	
		possess anti-inflammatory and antioxidant activities	beneficial in the management of metabolic syndrome and other inflammation-related metabolic disorders.	Feng *et al.*, 2018
		Emerging evidence also suggests that these compounds can modulate immune responses by affecting immune cell activity and cytokine production; however, further mechanistic research is needed, particularly in relation to formulations derived from *C. asiatica*	Overall, phytosterols may contribute to broader systemic benefits, including positive effects on cardiovascular, metabolic, and immune function, especially in products designed to address dyslipidemia and chronic inflammatory states.	Shen, *et al.*, 2024 Hu, *et al.*, 2017
VI.	**Polyacetylenes**	mainly concentrated in the roots, with moderate amounts also found in the leaves.		
a)	**Cadiyenol and Cadiyenone,**	can promote fibroblast migration, stimulate angiogenesis, and enhance skin regeneration properties,	consistent with applications in wound and skin care preparations	Scherer *et al.*, 2009 Li *et al.*, 2022
		These constituents may enhance the wound-healing process by influencing extracellular matrix remodeling and regulating cellular signaling pathways involved in tissue repair.		
		act as internal signaling molecules, particularly under environmental stress conditions.	This adaptive function may also have pharmacological significance in humans, as their role in stress-response modulation could contribute to the plant's defense-related and adaptogenic properties	Divekar *et al.*, 2022 Minto *et al.*, 2008
VII.	**Tannins**, S**ugars**, R**esins**, I**norganic acids**, and amino acids such as A**spartic acid**, G**lycine**, G**lutamic acid**, **α-Alanine**, and P**henylalanine**.			

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VIII.	Rich in vitamins **B**, **C**, and **G**, the total ash includes **chlorides**, **sulfates**, **phosphates**, **iron**, **calcium**, **magnesium**, **sodium**, and **potassium**.

Traditional and Modern Medicinal Uses

Centella asiatica has a long-standing presence in the traditional medicine systems across various continents[46, 47]. It has been used by multiple indigenous communities for centuries to treat a wide range of health issues, particularly related to skin, inflammation, and cognition. Its cross-cultural therapeutic use is a testament to its versatility and effectiveness.

In Ayurvedic medicine, *Centella asiatica* is considered a *Rasayana*a category of rejuvenating herbs. Traditionally, it is believed to improve cognitive function, enhance skin texture, and support wound healing. Its extracts are used in modern Indian pharmacology for treating skin disorders such as **leprosy**, **eczema**, and **psoriasis**(Feng *et al.*, 2021 Gupta *et al.*, 2000) and for anti-acne application (Kuo *et al.*, 2021).

The plant has demonstrated:

- **Neuroprotective and cognitive-enhancing properties**: *Centella asiatica* has been reported to exert multiple beneficial effects on the nervous system, including neuroprotective activity, improvement of memory and cognitive function, as well as antidepressant and anxiolytic effects(Hengjumrut*et al.*, 2018; Khemawoot*et al.*, 2018). Clinical evidence suggests that CA supplementation reduced stress levels, alleviated symptoms of anxiety and depression, and improved attention and adaptive functioning in individuals diagnosed with generalized anxiety disorder, without producing significant adverse effects(Tan *et al.*, 2021).
- **Therapeutic applications in vascular and inflammatory disorders:** CA has been traditionally and clinically utilized in the management of anxiety,inflammatory conditions, venous insufficiency, and certain types of cancer(Brinkhaus *et al.*, 2000). It has shown relevance in treating vascular-related disorders such as venous hypertensive microangiopathy, diabetic microangiopathy, and chronic venous insufficiency. Additionally, clinical investigations have explored its potential benefits in other conditions, including leprosy, chronic liver diseases, and gastric ulcers (Tan *et al.*, 2021).
- Used in **wound care**, **antiviral**, **antibacterial**, **diuretic**, **antipyretic**, and **rheumatic** treatments
- *Centella asiatica* is also actively explored in **clinical research** due to its broad therapeutic potential as it is widely used for its antimicrobial, antioxidant, neuroprotective and wound healing properties (Prakash *et al.*, 2017 Tan *et al.*, 2021 Hafiz, *et al.*, 2020**)**.
- It is used for the treatment of a variety of dermatological conditions as lupus, eczema, psoriasis, leprosy and varicose ulcers. Its extracts exhibited positive influence on wound healing(Ahmed *et al.*, 2019 and Arribas-López *et al.*, 2022) by improving collagen synthesis and microcirculatory function (Brinkhaus *et al.*, 2000 Cesarone *et al.*, 2001 Incandela *et al.*, 2001.)
- The effects of a standardized extracts of *Centella asiatica*were studied by Damkerngsuntorn, *et al.*, 2020 on postlaser resurfacing wound healing on the face: A Split-Face, Double-Blind, Randomized, Placebo-Controlled Trial and concluded this treatment regimen might be an option for post-laser resurfacing.

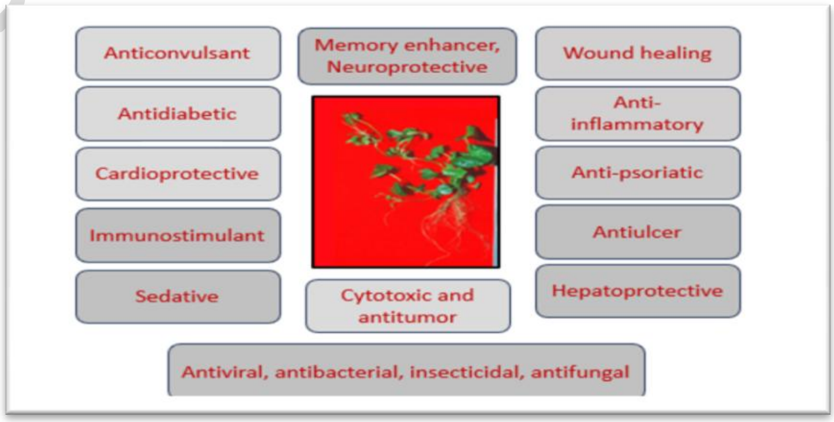

Fig. 4 Therapeutic Properties of *C. asiatica*(Brinkhaus *et al*., 2000, Orhan *et al*., 2012)

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Commercial Applications

Due to the presence of its secondary metabolites *C asiatica* is mostly used in

- Cosmetics and Skincare (Cosmeceuticals):
- Pharmaceuticals & Medicine:
    - Wound Healing: Used in topical creams and dressings for surgical lesions, bedsores, and skin ulcers asMadecassol® and Centelase®
    - Therapeutic Use: Used to treat inflammatory diseases, chronic hepatic disorders, and for promoting cognitive function.
- Functional Foods and Nutraceuticals:
    - Beverages/Food: Used in teas, juices, and herbal products to promote overall health.
    - Health Supplements: Capsules, tablets, and powders for enhancing cognitive function and circulation.
- In the food industry, *C. asiatica* extract represents a promising natural alternative for enhancing product preservation. Extracts of *Centella asiatica* demonstrate strong free-radical scavenging capacity along with notable antimicrobial effects, indicating their suitability as functional additives in food packaging materials. The bioactive compounds present in the plant, particularly terpenoids and phenolic constituents, contribute to its effectiveness against food-borne pathogens by damaging microbial cell membranes and suppressing a broad range of microorganisms. Consequently, incorporating *C. asiatica* extracts into packaging films may provide an innovative approach for **active food packaging applications**. Its antioxidant and antibacterial properties can support food quality maintenance, extend shelf life, and reduce spoilage, ultimately helping to minimize food waste(Pillai *et al.*, 2024).

Table 2 Some commercial products of *C asiatica*

1.	Centellaeasiaticae herba	commercial formulations such as skin creams, wound healing agents, and moisturizers(Zainol *et al.*, 2008).	global marketplace, particularly in Germany
2.	SBL Hydrocotyle Asiatica Dilution 30 CH	Ithelps with skin-related comfort, may support overall vitality and may assist during phases of general weakness sensations as well.	
3.	Himalaya Gotu Kola / *Centella asiatica* (Capsules)	Improving Memory and Concentration, helps to maintain an excellent cognitive performance It helps to Improve memory and concentration in stressful periods.	
4.	Himalaya Organic Gotu Kola	Nootropic Supplement with Adaptogens for Energy, Focus, Memory, and Calming Relaxation - Vegan, Non-GMO, Gluten Free	
5.	*Centella asiatica* Extract	The product addresses broad spectrum dermatological concerns.	Alchem International Pvt. Ltd.
6.	*Centella asiatica* Powder Extract EMPEROR	Strong anti-inflammatory, help comfort skin, Boosts Blood Circulation, Regulates Blood Sugar Level, Stress Buster, Wound Healing. Relieves	

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	HERBS®	Joint Pain. Skin Treatment	
7.	Merlion Naturals Gotu kola	Help with memory and mood relaxant	
8.	Dr Willmar Schwabe Germany Hydrocotyle Asiatica (*Centella asiatica*)	anti-ageing properties. It has a mild laxative effect.It is used to relieve constipation. It works as a diuretic	
9.	Dr. Reckeweg Hydrocotyle Asiatica	Helps manage leprosy, gonorrhoea and leucorrhoea. Helps deal with skin related issues. Assists in improving memory	
10.	*Centella asiatica*Gotu Kola Cream,Madecassol	Topical cream with 1% titrated *Centella asiatica*extracts for skin repair. Supports soothing and healing of dry, irritated, or damaged skin	
11.	Natier Centella Asiática y Jengibre (Natural Asian Centella juice with ginger)	Dietary Supplement Nutritional Benefits	
12.	Organic Gotu Kola Powder- *Centella asiatica* Superfood Powder by IyasaHolistics	for Focus, Calm & Skin Support – Raw Ayurvedic Herb for Drinks & Smoothies – Gotu Kola Supplement	
13.	Gotu kola, Herbal Tea	Memory Boost, Brain Nourishment, Cognitive Function	
14.	One Herb - Gotu Kola Tea Pure*Centella asiatica* Leaves | Single Ingredient Ayurvedic Tea | Loose Leaf Infusion	BRAIN TONIC: Improves memory retention and overall cognitive function. Supports mental clarity & stress relief. anti-ageing properties. Supports deep & restful sleep: Herb for longevity healthy hair and skin	
15.	*Centella asiatica* Serum	Mary & May is a Korean brand of natural cosmetics. It is a serum to instantly soothe irritated, sensitive skin without leaving a sticky feeling	

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16.	Ecoberry*Centella asiatica* Soothing Gel Cream	Safe and effective agent for Anti-ageing, soothing, moisturizing and healing	

Dose dependent cytotoxicity

Natural medicinal products derived from the food chain have gained increasing attention for their potential role in managing chronic diseases. To ensure their safe application, comprehensive toxicity evaluations are essential. International regulatory authorities emphasize this requirement in their safety guidelines for botanical products, dietary supplements, and herbal medicines(Speijers*et al.*, 2010).

The phytochemical composition of plant extracts, particularly terpenoid content in leaves, can vary depending on several factors, including plant maturity and nutrient availability(Mangas *et al*., 2008; Sharma *et al.*, 2014; Müller *et al.*, 2013). Such variability highlights the importance of standardized extracts when assessing biological activity and safety.

Standardized extracts of *Centella asiatica* (L.) Urban (INDCA)have shown potential in addressing stress-related behavioural disorders. Because therapeutic management of stress-associated conditions typically requires prolonged administration over days or weeks to achieve clinical benefits, evaluating long-term safety becomes crucial. Preclinical toxicological assessments conducted according to established regulatory protocols are therefore necessary. Previous investigations have reported that leaves extracts were well tolerated in acute oral toxicity, sub-chronic toxicity, and mutagenicity studies in rats(Deshpande *et al.*, 2015).

In a more recent clinical context,Wright *et al.*, (2023) examineda standardized *Centella asiatica* water extract product was examined. The analytical method used for its evaluation met the United States Food and Drug Administration criteria for linearity, precision, accuracy, and recovery in plasma and urine samples. The extract was further assessed in a Phase I randomized, double-blind, crossover study involving eight healthy older adults who received single doses of 2 g or 4 g. Both doses were reported to be safe and well tolerated, supporting further clinical development of this formulation.

Additionally, under OECD GLP 408 guidelines for a 90-day repeated-dose oral toxicity study(Junsai*et al.*, 2024) in 100 Wistar rats, Centell-S demonstrated a no-observed-adverse-effect level (NOAEL) of 800 mg/kg/day. These findings provide supportive evidence for the continued development of Centell-S as a phytopharmaceutical candidate for clinical use.

Biotechnological Advances

This herb is in high demand in national as well as international market as it is part of Ayurveda and traditional Chinese medicine system, there is a concern regarding overexploitation of this herb. IUCN has listed it in least concern species but wild scale uncontrolled harvesting due to lack of awareness of good agricultural and collection practices cannot be denied at local rural or in forests areas (Singh *et al*., 2010). As a prevention measure many *in vivo* and *in vitro* studies have been done on *Centella asiatica*in past years for sustainable cultivation, micropropagation and *in vitro* production of medicinal principles of this plant (Sharma *et al*., 2014, Sharma and Vimala 2010, Sharma and Vimala 2015, Tiwari *et al.*, 2000, Singh *et al.*, 2023). The biosynthesis of triterpenoids in *Centella asiatica* occurs mainly via the mevalonate pathway, a fundamental plant metabolic pathway producing isoprenoid building blocks by key enzymes such as β-amyrin synthase that forms the core triterpenoid skeleton, which is subsequently modified by cytochrome P450 monooxygenases to generate diverse bioactive compounds. Recent transcriptomic and metabolomic investigations have identified specific gene clusters that regulate the formation of major constituents, including Asiaticoside and Madecassoside(Wan et al., 2024). These findings have opened new opportunities for metabolic engineering approaches enhancing both the production levels and consistency of valuable metabolites.

Further*in vitro* culture systemssuch as cell suspension cultures and hairy root cultures aredeveloped to enable controlled and large-scale production of triterpenoids(Baek et al., 2022). These systems offer advantages including improved yield stability, standardized quality, and minimized environmental variability. Moreover, advanced molecular techniques, including CRISPR-Cas9-based genome editing and transgenic strategies, are being used to upregulate essential biosynthetic genes and redirect metabolic flux towards production of required secondary metabolites(Arribas-López et al., 2021).

In addition,the neuroprotective potential of Asiaticoside, Madecassoside, and Asiatic acid *present in C. asiatica*were examined as natural inhibitors of acetylcholinesterase (AChE), an enzyme closely associated with

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neurodegenerative conditions like Alzheimer's disease. *in silico* study incorporated multiple ligand mapping, molecular docking, molecular dynamics (MD) simulations, and MM-PBSA binding free energy analyses. The docking results demonstrated strong binding affinities of Asiaticoside and madecassoside toward the AChE active site, surpassing the reference drug donepezil (−133.51 kJ/mol). Molecular dynamics simulations further supported the stability of these ligand–enzyme complexes, reinforcing their potential as effective AChE inhibitorsKhairinisa*et al.*, (2025).

Overall, these scientific and technological advances highlight the considerable promise of *Centella asiatica* as a sustainable source of bioactive compounds and support ongoing efforts to develop novel therapeutic agents for cognitive impairment and other neurodegenerative disorders.

Conclusion

Centella asiatica, known traditionally as Mandukparni or Brahmi and globally as Gotu Kola, is a plant of immense medicinal, nutritional, and cultural significance. Its widespread use in both traditional systems like Ayurveda and in modern pharmacology highlights its therapeutic versatility. The plant is rich in bioactive compounds such as triterpenoids, flavonoids, alkaloids, glycosides, and essential fatty acids, which contribute to its wide range of pharmacological activitiesincluding neuroprotection, wound healing, anti-inflammatory, antibacterial, and cognitive enhancement effects.

With applications spanning from herbal medicines and skincare products to edible leafy greens in various cuisines, *Centella asiatica* holds a unique place in both health and nutrition sectors. Advances in propagation methods, including tissue culture, further enable sustainable cultivation and conservation of this valuable plant species.

As global interest in natural and plant-based remedies continues to grow, *Centella asiatica* remains a key botanical resource for developing safe, effective, and affordable therapeutic agents across traditional and modern healthcare systems.

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