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REVIEW ARTICLE

Phytochemistry, Molecular Mechanisms, and Therapeutic Applications of *Centella asiatica* (L.) Urban: A Critical Review for Modern Herbal Medicine and Drug Development

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Abstract

Centella asiatica (L.) Urban is a widely recognized medicinal plant extensively used in traditional systems of medicine and increasingly explored for its pharmacological potential. Despite numerous reports on its therapeutic properties, a critical integration of its phytochemical composition with underlying molecular mechanisms and clinical relevance remains limited. This review provides a comprehensive and critical evaluation of the phytochemistry, biological activities, and therapeutic applications of *C. asiatica*, with particular emphasis on its major triterpenoid constituents, including asiaticoside, madecassoside, asiatic acid, and madecassic acid. These compounds are analyzed in relation to their roles in modulating key signaling pathways associated with oxidative stress, inflammation (notably nuclear factor kappa and mitogen-activated protein kinase pathways), neuroprotection, and collagen synthesis. Current experimental evidence is examined to highlight both the pharmacological potential and the limitations of existing studies, including variability in extract composition, lack of standardization, and insufficient clinical validation. In addition, emerging approaches to enhance bioavailability and therapeutic efficacy are discussed. By bridging traditional knowledge with mechanistic and pharmacological insights, this review outlines critical research gaps and provides a framework for the rational development and application of *C. asiatica* in modern herbal medicine and drug discovery.

Key words: *Centella asiatica*, cultivation practices, herbal medicine, medicinal plants, pharmacological activity, phytochemistry

INTRODUCTION

Medicinal plants have been vital in promoting health care systems in human societies. Plants are primary sources of therapeutic agents that have been used in the prevention and treatment of many diseases over thousands of years. Medicinal plants continue to play a critical role in health care in the world, especially in developing countries, when access to conventional medicines may be restricted even in the modern age of advanced health-care pharmaceutical development. The World Health Organization reports that a large number of the world's population still uses traditional herbal medicine as their major source of medical care.[1] The growing use of natural remedies, in addition to the growing

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concern of the side effects of synthetic medicines, has led to a resurgence of scientific interest in medicinal plants and their bioactive compounds.[2]

Centella asiatica (L.) Urban is one of the many medicinal plants, which have received great attention from scientists due to its various therapeutic attributes and wide usage in traditional medicine. Gotu kala or Indian pennywort or Mandukaparni is a perennial creeping herb that is part of the Apiaceae family and is ubiquitous in tropical and subtropical areas, such as South Asia, Southeast Asia, Africa, and Australia.[3] The plant usually thrives in wet and semi-aquatic areas such as wetlands, paddy fields, and riverbanks whereby it propagates in a dense mat through vegetative growth of stolons.

The medicinal value of *C. asiatica* has been recorded in a number of ancient medical systems such as Ayurveda, Traditional Chinese Medicine, and Southeast Asian folk medicine. The plant has been used as a rejuvenating herb with the capacity to improve cognitive functions, memory, and longevity in Ayurvedic medicine. The plant has also been used by the traditional practitioners in the treatment of skin disorders, wounds, burns, as well as inflammatory conditions. Likewise, *C. asiatica* has been utilized in non-Western medicine by the Chinese as a treatment agent against fever, infection, or circulatory disease.[4] In most of the nations, the plant leaves are taken as a consumable medicinal vegetable or herbal tonic which is assumed to bring health and vitality to the body in general. These conventional applications point to the fact that the plant is rich in bioactive compounds that can exercise a variety of effects on various physiological processes.

Scientific research studies in modern times have shown significant evidence about most of the traditional medicinal uses of *C. asiatica*. Most phytochemical studies have indicated that the plant comprises a wide variety of bioactive compounds, triterpenoid saponins, flavonoids, phenolic acids, and volatile constituents.[5] Of these compounds, the triterpenoid saponins that include asiaticoside, madecassoside, asiatic acid, and madecassic acid are supposed to be the main active constituents with regard to most of the therapeutic effects of the plant. These substances were found to stimulate collagen formation, enhance the healing process, and possess antioxidant and anti-inflammatory effects.[6]

Pharmacological research has also shown that *C. asiatica* extracts have diverse biological activities; they are antioxidant, anti-inflammatory, antimicrobial, neuroprotective, and anti-aging.[7] These pharmacological effects have enhanced the rising popularity of *C. asiatica* in contemporary pharmaceutical products, nutraceuticals, and cosmetic formulations. The plant has also become of significant use in the cosmeceutical business, whereby extracts of *C. asiatica* are used in skincare preparations to enhance collagen synthesis, fibrousness to the skin and scarring. Consequently, *C. asiatica* has ceased to be a highly treasured medicinal herb but has emerged as a valuable source of botanical ingredients in various industries across the world such as pharmaceuticals, functional foods, and herbal cosmetics.[8]

Although there has been an increasing amount of scientific data on *C. asiatica*, there are a number of issues concerning the standardization and uniform therapeutic effectiveness of the medicinal products produced by this plant. The variability in phytochemical content due to differences in environmental factors, cultivation methods, genetic variations, and post-harvest processing methods is one of the key issues that determine the medicinal quality of products of plant origin.[9] The production of secondary metabolites in medicinal plants may be highly affected by the environmental conditions, including soil composition, temperature, rainfall, and the amount of light that the plants receive. It therefore follows that differences in these factors can cause differences in the concentration of bioactive compounds, which ultimately causes a change in the pharmacological effects of herbal preparations.

The other crucial complication in the study of medicinal plants is the inadequate interrelations between horticultural activities and pharmacological studies. Although many have investigated the pharmacological effects of *C. asiatica*, very few have investigated the impacts of the cultivation practices and environmental factors on the production of phytochemicals and quality of medicine.[10] This relationship needs to be understood to be able to come up with the common cultivation protocols that yield predictable phytochemical profiles and therapeutic efficacy.

Moreover, in spite of the fact that some experimental studies have proven the biological activities of *C. asiatica*, the clinical trials designed to assess its therapeutic efficiency have not been conducted. The uncertainties that exist regarding the standardized approaches in the extraction process, dosage protocol, and clinical trials have acted as a barrier to the complete adoption of this medicinal plant as an evidence-based medical treatment.[11] It is necessary to solve these challenges through interdisciplinary research in horticulture, phytochemistry, pharmacology, and clinical science. Even today, medicinal plants constitute an essential part of the healthcare system of the world, especially in the areas where traditional medicine is the only available system of healing. Active constituents of plants also play an important role in modern biomedicine as the starting point for the synthesis of new drugs. One of the several medicinal plants that have moved beyond traditional uses to scientific uses is *C. asiatica* (L.) Urban, which has a rich ethnomedicinal past and a growing body of evidence for its therapeutic efficacy.[12,13]

Against this backdrop, the current review will seek to give an in-depth discussion on the medicinal importance of *C. asiatica* by analyzing its botanical features, methods of cultivation, phytochemical constituents, and the pharmacological effects also outlined in Figure 1.

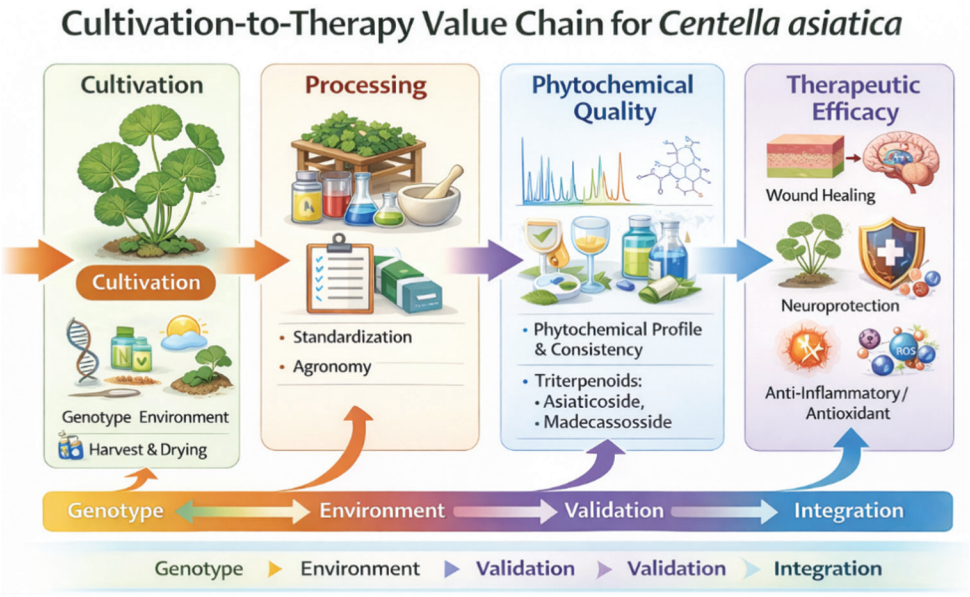


Figure 1: Cultivation→post-harvest processing→phytochemical quality→therapeutic efficacy value chain of *Centella asiatica*

BOTANY AND DISTRIBUTION

C. asiatica (L.) Urban is an herbaceous perennial of the family Apiaceae (order Apiales, class Eudicots), a small genus of creeping herbs native to tropical and subtropical regions and the most widely studied species in traditional and pharmacological research. Formerly classified under the genus Hydrocotyle as *Hydrocotyle asiatica*, taxonomic revision based on morphological and molecular evidence established *C. asiatica* as the accepted name.[4] It is known regionally as Gotu kola (Sri Lanka), Mandukaparni (India), Asiatic pennywort (English), and Pegaga (Southeast Asia).

The morphological features of *C. asiatica* include a creeping growth pattern and vegetative propagation. The plant is normally low-growing and perennialized with slender stolons that are laid out horizontally on the soil surface. These stolons also generate roots at the nodes, hence enabling the plant to spread very fast and create large mats in the right habitats. This vegetative reproduction plan allows the species to efficiently colonize damp habitats and this leads to its ecological adaptability. *C. asiatica* has simple, rounded, kidney-shaped (reniform), and typical crenate or scalloped margins. The leaves are supported by long petioles which are produced in nodes along the stolons. The leaf blades are usually shiny green and smooth in nature and they range in diameter between 2 and 5 cm depending on the environmental factors and the maturity of the plant. One of the most common identifying characteristics of the plant is the leaf morphology.

C. asiatica has flowering structures that are very small and inconspicuous as compared to most of the other members of the Apiaceae family. The flowers are grown in simple umbels and are most often white, pink, or light purple. The growth of these flowers is near the earth's surface on short peduncles that form out of the axils of the leaves. The plant usually flowers in warm and moisture seasons when the environmental conditions are favorable to high vegetative growth. After pollination, the plant generates small dry fruits called schizocarps that split into two mericarps at maturity. One seed is usually found in each mericarp. Sexual reproduction of seeds is natural, but vegetative through stolons is the main mode of reproduction of this species both in natural and cultivated conditions.[9]

C. asiatica has a wide geographical spread in tropical and sub-tropical areas around the globe. It is assumed that the species is native to Asia, but it has spread considerably to other parts of the world through its ecological plasticity and medical importance. The plant is located in countries of South Asia like India, Sri Lanka, Bangladesh, and Nepal and in Southeast Asia such as Indonesia, Malaysia, Thailand, and Vietnam. Moreover, the plant is found in some regions of China, Madagascar, and some African states. Cases have also been reported in the northern parts of Australia where climatic conditions are favorable to grow.[8] Due to its medicinal importance, *C. asiatica* has been introduced and grown in several other localities to produce in large quantities, especially to provide raw materials to pharmaceutical, nutraceutical, and cosmetic companies.

CULTIVATION AND HORTICULTURAL PRACTICES

The expansion of use for *C. asiatica* in the fields of pharmaceuticals, cosmetics, and nutraceuticals has increased the demand for standardization and dependable systems of cultivation. Conventionally, wild harvesting has resulted in a host

of problems including harvesting quality that is inconsistent and potential harvesting of a population that is endangered. Starting with a cultivation-based production method is preferred as it is more sustainable and helps with yield control, consistency in phytochemicals, and the traceability of the raw material.[14] These cultivation to quality relationships, summarized in Table 1, illustrate how specific agronomic choices translate into measurable yield and phyto-chemical quality.

Propagation is classed as vegetative where seed germination is considered slow and lacks irregular and viable occurrences. For this reason, propagative vegetative using storns, runners, or node rooting is preferred as it is more accelerated and it is more likely to produce a stand of plants that are genetically uniform.[15] The use of plants that are devoid of disease is paramount as the quality of propagules initially impacts the material that is subsequently produced during the vegetative phase along with the phytochemical constituents and the amount of biomass produced. The use of tissue culture has also been attempted for the sake of consistently producing the precursors of triterpenoids, but the use of this method has been limited due to economic and technical reasons on a large scale.[16]

Decisive agronomic practices influence the yield and medicinal quality of *C. asiatica*. The plant prefers a slightly acidic to neutral (pH 6.5) loamy soil range abundant in organic matter, and well-drained (over moist). With a high moisture requirement and a shallow root system, irrigation is essential for sustained vegetative growth.[17] Water deficiency has been shown to cause a reduction in the leaf area and biomass of a plant; however, excessive irrigation increases the likelihood of infection by fungal pathogens. Thus, balanced irrigation is essential to optimize the developmental potential and vitality of the plant.

The growth and biosynthesis of secondary metabolites are affected by nutritional supply, particularly in the various types of nutrient management systems. The different studies that have been conducted in various locations on the comparison of organic, inorganic, and integrated nutrient management systems have shown that the organic forms of nutrients (such as farmyard manure and compost) improve soil structure, the activity of the microbes, and the availability of nutrients, and as a result, improve biomass and the accumulation of phytochemicals.[18,19] The vegetative growth provided by nitrogenous fertilizers is generally in excess. However, in a case such as this, the secondary metabolite concentration may be significantly decreased; i.e., for medicinal value, the nitrogenous fertilizers should be reduced to a minimum.[20]

The yield and quality of *C. asiatica* can be influenced by environmental elements, including light intensity, temperature, and seasonal changes. *C. asiatica* typically grows best in partial shade, and leaf expansion as well as biomass increase under these conditions. It has been noted that moderate shade can increase plant growth, and moisture stress can be a result of high direct sun exposure; moderate shade can result in higher triterpenoid content.[21] In seasonal studies, under warm and moist conditions that facilitate active vegetative growth, higher biomass and phytochemical concentrations are noted.[22]

The harvest method and timing also influence yield and quality, and in addition to field management, these aspects are important to obtain and enhance quality. Younger plant tissues and leaves contain higher concentrations of triterpenoid saponins; therefore, younger leaves are expected to be harvested to increase the triterpenoid saponin concentration in a given set of leaves.[23] Sustainable practices in the cultivation of medicinal plants have received increased scrutiny recently. Sustainable practices focus on minimizing chemical use, optimizing water utilization, and conserving the planet's genetic resources. These practices address the socio-economic and environmental facets of sustainable development. Emphasizing good agricultural practices and good collection practices improves consistency with regulations and consumer expectations, and increases quality and market acceptance.

Table 1: Cultivation practices and their effects on yield and phytochemical quality

Cultivation factor	Practice/Condition	Observed effect on yield	Effect on phytochemical quality	Key implication
Propagation method	Vegetative propagation (stolons/nodes)	Rapid establishment and uniform growth	Consistent triterpenoid profile	Preferred for commercial cultivation
Soil type	Loamy, organic-rich soil	Higher biomass production	Enhanced accumulation of triterpenoid saponins	Soil fertility influences medicinal value
Irrigation	Regular irrigation without waterlogging	Sustained vegetative growth	Maintains phytochemical stability	Adequate moisture essential
Nutrient management	Organic and integrated fertilization	Moderate yield improvement	Higher asiaticoside and madecassoside levels	Balanced fertilization improves quality
Light exposure	Partial shade conditions	Improved leaf expansion	Increased triterpenoid concentration	Excess sunlight reduces phytochemical content
Harvest stage	Young to mid-mature leaves	Optimal biomass yield	Higher concentration of bioactive compounds	Early harvesting recommended

PHYTOCHEMICAL COMPOSITION

The phytochemical constituents identified in *C. asiatica* [summarized in Table 2] display noteworthy variability owing to the interplay between genetic factors, environmental conditions, and even the method used to cultivate the plants. Differences in figures relating to the total quantity of triterpenoids along with the differing percentages of each individual compound have been demonstrated to occur as a result of genotypic variance of the populations.[24] Chemotypes that differ have been identified in population studies performed in different geographic locations, reinforcing the idea that a given region's genetic disposition critically influences the phytochemical constituents and the medicinal value of the plants.[25]

Environmental conditions strongly influence the biosynthesis of secondary metabolites in *C. asiatica*. Phenomena of a varying nature, such as the composition of the soil, height above sea level, temperature, amount of precipitation, and periods of light, have been shown to influence the amount of triterpenoids that can be found in *C. asiatica*. It has been shown that plants that grow in the presence of water in sufficient quantities and receive a moderate to high amount of shade tend to have more of the triterpenoids, and, conversely, high amounts of environmental stress can lead to a decrease in triterpenoids.[26,27] Based on spring and autumn seasonal variations, subordinate metabolites can have a cyclic occurrence, and those with a high demand can be replenished to a similar level of demand as that of previously replenished metabolites.

The interaction between cultivation practices and production factors determines the quantity and constancy of phytochemical production. For example, the accumulation of certain metabolites is influenced by the application of certain fertilizers, the management of irrigation, and the timing of harvest. Integrated or organic nutrient management has been shown to foster better soil health and nutrient balance which is likely the reason for the increased soil crops in triterpenoids.[28] Harvest cut-off is another crucial aspect to consider, as both premature and overdue harvests can lead to unideal phytochemical compositions.[29]

In general, the medicinal value of *C. asiatica* is based on its phytochemical abundance. The fact that there are various types of bioactive compounds (especially triterpenoid saponins, flavonoids, and phenolic acids) makes the plant a multifunctional product in terms of pharmacological effects. The next step toward understanding how phytochemical composition is affected is thus necessary to enhance cultivation conditions, guarantee quality of the product, and to exploit the therapeutic potential of this significant medicinal plant.

PHARMACOLOGICAL MECHANISMS

The synergistic effects of *C. asiatica's* diverse bioactive phytochemicals on different molecular and cellular mechanisms give the plant its potential pharmacological value. The plant's poly-target effect, unlike single-target synthetic pharmaceuticals, justifies its broad range of therapeutic applications and its historical use in conventional and contemporary medicine. A wealth of experimental data shows that triterpenoid saponins and their aglycones are instrumental in mediating wound healing, neuroprotection, and the inflammatory and oxidative stress response [Figure 2].[30,31]

C. asiatica's pharmacological applications have been most extensively studied for wound healing, which is a complex process that consists of several phases that overlap and are progressively sequenced. In addition to inflammation and tissue remodeling, there is a proliferation phase where the growth of new tissue occurs. Fibroblast proliferation and migration have been shown to be enhanced by asiaticoside and madecassoside.[32] Madecassoside also stimulates the synthesis of type I collagen, which is necessary for restoring the tensile strength and structural integrity of the collagen in damaged tissue. One of the key mechanisms that *H. madecassoside* activates to restore the collagen tensile strength and structural integrity of damaged tissue is the upregulation of transforming growth factor-β.[33]

Besides collagen synthesis, angiogenesis is vital for adequate supply of oxygen and nutrients to the tissue in the process of wound healing. Studies have shown that at the wound site, *C. asiatica*

Table 2: Major phytochemicals of *Centella asiatica* and their biological activities

Phytochemical class	Major compounds	Biological activities	Therapeutic relevance
Triterpenoid saponins	Asiaticoside, Madecassoside	Stimulate collagen synthesis, wound healing	Skin regeneration, tissue repair
Triterpenoid aglycones	Asiatic acid, Madecassic acid	Anti-inflammatory, neuroprotective	Cognitive health, neurodegenerative disorders
Flavonoids	Quercetin, Kaempferol, Rutin	Antioxidant, anti-inflammatory	Protection against oxidative stress
Phenolic acids	Caffeic acid, Chlorogenic acid, Ferulic acid	Free radical scavenging	Cellular protection and immune support
Volatile compounds	Minor terpenes	Supportive biological activity	Synergistic therapeutic effects

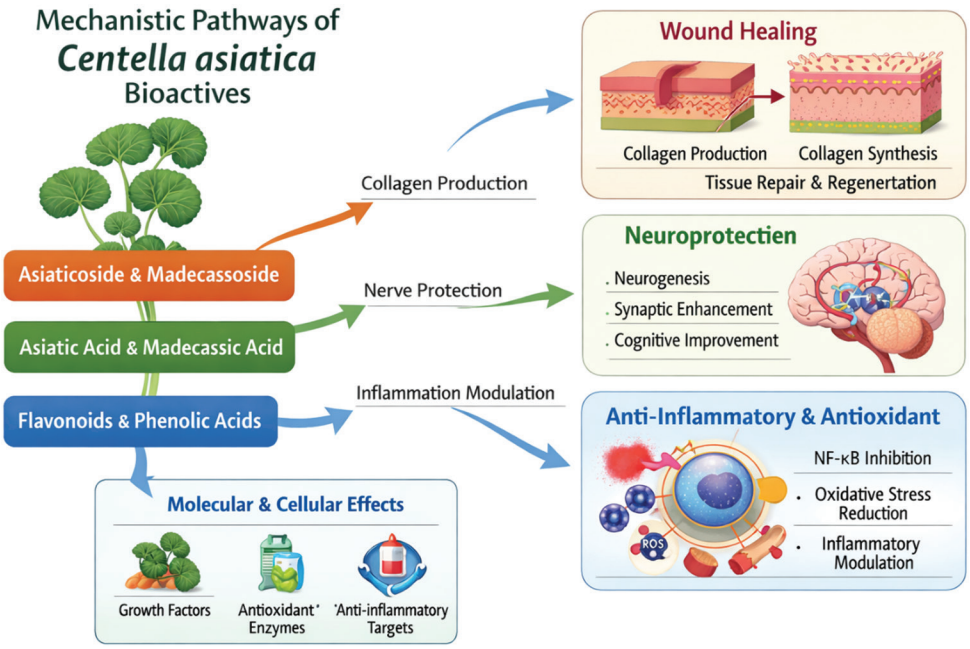


Figure 2: Mechanistic pathways of major bioactive compounds of *Centella asiatica* involved in wound healing, neuroprotection, and anti-inflammatory responses

extracts enhance endothelial cell and blood vessel formation, resulting in rapid tissue regeneration.[34] The synergistic effects of tissue fibroblast activity, collagen deposition, and angiogenesis result in further improved wound healing, reduced scarring, and enhanced remodeling of the tissue.

The neuroprotective effects of *C. asiatica*, especially on cognitive decline and neurodegenerative diseases, are relatively new. The bioactive components of the plant have been found to help neurons survive and increase synaptic plasticity and neurite outgrowth.[35] These are effects of oxidative stress and neuroinflammation as they are mechanisms of most neurodegenerative diseases. Asiatic acid, for example, by exerting its effects in stabilizing mitochondrial apoptosis and reducing reactive oxygen species, is able to protect neurons from apoptosis.[36]

At a molecular level, *C. asiatica* impacts important signaling pathways involved with neuronal health. Studies document defensive responses to neuronal oxidative damage through upregulation of endogenous antioxidant enzymes neuronal protection.[37] Furthermore, the reduced function of neuroinflammation and improved neuronal functioning can be attributed to the reduced activity of pro-inflammatory mediators and microglia. These actions reiterate the need to further evaluate *C. asiatica* as a neuroprotective cognitive enhancer.

Another overview of the ethnopharmacological activity of *C. asiatica* is its antioxidant and anti-inflammatory activity. Oxidative stress and chronic inflammation are the core underlying causes of several pathologies such as cardiovascular illnesses, neurodegenerative diseases, and metabolic syndromes. *C. asiatica* contains triterpenoids and phenolic compounds that inhibit linear chain reactions of pro-inflammatory cytokine production and several important pathways of the inflammatory process.[38] One of the most important molecular targets for inflammatory control is the inhibition of nuclear factor-κB.[39]

The antioxidant activity of *C. asiatica*, as well as all its pharmacological properties, is the result of a combination of direct scavenging and the promotion of endogenous antioxidant systems. *C. asiatica* triterpenoids improve the antioxidant defensive systems of the organism which is a fundamental element to avoid oxidative damage.[40] Phenolics and flavonoids are cellular systems that improve free radical scavenging. The result of all these properties of *C. asiatica* is that the processes of repair and regeneration of affected tissues are increased.

With regard to the molecular or cellular level, the pharmacological impact of *C. asiatica* concerns changes in the level of gene expression, enzyme function, and the activity of signal transduction processes. The synergistic effects from the multi-component nature of the plant enhance the therapeutic effects of the various phytochemicals.[41] Conversely, the complexity means that the pharmacological effects can be lost with even minor changes in the composition of the phytochemicals. Therefore, to ensure therapeutic effects, the cultivation and processing practices must be controlled to maintain phytochemicals.

POST-HARVEST HANDLING AND PROCESSING EFFECTS

The handling and processing that occur after harvesting *C. asiatica* are vital for assessing the efficacy of the plant's

therapeutic usefulness. The time period right after harvesting is critical because plant tissues are still metabolically active and can undergo processes like enzymatic degradation, oxidation, and decay from microorganisms. The shorter the time period after harvesting, the more the bioactive compounds can degrade, which negatively impacts the quality of the plant's therapeutic effect.[18]

Drying is a key example of a post-harvest activity that should be performed for *C. asiatica* that allows for the preservation and the extension of the shelf life of the plant material. While sun-drying is the simplest and most cost-effective method of drying, it is often limited due to heat and ultraviolet (UV) damage, which ultimately can degrade some of the phytochemicals that are highly sensitive to heat and UV light.[14] In studies that have looked at the preservation of the triterpenoid and antioxidant activity, controlled low-temperature drying and shade drying have been deemed to be better methods.[15] While freeze drying is more costly than the other methods of drying, it is often the preferred method for drying due to its ability to better preserve the bioactive compounds, especially with products that are considered to be medicinal and high-value.

Without the right way of handling and processing, valuable phytochemicals might be destroyed and this causes decreased medicinal effectiveness of the plant substance. Thus, genetic preservation of the phytochemical integrity of *C. asiatica* and quality control in medicinal products requires careful management of post-harvest operations, such as drying, storage, extraction, and quality control.

After the drying process, the stability of phytochemicals found in *C. asiatica* needs to be maintained under proper conditions of storage. A number of environmental factors affect storage stability, and they include temperature, humidity, light exposure, and availability of oxygen. In case of improper storage of plant materials, oxidative degradation and microbial contamination can be experienced, causing the degradation of concentration of active compounds. To avoid this degradation, dried plant materials are typically put in airtight containers and kept in cool, dry, and dark conditions. Water-resistant and light-resistant packaging materials are especially significant to ensure the stability of the product. It has been revealed that triterpenoid saponins and other bioactive compounds that the plant contains can be considerably lowered by exposure to high humidity and high temperatures. Thus, it is necessary to observe the conditions of controlled storage to secure the quality of *C. asiatica* as a medicine.[9]

COMMERCIAL APPLICATIONS

Apart from topical applications, oral pharmaceutical formulations of *C. asiatica* [Table 3] are also used for chronic venous insufficiency, disorders of the microcirculation, and cognitive impairment. Symptom relief of vascular diseases has been achieved with venous tone and capillary permeability improvements by certain triterpenoid-rich extracts.[42] For oral formulations in the neurological field, they are usually advertised for cognitive assistance and stress relief, but formulation and dosage quality remain the primary factors for inconsistent clinical results.[29]

The nutraceutical industry is one of the fastest-growing sectors for *C. asiatica.* Antioxidant, neuroprotective, and adaptogenic supplements are marketed in various forms such as capsules, tablets, powders, and liquid extracts, not forgetting to advertise them for cognitive improvement, stress reduction, and general wellness. These supplements are marketed for the prevention of diseases, especially to those who wish to have natural remedies for their ailments.[43] However, the variations in the active ingredients found in different formulations result from the source of the raw materials, the methods used in the cultivation of the plants, and the methods used to extract the active ingredients.[44] This highlights the need to establish control measures in cultivation and the standardization of procedures in the quality-control process to provide effective products for the consumer.

The pharmaceutical industry is one of the commercial uses of *C. asiatica* that is of paramount importance. The plant extracts have been extensively used as part of the medicinal preparations to stimulate wound healing, tissue regeneration, and treatment of skin-related diseases.

Table 3: Commercial products derived from *C. asiatica* and their major therapeutic applications

Product category	Formulation type	Major active constituents	Therapeutic application	Industry sector
Pharmaceutical	Creams, gels, ointments	Asiaticoside, Madecassoside	Wound healing, scar reduction	Medical
Pharmaceutical	Oral tablets, capsules	Triterpenoid extracts	Chronic venous insufficiency	Medical
Nutraceutical	Capsules, powders, liquid extracts	Standardized plant extracts	Cognitive enhancement, stress reduction	Wellness
Functional foods	Herbal teas, beverages, fortified juices	Whole plant extract	Antioxidant support, general health	Food industry
Cosmeceuticals	Serums, lotions, anti-aging creams	Triterpenoid-rich fractions	Skin regeneration, anti-aging	Cosmetic industry

Standardized extracts of *C. asiatica* are commonly utilized as pharmaceutical preparations in topical practices (creams, gels, ointments, and lotions). These products are consumed mostly to treat wounds, burns, surgical wounds, and dermatological diseases such as psoriasis and eczema. Another application of *C. asiatica* that is emanating is in the production of functional foods. Functional foods can be described as food products which offer supplementary health advantages to nutritional value. In some of the Asian nations, *C. asiatica* has been used as a leafy vegetable or beverage or in herbal preparations. Food industries today have changed all these traditional applications, and now, *C. asiatica* extracts are used widely as functional food in different products including herbal teas, health drinks, fortified juices, and nutritional snacks. These products can be promoted based on their antioxidant and adaptogenic effects, which have the potential to maintain cognitive activity, decrease oxidative stress, and enhance health in general. Nevertheless, the process of creating functional foods with *C. asiatica* must take into account other aspects, such as taste, bioactivity constituents' stability, and phytochemicals bioavailability.

On the whole, the sphere of commercial usage of *C. asiatica* is steadily increasing in various industries, which is also attributed to the growing awareness of the therapeutic value of this plant. The combination of traditional knowledge and the application of modern scientific studies has enabled the creation of new products that employ the medicinal value of this plant. With more research still underway on new pharmacological actions and more effective cultivation methods, the commercial value of *C. asiatica* is likely to gain even more in the world market of herbal medicine.

RESEARCH GAPS AND FUTURE PROSPECTS

C. asiatica has been widely researched and utilized commercially, but there are many significant gaps defining the full therapeutic and industrial potential of the plant. A significant gap is the lack of consistency in plant material used during the experimental and clinical studies. Differences in plant genotype, farming environment, and post-harvest handling have been shown to cause variability in the phytochemical composition of plants. This impacts the ability to compare the results of studies and to determine the clinical efficacy of the compound in the studies done.[30]

Another significant gap in research is the inadequate horticulture variables and pharmacological outcomes. A large number of research studies have been done to assess the impact of certain mechanical conditions such as soil type, fertilization, and irrigation on the growth of plants. A very small number of studies have been done to assess the same impact on the phytochemical composition of the plant and the therapeutic functions of the plant.[31] This has caused a large number of cultivation methodologies to be designed to increase the biomass rather than the therapeutic value of the plant. There is a high demand for research to assess and determine cultivation systems that are designed to increase both the bioactive phytochemicals of the plant as well as the therapeutic efficacy of the plant.

A lack of standardized formulations and plant material is a major barrier to research and commercialization of *C. asiatica*. Chemical composition varies with genetics, environment, and post-harvest processing, and levels of asiaticoside and madecassoside differ considerably across geographic populations, complicating quality assurance. With no universally agreed standards for active-compound concentrations, standardized cultivation, extraction, and phytochemical benchmarks, along with validated reference materials and analytical procedures, are essential to ensure consistency and credibility of herbal preparations.

A further gap is the scarcity of well-designed clinical trials assessing the therapeutic value of *C. asiatica*. While preclinical and experimental studies have validated its pharmacological activity, human clinical evidence remains limited, with most trials constrained by small sample sizes, short durations, or inconsistent dosing, making it difficult to establish standardized dosing or clear clinical recommendations. Large-scale, randomized controlled trials are needed to confirm the safety, efficacy, and optimal dosage of *C. asiatica* preparations, supporting the integration of plant-based treatments into evidence-based medical practice.

Another research gap concerns the link between cultivation practices and phytochemical composition. Soil fertility, irrigation, light, temperature, and harvest timing all influence secondary metabolite accumulation, yet few studies have systematically examined how horticultural practices affect the phytochemical profile and pharmacokinetic quality of *C. asiatica*. Most agricultural research has prioritized biomass over phytochemical yield; future studies should target cultivation strategies that optimize both productivity and the concentration of pharmacologically active compounds, improving the consistency of medicinal plant material.

The prospects for enhancing medicinal value and commercial production of *C. asiatica* are promising due to the advancement of biotechnology and molecular breeding. High-yielding and improved phytochemical plant varieties can be created with modern methods of biotechnology including tissue culture, genetic transformation, and molecular marker-assisted selection. A method of producing disease-free planting material and maintaining a genetically uniform population of plants has already been investigated using tissue culture techniques. Furthermore, cell culture systems and bioreactor-based cultivation systems can perhaps enable the generation of valuable

phytochemicals in a controlled environment. The methods might assist in addressing the issues related to variability of the environment and provide stability in the production of bioactive compounds.

Molecular breeding techniques can also be used to identify and choose plant genotypes that possess desirable characteristics, e.g., increased triterpenoid levels, better stress resistance, and growth. The discoveries in the area of genomics, transcriptomics, and metabolomics have created new opportunities in comprehending the biosynthetic pathways that lead to the biosynthesis of pharmacologically significant compounds in *C. asiatica*. By discovering the major genes that are participated in the triterpenoid biosynthesis, it might enable the researcher to come up with the better type of plants by applying targeted breeding, or genetic engineering strategies.

Besides biotechnological developments, sustainable crops and conservation measures ought to be given top priority to conserve the natural populations of *C. asiatica*. Possible threats to the long-term availability of this useful medicinal species include overharvesting of the wild plants and deterioration of the habitat. The introduction of sustainable cultivation technologies, preservation of genetic diversity, and responsible harvesting methods are necessary to ensure the preservation of the ecological balance and sustainability of the ever-increasing demand for plant-based medicinal products. Developing new systems for increasing bioavailability and clinical effectiveness is a potential focus for future research, particularly in a therapeutic capacity. More research focused on delivery methods and the synergistic combinations of phytochemicals may also be warranted. The integration of various "omics" technologies will assist in understanding the biochemical pathways which are responsible for the production and therapeutic effect of the specific phytochemicals.[45] Integrating various technologies will be instrumental in addressing the challenges of merging horticultural and therapeutic fields.

All in all, future studies on *C. asiatica* must concentrate on the combination of horticultural science, phytochemistry, pharmacology, and biotechnology to overcome the current shortcomings and increase the therapeutic potential of the plant. Researchers can enhance the reliability and commercial feasibility of products based on *C. asiatica* through the creation of standardized cultivation techniques, the conduction of strict clinical trials, and the help of the latest biotechnological tools. This type of interdisciplinary work will be needed to achieve all the potential of this valuable medicinal plant in contemporary healthcare and pharmaceutical practice.

CONCLUSION

The importance of *C. asiatica* has always been well known in the world of traditional healthcare systems, and its therapeutic value is still receiving more and more attention in contemporary scientific studies. The current review demonstrates the wide range of pharmacological activity and commercial use of *C. asiatica* with the critical role of botanical, cultivation, phytochemical, and pharmacological investigations in comprehending the medicinal potential of this plant. This type of cultivation-to-therapy is not only the key to the uniform quality and therapeutic trustworthiness of herbal medicines based on *C. asiatica* but also the condition of their worth.

C. asiatica is thought to have medicinal value largely because of its abundant phytochemical composition in terms of triterpenoid saponins including asiaticoside, madecassoside, asiatic acid, and madecassic acid. Such bioactive compounds help in the pharmacological properties of the plant such as wound healing, neuroprotection, anti-inflammatory activity, and antioxidant activity. Nevertheless, the levels of such compounds may be quite different according to environmental factors, the ways of cultivation, genetic variations, and the processing of products after harvest. This inconsistency raises the concern of standardized cultivation and processing procedures which will be capable of producing consistent phytochemical profiles in medicinal plant materials. Phytochemical consistency is important to ensure therapeutic efficacy as well as to enhance reliability and reproducibility of herbal medicines in clinical practice.

C. asiatica has also gained significance in different commercial markets, such as pharmaceuticals, nutraceuticals, functional foods, and cosmeceuticals, in addition to having medicinal value. This has been enhanced by the rising demand for plant-based therapeutics and natural health products that have led to the increasing popularity of the global market for herbal medicines. Topical preparations of *C. asiatica* in the form of standardized extracts are currently utilized in topical wound healing and skin regeneration preparations and in dietary supplements to enhance cognitive and general health. The combination of ancient knowledge with new scientific studies has contributed to changing the plant to a precious botanical tool for various industries. Nevertheless, the business success of *C. asiatica* is also attached to the observance of high quality control standards and the safety and efficacy of the plant-based products.

Even though significant advancements were achieved in learning about pharmacology and medical uses of *C. asiatica*, there are many areas that should be explored. The research in the future must aim at establishing standardized methods of cultivation to maximize biomass growth as well as phytochemical yield. There is also a need to have large-scale clinical trials of the efficacy and safety of the *C. asiatica*-based formulations in treating different health conditions. Moreover, biotechnology and molecular breeding can become prospects of working out the improved plant varieties in terms of phytochemical content and compatibility with environmental conditions.

C. asiatica, on the whole, is a perspective and promising medicinal plant which can find its application in modern health care and pharmaceutical industry. Through a combination of cultivation science, phytochemical studies, pharmacological studies, and clinical validation, researchers and industry experts could improve the therapeutic and commercial viability of this plant. Further interdisciplinary studies will be likely to unlock potential of *C. asiatica* fully and make sure that the full potential of *C. asiatica* is used in the development of plant-based therapeutic products in the future.

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