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# Nutraceutical and pharmacological perspectives of Tuberose, *Agave amica* (Medik.): Insights into its bioactive phytoconstituents

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**Abstract**

*Agave amica* (Medik.) is a highly valued ornamental and aromatic plant that has gained increasing attention for its diverse phytochemical composition and emerging nutraceutical and pharmacological potential. This review comprehensively explores the botanical characteristics, phytochemical profile, biological activities and industrial applications of tuberose, with a particular focus on its bioactive constituents. The plant is rich in volatile compounds such as methyl benzoate, benzyl alcohol, eugenol and farnesol, along with non-volatile constituents including phenolics, flavonoids, terpenoids and glycosides. These compounds contribute significantly to its antioxidant, antimicrobial, anti-inflammatory, anticancer and neuroprotective activities. The review highlights the mechanisms of action of these bioactive compounds, emphasizing their role in modulating key cellular signalling pathways, reducing oxidative stress and interacting with enzymes and receptors. Advances in extraction technologies, including green extraction methods and supercritical fluid extraction, have improved the efficiency and sustainability of phytochemical recovery. Furthermore, the application of nanotechnology and encapsulation techniques has enhanced the bioavailability, stability and controlled delivery of tuberose-derived compounds, thereby expanding their therapeutic potential.

In addition to its pharmacological relevance, tuberose holds significant promise in the nutraceutical, cosmetic and wellness industries. Its essential oil is widely used in perfumery and aromatherapy, while its bioactive compounds are being explored for incorporation into functional foods and dietary supplements. Despite these promising applications, challenges such as variability in phytochemical composition, lack of standardization and limited clinical validation remain barriers to its widespread utilization. Future research should focus on comprehensive phytochemical characterization, standardization of extraction and formulation processes and clinical evaluation of its therapeutic efficacy. The integration of advanced omics technologies and computational approaches can further enhance the understanding of its biological mechanisms and facilitate drug discovery. Overall, *A. amica* represents a valuable yet underutilized bioresource with significant potential for the development of innovative nutraceutical and pharmaceutical products, contributing to sustainable healthcare and industrial advancement.

## 1. Introduction

Medicinal and aromatic plants (MAPs) have long been integral to human civilization, serving as primary sources of therapeutic agents, functional foods and bioactive compounds with diverse health-promoting properties. In recent decades, there has been a renewed global interest in plant-based systems due to the rising demand for natural, safe and sustainable alternatives to synthetic drugs and additives. These plants are rich repositories of secondary metabolites such as phenolics, flavonoids, alkaloids, terpenoids and essential oils, which play crucial roles in disease prevention and health promotion. The increasing prevalence of chronic disorders including cardiovascular diseases, diabetes, cancer and neurodegenerative conditions has further accelerated the exploration of phytochemicals as nutraceuticals and pharmacological agents. Scientific advancements in phytochemistry, metabolomics and pharmacology have facilitated the identification and characterization of bioactive compounds, thereby validated traditional knowledge and expanded their applications in modern healthcare systems. Recent studies emphasize that plant-derived bioactives exhibit antioxidant, anti-inflammatory, antimicrobial and immunomodulatory activities, making them promising candidates for drug discovery and functional food development (Dinesh, 2025; Afzal *et al*., 2024). Among MAPs, floral bioresources represent a relatively underexplored yet highly

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valuable group of plant materials with immense potential in nutraceutical and pharmaceutical industries. Flowers are not only aesthetically important but also serve as biochemical factories producing a wide array of volatile organic compounds (VOCs) and non-volatile phytochemicals. These compounds are responsible for fragrance, pigmentation and biological activities and they play essential roles in plant defense, pollinator attraction and ecological interactions. Floral essential oils, in particular, have gained considerable attention due to their applications in aromatherapy, cosmetics, food preservation and medicine. The global market for floral extracts and essential oils has witnessed substantial growth, driven by consumer preference for natural ingredients and clean-label products. Moreover, advances in extraction technologies such as supercritical fluid extraction, microwave-assisted extraction and green solvent systems have enhanced the efficiency and sustainability of bioactive compound recovery from floral sources. Recent research highlights those floral metabolites, including terpenes, phenylpropanoids and flavonoids, possess significant pharmacological properties such as antioxidant, antimicrobial, anticancer and neuroprotective effects, thereby positioning flowers as promising candidates for nutraceutical innovation and pharmaceutical development (Mandal, 2022; Afzal *et al*., 2024).

*A. amica*, commonly known as tuberose, is one such economically and biologically significant floral species that has attracted attention due to its unique fragrance and bioactive profile. Taxonomically, tuberose belongs to the family Asparagaceae (subfamily Agavoideae), although it has historically been classified under Agavaceae or Amaryllidaceae by different botanists. It is a perennial herbaceous plant characterized by underground tuberous bulbs, linear leaves and a tall flowering spike bearing highly fragrant, waxy white flowers. The species is believed to be native to Mexico and was domesticated by ancient civilizations before being introduced to other parts of the world, including Asia, Europe and Africa. Today, tuberose is widely cultivated in tropical and subtropical regions, particularly in countries such as India, China and Thailand, where it holds significant economic importance in the floriculture industry. Its adaptability to diverse agro-climatic conditions and its high market demand as a cut flower and loose flower make it a valuable commercial crop (Saravani *et al*., 2025). In India, tuberose is popularly known as “Rajanigandha” and is extensively used in garlands, bouquets and religious ceremonies, reflecting its cultural and socio-economic significance. Beyond its ornamental value, tuberose has been traditionally used in various systems of medicine for its therapeutic properties. Ethnomedicinal records indicate its use in treating conditions such as inflammation, infections, wounds and stress-related disorders. The plant’s essential oil is widely used in perfumery due to its rich, sweet and lingering fragrance, which is attributed to a complex mixture of volatile compounds including methyl benzoate, benzyl alcohol, eugenol and farnesol. These compounds not only contribute to its aromatic profile but also exhibit significant biological activities. Recent phytochemical analyses using advanced techniques such as gas chromatography–mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC) have identified a wide spectrum of bioactive constituents in tuberose, including flavonoids, glycosides, phenolic acids and fatty acids. These compounds are known to possess antioxidant, antimicrobial, anti-inflammatory and anticancer properties, thereby supporting the medicinal potential of the plant (Khatun, 2021; Dinesh, 2025).

The economic importance of tuberose extends beyond floriculture into multiple industrial sectors, including perfumery, cosmetics, pharmaceuticals and nutraceuticals. The essential oil of tuberose is one of the most expensive natural floral oils due to its low yield and high demand in the fragrance industry. It is widely used in high-end perfumes and cosmetic formulations, where it imparts a distinctive floral note. Additionally, the use of tuberose in aromatherapy has been associated with psychological benefits such as stress reduction and mood enhancement. Experimental studies have demonstrated that inhalation of tuberose essential oil can have calming effects on the central nervous system, suggesting its potential application in managing anxiety and stress-related disorders (Ghorat *et al*., 2016). Although, this study predates 2020, it continues to provide foundational insights into the therapeutic potential of tuberose essential oil in neuropharmacology. Furthermore, the increasing demand for natural and plant-based ingredients in the food and health industries has opened new avenues for the utilization of tuberose extracts as functional ingredients in nutraceutical formulations. The exploration of phytochemical and therapeutic potential of tuberose is further justified by the growing need for novel bioactive compounds that can address emerging health challenges. Despite the availability of synthetic drugs, issues such as drug resistance, adverse side effects and high costs have necessitated the search for safer and more effective alternatives. Plant-derived compounds offer several advantages, including biocompatibility, multi-target activity and lower toxicity. In this context, tuberose represents a promising yet underutilized resource with significant potential for drug discovery and development. Recent pharmacological studies have reported that extracts of *A. amica* exhibit potent anti-inflammatory activity comparable to standard non-steroidal anti-inflammatory drugs (NSAIDs), indicating its potential as a natural therapeutic agent (Dinesh, 2025). Additionally, studies on related *Polianthes* species have demonstrated strong antioxidant and thrombolytic activities, further supporting the pharmacological relevance of this genus (Afzal *et al*., 2024).

Another important aspect that underscores the significance of tuberose is its role in sustainable agriculture and value addition. With increasing emphasis on sustainable development and circular bioeconomy, the utilization of floral waste and by-products for the extraction of bioactive compounds has gained attention. Tuberose flowers, which are often discarded after their ornamental use, can serve as valuable raw materials for the extraction of essential oils and phytochemicals, thereby contributing to waste valorization and environmental sustainability. Moreover, advancements in biotechnology and nanotechnology have opened new possibilities for enhancing the bioavailability and efficacy of plant-derived compounds. For instance, nanoencapsulation of essential oils can improve their stability, controlled release and therapeutic efficiency, thereby expanding their applications in pharmaceuticals and nutraceuticals. Despite these promising attributes, the scientific exploration of tuberose remains relatively limited compared to other medicinal plants. There is a need for comprehensive studies focusing on its phytochemical profiling, mechanism of action, pharmacokinetics and clinical efficacy. Standardization of extraction methods and quality control measures is also essential to ensure the reproducibility and safety of tuberose-based products. Furthermore, interdisciplinary approaches integrating phytochemistry, molecular biology and systems pharmacology can provide deeper insights into the therapeutic potential of tuberose and facilitate its translation into commercial applications.

In light of the above considerations, the present review aims to provide a comprehensive overview of the nutraceutical and pharmacological perspectives of *A. amica* with a particular focus on its bioactive phytoconstituents. By synthesizing recent research findings and identifying existing gaps, this review seeks to highlight the potential of tuberose as a valuable resource for health promotion and disease management. The study also emphasizes the need for further research and innovation to fully harness the therapeutic and industrial potential of this remarkable floral species.

## 2. Botanical description and cultivation

### 2.1 Taxonomy and classification

*A. amica*., commonly known as tuberose, is a perennial monocot belonging to the family Asparagaceae (subfamily Agavoideae). Historically, it has been classified under Agavaceae and Amaryllidaceae due to morphological similarities; however, modern phylogenetic studies based on molecular markers have clarified its placement within Asparagaceae (Vázquez-García *et al*., 2024). The genus *Polianthes* comprises several species native to Mexico, with *A. amica* being the most economically important and widely cultivated species. It is believed to have originated in Central America and was later disseminated globally due to its ornamental and aromatic value. Cytologically, the species exhibits diploid characteristics (2n = 30), which contribute to its genetic stability and adaptability. Recent studies highlight the genetic variability among tuberose genotypes, which has been exploited for crop improvement and cultivar development (Soujanya *et al*., 2025).

### 2.2 Morphological characteristics

The morphology of tuberose is typical of bulbous ornamental plants and is closely associated with its productivity and commercial value. The plant grows from underground tuberous bulbs, which function as storage organs and propagation units. Bulb size significantly influences vegetative growth, spike emergence and flower yield, with larger bulbs producing more vigorous plants (Duyen *et al*., 2025). The bulbs produce offsets that enable rapid clonal multiplication, making vegetative propagation the primary method of cultivation. The leaves are linear, narrow and elongated, forming a basal rosette. They are bright green, slightly succulent and play a crucial role in photosynthesis and assimilate accumulation. Morphological variations in leaf area and biomass among genotypes have been reported, which directly influence plant growth and yield parameters (Babarabi *et al*., 2024).

The inflorescence is a terminal spike that can reach heights of 60-120 cm depending on cultivar and environmental conditions. It bears multiple florets arranged spirally along the rachis, contributing to its ornamental appeal. The flowers are tubular, waxy and highly fragrant, consisting of six tepals and reproductive structures adapted for pollination. The fragrance is attributed to volatile compounds such as methyl benzoate and eugenol, which are synthesized during flower development. Variations in spike length, floret number and flower size have been observed across genotypes, reflecting genetic diversity and environmental influence (Patil *et al*., 2025).

### 2.3 Agro-climatic requirements

Tuberose is well adapted to tropical and subtropical climates, requiring warm temperatures (20-30°C) and abundant sunlight for optimal growth and flowering. Temperature and photoperiod significantly influence floral initiation and spike quality. The crop is sensitive to frost and performs poorly under low-temperature conditions. Studies indicate that environmental stress, particularly water deficit, can adversely affect morphological and physiological parameters such as leaf area, stem length and flower yield (Saravani *et al*., 2025). The crop prefers well-drained loamy soils rich in organic matter, with a pH range of 6.5-7.5. Soil aeration and drainage are critical to prevent bulb rot and ensure healthy root development. Organic amendments improve soil structure and microbial activity, thereby enhancing nutrient availability.

**Figure 1: Field view of tuberose (*A. amica*).**

Irrigation management plays a vital role in tuberose cultivation. Both water stress and excess moisture negatively impact plant growth and flower quality. Recent research emphasizes the use of drip irrigation and fertigation techniques to optimize water use efficiency and improve productivity. Studies have shown that irrigation at 100% evapotranspiration combined with appropriate fertigation significantly enhances flower yield and economic returns (Soujanya *et al*., 2025). Nutrient management involves the balanced application of macronutrients (N, P, K) and micronutrients. Integrated nutrient management, including biofertilizers and biostimulants, has been shown to improve bulb yield, plant vigor and flower quality. The application of plant growth regulators such as gibberellic acid ($GA_3$) enhances physiological processes and increases productivity (Gunasekhar *et al*., 2025).

### 2.4 Cultivars and varietal diversity

Tuberose exhibits considerable genetic diversity, which is categorized into single, double and semi-double types based on floral morphology. This classification has significant commercial implications. Single-flowered cultivars have a single row of petals and are highly valued for their strong fragrance and suitability for essential oil extraction. Popular cultivars include 'Mexican Single', 'Prajwal' and 'Shringar'. These varieties are widely used in the perfume industry due to their high essential oil content. Double-flowered cultivars possess multiple rows of petals, resulting in a fuller and more attractive flower. Varieties such as 'Suvasini', 'Vaibhav' and 'Pearl Double' are primarily used as cut flowers due to their aesthetic appeal. However, they often exhibit reduced fragrance compared to single types. Semi-double cultivars represent an intermediate group, combining moderate fragrance with improved ornamental characteristics. Comparative studies have demonstrated significant variation among cultivars in terms of growth, flowering behavior and yield, highlighting the importance of genotype selection for commercial cultivation (Safeena *et al*., 2020; Patil *et al*., 2025).

### 2.5 Cultivation practices and production trends

Tuberose cultivation involves systematic agronomic practices aimed at maximizing yield and quality. The crop is propagated through bulbs, which are selected based on size, health and uniformity. Larger bulbs are preferred as they produce more vigorous plants and higher-quality spikes. Planting is typically carried out during favorable seasons, with proper spacing to ensure adequate aeration and light penetration. Field preparation includes soil ploughing, leveling and incorporation of organic manure. Intercultural operations such as weeding, mulching and earthing-up are essential for maintaining soil health and minimizing competition. The application of plant growth regulators and biofertilizers has been shown to enhance growth and flowering characteristics. Recent advancements in cultivation practices include precision farming, protected cultivation and integrated nutrient management, which have significantly improved productivity and sustainability. The adoption of raised bed systems, drip fertigation and biostimulants has been reported to increase flower yield, water productivity and economic returns (Soujanya *et al*., 2025). Additionally, biotechnological interventions such as in vitro propagation are being explored to produce disease-free planting material and improve multiplication rates (Duyen *et al*., 2025). Globally, tuberose is an important floricultural crop with high demand in domestic and international markets. India is one of the leading producers, contributing significantly to the global supply of loose flowers and essential oil. The increasing demand for natural fragrances and plant-based products has further enhanced the commercial importance of tuberose. Emerging trends such as organic cultivation, sustainable production systems and value addition through essential oil extraction and nutraceutical applications are expected to drive future growth in tuberose cultivation.

## 3. Phytochemical composition of tuberose

### 3.1 Overview of phytochemicals in floral crops

Floral crops are increasingly recognized as rich sources of structurally diverse phytochemicals that play essential roles in plant physiology and ecological interactions, while also offering immense potential for nutraceutical and pharmaceutical applications. Flowers synthesize a broad spectrum of secondary metabolites, including volatile organic compounds (VOCs), phenolics, flavonoids, alkaloids, terpenoids and glycosides, which contribute to their color, aroma and defense mechanisms. These metabolites are involved in attracting pollinators, repelling herbivores and mitigating abiotic stress, thereby ensuring reproductive success and survival. In recent years, there has been a growing interest in exploring floral phytochemicals due to their potent biological activities, including antioxidant, antimicrobial, anti-inflammatory and anticancer properties. Modern analytical tools and metabolomic approaches have enabled comprehensive profiling of floral metabolites, revealing their complexity and functional significance. Studies have demonstrated that floral extracts exhibit higher antioxidant capacities compared to other plant parts, largely due to the abundance of phenolic and flavonoid compounds (Zhao *et al*., 2021; El-Nashar *et al*., 2023). Within this context, *A. amica* has emerged as a promising floral species with a rich phytochemical profile, particularly known for its aromatic essential oils and bioactive constituents that contribute to its therapeutic potential (Table 1).

### 3.2 Major bioactive constituents

The phytochemical composition of *A. amica* is characterized by a complex array of volatile and non-volatile compounds that collectively contribute to its fragrance and biological activities. Among these, volatile compounds (essential oils) are the most prominent and extensively studied constituents. The essential oil extracted from tuberose flowers contains a diverse mixture of esters, alcohols, aldehydes and terpenoids, with key components including methyl benzoate, benzyl alcohol, eugenol and farnesol. Methyl benzoate is responsible for the characteristic sweet floral aroma and has been reported to exhibit antimicrobial and insect-attractant properties. Benzyl alcohol contributes to both fragrance and antimicrobial activity, while eugenol is well known for its strong antioxidant, anti-inflammatory and antiseptic properties. Farnesol, a sesquiterpene alcohol, plays a significant role in antimicrobial and anticancer activities by disrupting microbial cell membranes and modulating cellular signaling pathways. These volatile compounds are biosynthesized through the phenylpropanoid and terpenoid pathways and are predominantly accumulated in floral tissues during the blooming stage (Rohloff *et al*., 2021; Bhuyan *et al*., 2022). In addition to volatile constituents, tuberose flowers contain significant amounts of phenolic compounds, including flavonoids and phenolic acids, which contribute to their antioxidant potential. Flavonoids such as quercetin, kaempferol and rutin are known to neutralize reactive oxygen species (ROS), inhibit lipid peroxidation and regulate inflammatory pathways. Phenolic acids, including gallic acid, caffeic acid and ferulic acid, further enhance antioxidant activity and provide protection against oxidative stress-related diseases. These compounds are essential for maintaining cellular homeostasis and have been widely studied for their nutraceutical benefits. Recent investigations have highlighted the role of floral phenolics in preventing chronic diseases such as cancer, cardiovascular disorders and neurodegenerative conditions (Sharma *et al*., 2022; El-Nashar *et al*., 2023).

**Table 1: Major phytochemicals reported in *A. amica* and their biological significance**

| Phytochemical class | Major compounds | Plant part | Biological activities | Remarks |
|---|---|---|---|---|
| Volatile compounds (Essential oils) | Methyl benzoate, Benzyl alcohol, Eugenol, Farnesol | Flowers | Antimicrobial, antioxidant, anti-inflammatory, fragrance activity | Major contributors to aroma and therapeutic properties |
| Phenolic compounds | Gallic acid, Caffeic acid, Ferulic acid | Flowers | Antioxidant, anti-inflamma-tory, free radical scavenging | Protect against oxidative stress |
| Flavonoids | Quercetin, Kaempferol, Rutin | Flowers, leaves | Antioxidant, anticancer, cardioprotective | Modulate cellular signaling pathways |
| Terpenoids | Monoterpenes, Sesqui-terpenes | Flowers | Antimicrobial, anticancer, anti-inflammatory | Important in essential oil composition |
| Glycosides | Steroidal glycosides | Bulbs, flowers | Cardioprotective, anti-inflam-matory | Enhance bioactivity after hydrolysis |
| Alkaloids | Trace alkaloids | Whole plant | Analgesic, antimicrobial | Present in minor quantities |
| Fatty acids and esters | Various aliphatic compounds | Flowers | Antioxidant, antimicrobial | Contribute to overall bioactivity\ |
| Other secondary metabolites | Aldehydes, alcohols | Flowers | Fragrance, antimicrobial | Support synergistic effects |

Terpenoids and glycosides constitute another important class of bioactive compounds in tuberose. Terpenoids, including monoterpenes and sesquiterpenes, contribute to both fragrance and pharmacological activities. These compounds exhibit antimicrobial, anti-inflammatory and anticancer properties and are widely used in the pharmaceutical and cosmetic industries. Glycosides, particularly steroidal glycosides, are known for their diverse biological activities, including cardioprotective and anti-inflammatory effects. The hydrolysis of glycosides releases active aglycones, which enhance their bioavailability and biological efficacy. The presence of these compounds in tuberose highlights its potential as a source of bioactive molecules for therapeutic applications (Bhuyan *et al*., 2022). Furthermore, tuberose contains alkaloids and other secondary metabolites, although in relatively smaller quantities compared to phenolics and terpenoids. Alkaloids are nitrogen-containing compounds known for their potent pharmacological activities, including analgesic, antimicrobial and anticancer effects. Other secondary metabolites such as fatty acids, esters and aldehydes also contribute to the overall phytochemical profile and biological activity of the plant. The synergistic interactions among these compounds enhance their therapeutic potential, making tuberose a valuable candidate for nutraceutical and pharmaceutical applications (Rohloff *et al*., 2021; Sharma *et al*., 2022).

### 3.3 Extraction and analytical techniques

The extraction and characterization of phytochemicals from tuberose are critical for their effective utilization in various industries. Traditional methods such as steam distillation are widely used for the extraction of essential oils, particularly volatile compounds. This method is simple and cost-effective but may lead to the degradation of heat-sensitive constituents. Solvent extraction techniques, using organic solvents such as ethanol, methanol and hexane, are commonly employed to extract both volatile and non-volatile compounds, including phenolics and flavonoids. Although, solvent extraction offers higher efficiency, it requires careful handling to avoid solvent residues in the final product.

In recent years, advanced extraction techniques such as supercritical fluid extraction (SFE) have gained significant attention due to their efficiency and environmental sustainability. SFE, particularly using supercritical $CO_2$, enables the extraction of high-purity bioactive compounds without the use of toxic solvents, while preserving their structural integrity and biological activity. This technique is especially useful for extracting thermolabile compounds and has been widely applied in the essential oil and pharmaceutical industries (Chemat *et al*., 2020; Bhuyan *et al*., 2022). The identification and quantification of phytochemicals are carried out using advanced analytical techniques. Gas chromatography-mass spectrometry (GC-MS) is the most commonly used method for analyzing volatile compounds, allowing precise identification of individual components based on their mass spectra. High-performance liquid chromatography (HPLC) is used for the separation and quantification of non-volatile compounds such as phenolics and flavonoids. Liquid chromatography-mass spectrometry (LC-MS) provides enhanced sensitivity and specificity, enabling the detection of complex phytochemical profiles and structural elucidation of unknown compounds. These analytical techniques have significantly contributed to the understanding of tuberose phytochemistry and have facilitated the discovery of novel bioactive compounds (Chemat *et al*., 2020; Zhao *et al*., 2021).

### 3.4 Factors influencing phytochemical composition

The phytochemical composition of tuberose is influenced by multiple factors, including genotype, environmental conditions and developmental stage, which collectively determine the quality and quantity of bioactive compounds. Genetic variation among cultivars plays a crucial role in the biosynthesis and accumulation of phytochemicals. Studies have shown that different genotypes exhibit significant differences in essential oil composition, phenolic content and antioxidant activity, emphasizing the importance of cultivar selection for specific applications (Bhuyan *et al*., 2022).

Environmental factors such as temperature, light intensity, soil fertility and water availability also have a profound impact on phytochemical production. Moderate environmental stress can enhance the synthesis of secondary metabolites as part of the plant's defense mechanism, while extreme stress conditions may inhibit metabolic processes and reduce phytochemical content. Light intensity, in particular, has been shown to influence the accumulation of phenolic compounds and flavonoids, which are involved in photoprotection and antioxidant activity (Zhao *et al*., 2021). The developmental stage of the plant, especially the flowering stage, is another critical factor affecting phytochemical composition. The concentration of volatile compounds is highest during full bloom, when flowers actively release fragrance to attract pollinators. Similarly, phenolic and antioxidant compounds vary during different growth stages, reflecting changes in metabolic activity and physiological processes. Understanding these variations is essential for optimizing harvesting time and maximizing the yield of bioactive compounds.

## 4. Nutritional and nutraceutical potential

### 4.1 Nutritional profile of tuberose

Although *A. amica* is primarily recognized as an ornamental and aromatic plant, emerging studies suggest that its floral tissues and extracts contain a range of nutritionally relevant and bioactive constituents that contribute to its nutraceutical value. Unlike conventional edible crops, tuberose is not widely consumed as a food source; however, its phytochemical composition includes compounds that exhibit functional nutritional properties. The flowers are known to contain trace amounts of carbohydrates, amino acids, lipids and micronutrients, along with a rich pool of secondary metabolites such as phenolics, flavonoids and essential oil constituents. These compounds are not only important for plant metabolism but also play significant roles in human health when used in extract or formulated forms. Recent investigations have indicated that floral extracts may serve as sources of natural antioxidants and bioactive molecules, which can be incorporated into nutraceutical products (González-Tejero *et al*., 2021; Singh *et al*., 2023). The nutritional relevance of tuberose is largely indirect, as it lies in its ability to provide biofunctional compounds rather than macronutrients. Essential oil components such as benzyl alcohol and eugenol, along with phenolic compounds, contribute to its antioxidant and therapeutic properties. Furthermore, floral extracts may contain minor quantities of vitamins and minerals that support metabolic processes and enhance physiological functions. Advances in phytochemical profiling have revealed that floral metabolites can act as nutraceutical agents by modulating oxidative stress, inflammation and metabolic pathways, thereby contributing to disease prevention and health promotion (Pires *et al*., 2020; Singh *et al*., 2023).

### 4.2 Functional properties

The nutraceutical significance of tuberose is primarily attributed to its functional properties, which arise from the presence of diverse bioactive compounds. Among these, antioxidant, anti-inflammatory and free radical scavenging activities are particularly important. The antioxidant potential of tuberose is largely associated with its phenolic and flavonoid content, which are capable of neutralizing reactive oxygen species (ROS) and preventing oxidative damage to cellular components. Oxidative stress is a major contributing factor in the pathogenesis of chronic diseases such as cancer, diabetes and cardiovascular disorders. Studies have demonstrated that floral extracts rich in phenolics exhibit strong antioxidant activity through mechanisms such as hydrogen atom donation, electron transfer and metal chelation. In tuberose, compounds such as flavonoids and phenolic acids contribute significantly to this activity, thereby enhancing its potential as a natural antioxidant source (Pires *et al*., 2020; El-Nashar *et al*., 2023).

Closely linked to antioxidant activity are the free radical scavenging properties of tuberose extracts. Free radicals, including superoxide anions, hydroxyl radicals and peroxyl radicals, can cause cellular damage by interacting with lipids, proteins and nucleic acids. Bioactive compounds present in tuberose have been shown to effectively scavenge these radicals, thereby reducing oxidative stress and preventing cellular injury. The ability of these compounds to stabilize free radicals is attributed to their chemical structure, particularly the presence of hydroxyl groups and conjugated systems, which enable them to donate electrons and neutralize reactive species (Zengin *et al*., 2022). The anti-inflammatory properties of tuberose further enhance its nutraceutical potential. Chronic inflammation is a key factor in the development of various diseases, including arthritis, cardiovascular disorders and neurodegenerative conditions. Bioactive compounds such as eugenol, flavonoids and terpenoids have been reported to inhibit inflammatory mediators, including cytokines, prostaglandins and nitric oxide. These compounds modulate signaling pathways such as NF-κB and MAPK, thereby reducing inflammation and associated tissue damage. The presence of these compounds in tuberose suggests its potential application as a natural anti-inflammatory agent in nutraceutical formulations (Barboza *et al*., 2021; Zengin *et al*., 2022).

### 4.3 Role in functional foods and dietary supplements

The increasing demand for natural and health-promoting ingredients has led to the exploration of tuberose as a potential component of functional foods and dietary supplements. Although, direct consumption of tuberose is limited, its extracts and essential oils can be incorporated into various formulations to enhance their nutritional and therapeutic value. Floral extracts rich in antioxidants and bioactive compounds can be used as natural additives in beverages, confectionery products and herbal formulations, contributing to both flavor and health benefits. In the nutraceutical industry, tuberose-derived compounds can be utilized in the development of dietary supplements aimed at improving health and preventing disease. For instance, encapsulated essential oils and standardized extracts can be formulated as capsules, tablets, or liquid supplements. The use of advanced delivery systems such as nanoencapsulation and liposomal formulations can further enhance the bioavailability and stability of these compounds, thereby improving their efficacy. Recent studies have highlighted the potential of plant-based bioactives in functional food systems, emphasizing their role in promoting gut health, enhancing immunity and reducing the risk of chronic diseases (González-Tejero *et al*., 2021; Barba *et al*., 2022).

### 4.4 Safety and toxicological aspects

The safety and toxicological evaluation of plant-based nutraceuticals is essential to ensure their suitability for human consumption. Tuberose is generally considered safe when used in traditional applications such as perfumery and aromatherapy; however, its use in nutraceutical formulations requires careful assessment of potential toxicity and side effects. Essential oils, including those derived from tuberose, are highly concentrated and may cause skin irritation, allergic reactions, or toxicity if used in excessive amounts. Therefore, proper dilution and formulation are necessary to ensure safe usage. Toxicological studies on floral extracts have indicated that most plant-derived bioactive compounds are safe at low to moderate concentrations, but their effects may vary depending on dosage, route of administration and individual sensitivity. Compounds such as eugenol, while beneficial at therapeutic levels, may exhibit cytotoxic effects at higher concentrations. Therefore, it is important to establish safe dosage limits and conduct comprehensive toxicity studies, including acute, sub-chronic and chronic evaluations (Barboza *et al*., 2021).

## 5. Pharmacological activities

### 5.1 Antioxidant activity

The antioxidant activity of *A. amica* is one of its most extensively studied pharmacological properties, primarily attributed to its rich content of phenolic compounds, flavonoids and volatile constituents such as eugenol and benzyl derivatives. These bioactive compounds play a crucial role in neutralizing reactive oxygen species (ROS) and preventing oxidative stress-induced cellular damage. Mechanistically, antioxidants derived from tuberose act through hydrogen atom transfer (HAT), single electron transfer (SET) and metal ion chelation pathways, thereby inhibiting lipid peroxidation and stabilizing free radicals B (Table 2). Experimental studies using in vitro assays such as DPPH, ABTS and FRAP have demonstrated significant radical scavenging activity of tuberose extracts, indicating their potential as natural antioxidants. Furthermore, these compounds enhance endogenous antioxidant defense systems by upregulating enzymes such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx). Recent research highlights those floral extracts with high phenolic content exhibit strong antioxidant capacity, which correlates with their ability to mitigate oxidative stress-related disorders (Santos-Sánchez *et al*., 2020; Ahmed *et al*., 2022).

### 5.2 Antimicrobial activity

The antimicrobial potential of tuberose is largely associated with its essential oil constituents, which exhibit broad-spectrum activity against bacterial and fungal pathogens. Compounds such as eugenol, farnesol and benzyl alcohol disrupt microbial cell membranes, increase permeability and interfere with intracellular metabolic processes, leading to cell death. These compounds also inhibit biofilm formation and quorum sensing, which are critical for microbial virulence and resistance. Experimental studies have reported that tuberose extracts exhibit significant antibacterial activity against Gram-positive bacteria such as *Staphylococcus aureus* and Gram-negative bacteria such as *Escherichia coli*. Similarly, antifungal activity has been observed against species such as *Candida albicans* and *Aspergillus niger*. The antimicrobial efficacy of tuberose essential oil is comparable to certain synthetic antimicrobial agents, highlighting its potential as a natural alternative for controlling microbial infections. Recent studies emphasize the role of plant-derived essential oils in combating antimicrobial resistance, making tuberose a promising candidate for pharmaceutical and food preservation applications (Burt, 2020; Nazzaro *et al*., 2021).

**Table 2: Pharmacological activities of *A. amica* with mechanisms**

| Pharmacological activity | Bioactive compounds | Mechanism of action | Biological effect |
|---|---|---|---|
| Antioxidant | Phenolics, flavonoids, eugenol | ROS scavenging, activation of antioxidant enzymes (SOD, CAT, GPx) | Reduces oxidative stress and cellular damage |
| Antimicrobial | Eugenol, farnesol, benzyl alcohol | Disruption of microbial cell membrane, inhibition of enzymes and biofilm formation | Antibacterial and antifungal effects |
| Anti-inflammatory | Flavonoids, phenolic acids, terpenoids | Inhibition of NF-κB, COX, LOX pathways | Reduces inflammation and cytokine production |
| Anticancer | Flavonoids, terpenoids | Induction of apoptosis, cell cycle arrest, inhibition of angiogenesis | Suppresses tumor growth |
| Neuroprotective | Eugenol, phenolics | Reduction of oxidative stress, modulation of neurotransmitters (GABA) | Protects neurons, improves cognition |
| Analgesic | Eugenol, flavonoids | Inhibition of prostaglandin synthesis (COX pathway) | Reduces pain |
| Antipyretic | Phenolics, terpenoids | Regulation of hypothalamic temperature control | Reduces fever |
| Anti-diabetic | Flavonoids, phenolics | Inhibition of α-amylase and α-glucosidase | Controls blood glucose levels |
| Hepatoprotective | Phenolics, antioxidants | Reduction of lipid peroxidation, detox enzyme activation | Protects liver cells |
| Cardioprotective | Flavonoids, phenolic acids | Anti-inflammatory, lipid-lowering, endothelial protection | Improves heart health |

### 5.3 Anti-inflammatory activity

The anti-inflammatory activity of *A. amica* is attributed to its ability to modulate key inflammatory mediators and signaling pathways. Bioactive compounds such as flavonoids, phenolic acids and terpenoids inhibit the production of pro-inflammatory cytokines, including tumor necrosis factor-alpha (TNF-$\alpha$), interleukin-6 (IL-6) and interleukin-1$\beta$ (IL-1$\beta$). These compounds also suppress the activity of cyclooxygenase (COX) and lipoxygenase (LOX) enzymes, thereby reducing the synthesis of prostaglandins and leukotrienes. At the molecular level, tuberose-derived compounds regulate signaling pathways such as nuclear factor-kappa B(NF-$\kappa$B) and mitogen-activated protein kinases (MAPKs), which play central roles in inflammation. Experimental studies have demonstrated that plant-derived phenolics exhibit significant anti-inflammatory effects both *in vitro* and *in vivo*, suggesting their potential for managing inflammatory disorders. The presence of these compounds in tuberose supports its use as a natural anti-inflammatory agent in nutraceutical and pharmaceutical formulations (Chen *et al*., 2021; Zhao *et al*., 2023).

### 5.4 Anticancer potential

The anticancer potential of tuberose is an emerging area of research, with studies indicating that its bioactive compounds exhibit cytotoxic effects against various cancer cell lines. Phenolic compounds, flavonoids and terpenoids present in tuberose have been shown to induce apoptosis, inhibit cell proliferation and suppress tumor growth. Mechanistically, these compounds activate intrinsic and extrinsic apoptotic pathways by regulating key proteins such as caspases, Bcl-2 family proteins and p53. They also interfere with cell cycle progression, leading to cell cycle arrest at specific phases. Additionally, tuberose-derived compounds exhibit antiangiogenic properties by inhibiting the formation of new blood vessels required for tumor growth. The antioxidant properties of these compounds further contribute to their anticancer activity by reducing oxidative stress and DNA damage. Recent studies on plant-derived phytochemicals have demonstrated their potential as chemopreventive and therapeutic agents, highlighting the importance of tuberose as a source of anticancer compounds (Greenwell and Rahman, 2020; Karthikeyan *et al*., 2022).

### 5.5 Neuroprotective and CNS effects

The neuroprotective potential of Polianthes tuberosa is primarily associated with its essential oil components and antioxidant compounds, which contribute to the protection of neuronal cells against oxidative stress and neuroinflammation. Compounds such as eugenol and other phenolic derivatives have been shown to modulate neurotransmitter systems, reduce oxidative damage and improve cognitive function. These compounds inhibit the accumulation of reactive oxygen species in neuronal tissues and enhance the activity of antioxidant enzymes, thereby protecting against neurodegenerative diseases such as Alzheimer's and Parkinson's. Additionally, tuberose essential oil has been reported to exhibit anxiolytic and sedative effects through its action on the central nervous system, possibly by modulating gamma-aminobutyric acid (GABA) receptors. Aromatherapy applications of tuberose oil have been associated with stress reduction, mood enhancement and improved sleep quality. Recent research highlights the potential of plant-derived essential oils in neuroprotection and mental health management, supporting the therapeutic relevance of tuberose (Ayaz *et al*., 2022; Dos Santos *et al*., 2023).

### 5.6 Analgesic and antipyretic properties

The analgesic and antipyretic properties of tuberose are linked to its ability to modulate pain perception and reduce fever through the inhibition of inflammatory mediators. Bioactive compounds such as flavonoids and terpenoids interfere with the synthesis of prostaglandins, which are responsible for pain and fever. These compounds inhibit the cyclooxygenase pathway, thereby reducing the production of prostaglandin E2 (PGE2), a key mediator of pain and inflammation. Experimental studies on plant-derived extracts have demonstrated significant analgesic effects in animal models, suggesting their potential as natural alternatives to conventional painkillers. Similarly, antipyretic activity is achieved through the regulation of hypothalamic temperature control mechanisms. The presence of these bioactive compounds in tuberose supports its potential application in the management of pain and fever, particularly in traditional and herbal medicine systems (Salehi *et al*., 2021).

### 5.7 Other biological activities

Beyond the primary pharmacological activities, *A. amica* exhibits several additional biological effects that contribute to its therapeutic potential. The antidiabetic activity of tuberose is attributed to its ability to regulate glucose metabolism and improve insulin sensitivity. Phenolic compounds and flavonoids inhibit carbohydrate-digesting enzymes such as $\alpha$-amylase and $\alpha$-glucosidase, thereby reducing postprandial blood glucose levels. These compounds also enhance glucose uptake in peripheral tissues and protect pancreatic â-cells from oxidative damage (Khan *et al*., 2021). The hepatoprotective activity of tuberose is associated with its antioxidant properties, which protect liver cells from oxidative stress and toxin-induced damage. Bioactive compounds in tuberose enhance the activity of detoxifying enzymes and reduce lipid peroxidation in hepatic tissues. Studies have shown that plant-derived antioxidants can significantly improve liver function and prevent hepatocellular injury (Ezzat *et al*., 2022). Similarly, the cardioprotective effects of tuberose are linked to its ability to reduce oxidative stress, inflammation and lipid peroxidation in cardiovascular tissues. Phenolic compounds and flavonoids improve endothelial function, regulate blood pressure and reduce the risk of atherosclerosis. These compounds also exhibit lipid-lowering effects by modulating cholesterol metabolism and preventing the formation of plaque in blood vessels (Alam *et al*., 2023).

## 6. Mechanisms of action of bioactive compounds

### 6.1 Interaction with cellular signaling pathways

The pharmacological efficacy of bioactive compounds present in *A. amica* is largely mediated through their interaction with complex cellular signaling pathways that regulate inflammation, apoptosis, proliferation and immune responses. Phytochemicals such as flavonoids, phenolic acids and terpenoids are known to modulate key signaling cascades, including the nuclear factor-kappa B(NF-$\kappa$B), mitogen-activated protein kinase (MAPK), phosphoinositide 3-kinase/protein kinase B (PI3K/Akt) and Janus kinase/signal transducer and activator of transcription (JAK/STAT) pathways. These pathways play central roles in cellular homeostasis and disease progression, particularly in inflammatory and cancer-related conditions. For instance, phenolic compounds inhibit the activation of NF-$\kappa$B by preventing the degradation of its inhibitory protein I$\kappa$B, thereby reducing the transcription of pro-inflammatory genes such as TNF-α, IL-6 and COX-2. Similarly, flavonoids modulate MAPK signaling by inhibiting phosphorylation of ERK, JNK and p38 kinases, leading to reduced cellular stress responses and inflammation. Terpenoids, including farnesol, have been shown to interfere with the PI3K/Akt pathway, thereby inhibiting cell proliferation and inducing apoptosis in cancer cells. These multi-target interactions highlight the ability of tuberose-derived compounds to regulate multiple signaling pathways simultaneously, enhancing their therapeutic potential (Gupta *et al*., 2021; Kim *et al*., 2022).

### 6.2 Role in oxidative stress modulation

Oxidative stress is a key factor in the pathogenesis of numerous chronic diseases and the ability of bioactive compounds to modulate redox balance is a critical aspect of their mechanism of action. The phytochemicals present in tuberose, particularly phenolics and flavonoids, act as potent antioxidants by directly scavenging reactive oxygen species (ROS) and enhancing endogenous antioxidant defense systems. These compounds donate electrons or hydrogen atoms to neutralize free radicals, thereby preventing oxidative damage to cellular macromolecules such as lipids, proteins and DNA. In addition to direct antioxidant activity, tuberose-derived compounds activate the nuclear factor erythroid 2-related factor 2 (Nrf2) pathway, which regulates the expression of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx). Activation of the Nrf2 pathway leads to increased cellular resilience against oxidative stress and improved detoxification of reactive intermediates. Furthermore, these compounds inhibit lipid peroxidation and reduce the formation of malondialdehyde (MDA), a marker of oxidative damage. Recent studies have emphasized the role of plant-derived antioxidants in maintaining redox homeostasis and preventing oxidative stress-related diseases, underscoring the importance of tuberose as a source of bioactive antioxidants (Lobo *et al*., 2021; Sies *et al*., 2022).

### 6.3 Enzyme inhibition and receptor binding

Another important mechanism underlying the pharmacological activities of tuberose bioactive compounds is their ability to inhibit key enzymes and interact with specific cellular receptors. Phenolic compounds and flavonoids are known to inhibit enzymes involved in inflammation, carbohydrate metabolism and oxidative stress, such as cyclooxygenase (COX), lipoxygenase (LOX), α-amylase, α-glucosidase and acetylcholinesterase (AChE). Inhibition of COX and LOX enzymes leads to reduced synthesis of inflammatory mediators, thereby exerting anti-inflammatory effects. Similarly, inhibition of α-amylase and α-glucosidase enzymes helps regulate blood glucose levels, contributing to antidiabetic activity. Flavonoids also exhibit inhibitory effects on acetylcholinesterase, which is associated with improved cognitive function and potential therapeutic applications in neurodegenerative diseases. In addition to enzyme inhibition, bioactive compounds in tuberose interact with various cellular receptors, including G protein-coupled receptors (GPCRs), nuclear receptors and ion channels. These interactions influence signal transduction processes and modulate physiological responses. For example, eugenol has been shown to interact with transient receptor potential (TRP) channels, contributing to its analgesic and anti-inflammatory effects. Similarly, certain terpenoids bind to nuclear receptors such as peroxisome proliferator-activated receptors (PPARs), which regulate lipid metabolism and inflammation. These receptor-mediated mechanisms further enhance the pharmacological potential of tuberose-derived compounds (Orhan *et al*., 2020; Chen *et al*., 2022).

### 6.4 Molecular docking and omics-based insights

Advances in computational biology and high-throughput technologies have significantly enhanced the understanding of the molecular mechanisms of plant-derived bioactive compounds. Molecular docking studies provide valuable insights into the interaction between phytochemicals and target proteins at the atomic level. These studies predict binding affinity, interaction energy and the stability of ligand–protein complexes, thereby facilitating the identification of potential drug candidates. In the context of tuberose, compounds such as eugenol, farnesol and flavonoid derivatives have been evaluated through in silico docking studies, demonstrating strong binding affinities toward key targets involved in inflammation, cancer and metabolic disorders. These findings support the potential of tuberose phytochemicals as lead compounds for drug development (Banerjee *et al*., 2021). In addition to molecular docking, omics-based approaches, including genomics, transcriptomics, proteomics and metabolomics, have provided comprehensive insights into the biological effects of phytochemicals. Metabolomic profiling enables the identification of bioactive compounds and their metabolic pathways, while transcriptomic and proteomic analyses reveal changes in gene and protein expression in response to phytochemical treatment. These approaches have demonstrated that plant-derived compounds can modulate multiple biological pathways simultaneously, leading to synergistic therapeutic effects. Systems biology approaches further integrate these datasets to provide a holistic understanding of the mechanisms of action. Recent studies highlight the importance of omics technologies in elucidating the complex interactions between phytochemicals and biological systems, thereby accelerating the development of plant-based therapeutics (Misra *et al*., 2021; Rai *et al*., 2023).

## 7. Industrial and pharmaceutical applications

### 7.1 Essential oil industry

*A. amica* is one of the most valued floral crops in the essential oil industry, primarily due to its intensely fragrant flowers that yield a highly prized absolute used in high-end perfumery. Tuberose essential oil is characterized by a complex aromatic profile composed of esters, alcohols and terpenoids such as methyl benzoate, benzyl alcohol, eugenol and farnesol, which collectively impart a rich, sweet and long-lasting fragrance. The extraction of tuberose absolute is typically achieved through solvent extraction or enfleurage, as conventional steam distillation often leads to the degradation of delicate aromatic compounds. Due to its low yield and high demand, tuberose absolute is considered one of the most expensive natural fragrances in the global perfume market. In perfumery, tuberose is widely used as a base or heart note in luxury fragrances, contributing to floral bouquets and enhancing scent longevity. Its fixative properties allow it to stabilize volatile components and improve the overall olfactory profile of perfumes. In addition to perfumery, tuberose extracts are extensively used in cosmetic formulations, including creams, lotions, soaps and personal care products. The presence of antioxidant and antimicrobial compounds in tuberose essential oil enhances its suitability for skincare applications, where it helps protect the skin from oxidative damage, microbial infections and premature aging. Recent studies highlight the increasing demand for natural and sustainable ingredients in the cosmetic industry, with floral extracts such as tuberose gaining prominence due to their multifunctional properties and consumer preference for plant-based products (Méndez-Tovar *et al*., 2021; Kapoor *et al*., 2023).

### 7.2 Pharmaceutical formulations

The pharmaceutical potential of tuberose is increasingly being recognized due to its diverse bioactive compounds and wide range of pharmacological activities. Tuberose extracts and essential oils have shown promising results in preclinical studies, demonstrating antioxidant, antimicrobial, anti-inflammatory and anticancer properties. These findings have stimulated interest in the development of pharmaceutical formulations based on tuberose-derived compounds. In drug development, phytochemicals from tuberose can serve as lead compounds or templates for the synthesis of novel therapeutic agents. For instance, compounds such as eugenol and farnesol have been extensively studied for their pharmacological properties and are being explored for their potential in treating infections, inflammation and cancer. The incorporation of these compounds into drug delivery systems, including nanoparticles, liposomes and emulsions, can enhance their bioavailability, stability and therapeutic efficacy. Additionally, tuberose extracts are being investigated for their use in herbal medicine, where they are formulated as tinctures, extracts, or topical preparations for the treatment of various ailments. The integration of tuberose into modern pharmaceutical systems aligns with the growing trend toward plant-based therapeutics and personalized medicine. However, further research is required to standardize extraction methods, determine optimal dosages and conduct clinical trials to validate their efficacy and safety. Recent advancements in phytopharmaceutical research emphasize the importance of combining traditional knowledge with modern scientific approaches to develop effective and safe herbal medicines (Atanasov *et al*., 2021; Efferth and Koch, 2022).

### 7.3 Nutraceutical industry

The nutraceutical industry represents a rapidly growing sector that focuses on the development of health-promoting products derived from natural sources. Although tuberose is not a conventional food crop, its rich phytochemical composition makes it a potential candidate for inclusion in functional ingredients and dietary supplements. The presence of antioxidants, anti-inflammatory compounds and bioactive metabolites in tuberose extracts supports their application in nutraceutical formulations aimed at preventing chronic diseases and promoting overall health. Tuberose-derived compounds can be incorporated into nutraceutical products such as capsules, tablets, beverages and fortified foods. These products may target specific health benefits, including immune enhancement, stress reduction and metabolic regulation. The use of advanced technologies such as microencapsulation and nanoencapsulation can improve the stability and bioavailability of tuberose bioactives, thereby enhancing their effectiveness. Additionally, the integration of tuberose extracts into functional foods aligns with current consumer trends toward natural, plant-based and clean-label products. Recent research highlights the importance of plant-derived nutraceuticals in addressing lifestyle-related diseases and improving quality of life. The multifunctional properties of tuberose phytochemicals make them suitable for incorporation into innovative nutraceutical formulations, although further studies are needed to establish standardized protocols and regulatory frameworks for their commercialization (Santini *et al*., 2021; Shahidi and Ambigaipalan, 2022).

### 7.4 Aromatherapy and wellness applications

Tuberose essential oil has gained significant attention in aromatherapy and wellness applications, where it is used for its calming, relaxing and mood-enhancing properties. The inhalation or topical application of tuberose oil is believed to influence the limbic system, which regulates emotions, memory and stress responses. Compounds such as eugenol and benzyl derivatives interact with neurotransmitter systems, contributing to anxiolytic, sedative and antidepressant effects. Aromatherapy using tuberose oil is commonly employed to alleviate stress, anxiety, insomnia and emotional fatigue. It is also used in massage therapy and spa treatments, where it promotes relaxation and improves overall well-being. The antimicrobial and anti-inflammatory properties of tuberose oil further enhance its therapeutic value, making it suitable for use in wellness products such as massage oils, bath oils and diffusers. Recent studies have demonstrated the potential of essential oils in modulating physiological and psychological functions, highlighting their role in integrative and complementary medicine. The growing popularity of wellness and holistic health approaches has further increased the demand for aromatherapy products, positioning tuberose as a valuable component of the global wellness industry. However, standardization, quality control and safety evaluation remain critical for ensuring the effective and safe use of tuberose essential oil in therapeutic applications (Ali *et al*., 2021; Gnatta *et al*., 2022).

## 8. Advances in extraction, processing and delivery systems

### 8.1 Green extraction techniques

The growing demand for sustainable and environmentally friendly processes has led to the development of green extraction techniques for isolating bioactive compounds from plant sources, including *A. amica*. Traditional extraction methods such as steam distillation and solvent extraction, although effective, often involve high energy consumption, long extraction times and the use of toxic organic solvents, which may compromise the quality and safety of the final product. In contrast, green extraction technologies aim to minimize environmental impact while maximizing extraction efficiency and preserving the integrity of thermolabile compounds. Among these, supercritical fluid extraction (SFE) using carbon dioxide has emerged as a highly efficient and eco-friendly technique for extracting essential oils and phytochemicals from tuberose. This method operates under moderate temperatures and pressures, thereby preventing the degradation of sensitive compounds and eliminating solvent residues. Similarly, ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) have gained popularity due to their ability to enhance mass transfer, reduce extraction time and improve yield. UAE utilizes acoustic cavitation to disrupt plant cell walls, facilitating the release of intracellular compounds, while MAE employs microwave energy to heat the solvent and plant matrix, accelerating extraction kinetics.

Another promising approach is the use of natural deep eutectic solvents (NADES), which are biodegradable, non-toxic and highly tunable solvents composed of natural components such as sugars, amino acids and organic acids. NADES have shown remarkable efficiency in extracting phenolics, flavonoids and other bioactive compounds, making them suitable for nutraceutical and pharmaceutical applications. These green extraction methods not only improve the sustainability of phytochemical extraction but also enhance the quality and functionality of the extracted compounds. Recent studies highlight the importance of optimizing extraction parameters such as temperature, pressure, solvent composition and extraction time to achieve maximum yield and bioactivity (Dai *et al*., 2020; Cvjetko Bubalo *et al*., 2021; Kumar *et al*., 2024).

### 8.2 Nanoformulations and encapsulation

The application of nanotechnology in the formulation of plant-derived bioactive compounds has revolutionized their delivery and therapeutic efficacy. Nanoformulations and encapsulation techniques are particularly important for improving the bioavailability, stability and controlled delivery of phytochemicals from tuberose, which are often limited by poor solubility, volatility and susceptibility to degradation. Encapsulation involves the incorporation of bioactive compounds into carrier systems such as nanoparticles, liposomes, nanoemulsions and polymeric matrices, which protect them from environmental factors and enhance their absorption in biological systems. Nanoemulsions and liposomal formulations have been widely used for encapsulating essential oils, including those derived from tuberose, due to their ability to improve solubility and facilitate targeted delivery. These systems increase the surface area of bioactive compounds, enhancing their interaction with biological membranes and improving their bioavailability. Additionally, polymeric nanoparticles and solid lipid nanoparticles (SLNs) provide controlled and sustained release of encapsulated compounds, reducing the frequency of administration and minimizing potential side effects.

Encapsulation also improves the stability of phytochemicals by protecting them from oxidation, light and thermal degradation. This is particularly important for volatile compounds such as methyl benzoate and eugenol, which are prone to rapid degradation under ambient conditions. Furthermore, nanoencapsulation enhances the sensory properties of essential oils by masking strong odors and improving their compatibility with food and pharmaceutical formulations. Recent advances in nanotechnology have enabled the development of multifunctional delivery systems that combine therapeutic efficacy with targeted delivery, thereby expanding the applications of tuberose bioactives in nutraceutical and pharmaceutical industries (McClements, 2020; Sharifi-Rad *et al*., 2021; Rehman *et al*., 2023).

### 8.3 Controlled release systems

Controlled release systems represent a significant advancement in the delivery of bioactive compounds, allowing for the gradual and sustained release of phytochemicals over time. These systems are designed to maintain therapeutic concentrations of active compounds within a specific range, thereby enhancing efficacy and reducing side effects. In the context of tuberose, controlled release systems are particularly valuable for delivering volatile and sensitive compounds that require protection and prolonged activity. Various delivery systems, including hydrogels, microcapsules, nanofibers and biodegradable polymers, have been developed to achieve controlled release of plant-derived bioactives. These systems can be tailored to respond to specific stimuli such as pH, temperature, or enzymatic activity, enabling targeted delivery and site-specific release. For example, pH-sensitive polymers can release encapsulated compounds in response to changes in the gastrointestinal environment, making them suitable for oral delivery in nutraceutical applications.

Controlled release systems also play a crucial role in enhancing the therapeutic efficiency of bioactive compounds by maintaining consistent plasma levels and reducing fluctuations associated with conventional delivery methods. In pharmaceutical applications, these systems improve patient compliance by reducing dosing frequency and minimizing adverse effects. In the food industry, controlled release technologies are used to incorporate bioactive compounds into functional foods, where they provide sustained health benefits and improved shelf life. Recent research highlights the integration of nanotechnology with controlled release systems to develop advanced delivery platforms that combine precision, efficiency and sustainability. These innovations are expected to play a key role in the future development of tuberose-based products, enabling the effective utilization of its bioactive compounds in various industrial and therapeutic applications (Fathi *et al*., 2021; Silva *et al*., 2022).

## 9. Future perspectives

The growing scientific interest in *A. amica* highlights its potential as a multifaceted bioresource for nutraceutical, pharmaceutical and industrial applications. However, despite the promising findings reported in recent years, the full potential of tuberose remains largely untapped, necessitating a more integrated and multidisciplinary research approach. Future research should focus on bridging the gap between traditional knowledge and modern scientific validation, enabling the translation of laboratory findings into practical applications. One of the key areas requiring attention is the comprehensive phytochemical profiling of tuberose using advanced analytical and metabolomic tools. While several bioactive compounds have been identified, there is still limited understanding of the complete metabolite spectrum and their synergistic interactions. High-throughput techniques such as metabolomics, proteomics and transcriptomics can provide deeper insights into the biosynthetic pathways and regulatory mechanisms governing the production of these compounds. Such studies will not only enhance our understanding of tuberose phytochemistry but also facilitate the identification of novel bioactive molecules with potential therapeutic applications. Another important research direction is the standardization and quality control of tuberose-derived products. Variability in phytochemical composition due to differences in genotype, environmental conditions and extraction methods poses a significant challenge for their commercialization. Developing standardized protocols for cultivation, harvesting, extraction and processing is essential to ensure consistency, safety and efficacy. The establishment of quality benchmarks and regulatory guidelines will further support the integration of tuberose into mainstream nutraceutical and pharmaceutical industries.

The pharmacological validation and clinical evaluation of tuberose bioactive compounds represent a critical step toward their therapeutic application. Although *in vitro* and *in vivo* studies have demonstrated various biological activities, there is a lack of well-designed clinical trials to confirm their efficacy and safety in humans. Future research should focus on conducting preclinical and clinical studies to evaluate pharmacokinetics, bioavailability, toxicity and therapeutic outcomes. Such studies will provide scientific evidence for the development of tuberose-based drugs and nutraceuticals, thereby enhancing their acceptance in modern medicine. Advancements in nanotechnology and drug delivery systems offer new opportunities for improving the bioavailability and therapeutic efficiency of tuberose-derived compounds. The development of nanoformulations, encapsulation techniques and targeted delivery systems can overcome the limitations associated with poor solubility and stability of phytochemicals. Future research should explore the design of innovative delivery platforms that enable controlled and site-specific release of bioactive compounds, thereby maximizing their therapeutic potential while minimizing side effects. The role of tuberose in functional foods and nutraceutical formulations is another promising area that warrants further exploration. With the increasing demand for natural and health-promoting products, tuberose extracts can be incorporated into functional beverages, dietary supplements and fortified foods. Research should focus on evaluating the stability, sensory properties and bioactivity of these formulations, as well as their impact on human health. Additionally, the concept of personalized nutrition can be integrated with tuberose-based nutraceuticals to develop tailored dietary interventions for specific health conditions.

From an agricultural perspective, there is a need to develop climate-resilient and high-yielding cultivars of tuberose through conventional breeding and modern biotechnological approaches. Genetic improvement programs should focus on enhancing traits such as essential oil content, disease resistance and stress tolerance. The application of molecular breeding, genome editing and tissue culture techniques can accelerate the development of improved varieties and ensure sustainable production under changing climatic conditions. The concept of sustainable production and value addition is also crucial for maximizing the economic potential of tuberose. The utilization of floral waste and by-products for the extraction of bioactive compounds can contribute to waste valorization and environmental sustainability. Integrated approaches combining green extraction technologies, circular bioeconomy principles and eco-friendly processing methods should be promoted to reduce environmental impact and enhance resource efficiency.

## 10. Conclusion

*A. amica* emerges as a highly promising floral bioresource with significant nutraceutical, pharmacological and industrial potential. Beyond its traditional role as an ornamental and aromatic plant, tuberose possesses a diverse array of bioactive phytoconstituents, including volatile compounds, phenolics, flavonoids and terpenoids, which collectively contribute to its wide spectrum of biological activities. Scientific evidence highlights its antioxidant, antimicrobial, anti-inflammatory, anticancer and neuroprotective properties, underscoring its relevance in modern healthcare and functional product development. The integration of advanced extraction techniques, nanotechnology-based delivery systems and controlled release formulations has further enhanced the applicability and efficacy of tuberose-derived compounds. These technological advancements not only improve bioavailability and stability but also expand its utilization in pharmaceutical formulations, nutraceutical products and wellness applications. Moreover, its growing demand in the essential oil, cosmetic and aromatherapy industries reflects its strong commercial value. However, despite these promising attributes, the full potential of tuberose remains underexplored. Challenges such as variability in phytochemical composition, lack of standardization and limited clinical validation need to be addressed through systematic and interdisciplinary research. Future efforts should focus on developing standardized protocols, conducting clinical trials and leveraging modern biotechnological tools to enhance its productivity and therapeutic efficiency.

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## Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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