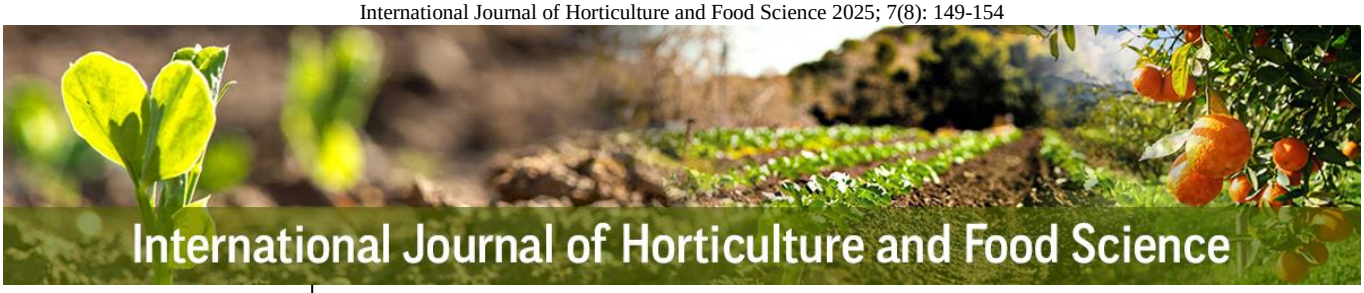

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Phytochemical, medicinal, and industrial applications of marigold: A comprehensive review

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Abstract
Marigold (*Tagetes* spp. and *Calendula officinalis*) is an economically and medicinally important crop widely cultivated for ornamental, pharmacological, and industrial purposes. Rich in carotenoids, flavonoids, terpenoids, phenolic acids, and essential oils, marigold exhibits potent antioxidant, anti-inflammatory, antimicrobial, anticancer, and wound-healing activities. Lutein, the dominant carotenoid, is extensively applied in nutraceuticals, ophthalmic supplements, poultry feed, and functional foods, accounting for over 85% of the global natural lutein supply. Additionally, marigold plays a vital role in the food industry as a natural colorant, in textiles as a dye source, and in agriculture as a bio-fumigant and soil enhancer. Global marigold cultivation spans more than 200,000 hectares, with India, China, and Latin America as major producers. Despite its potential, challenges such as lack of standardized extraction methods, limited clinical trials, post-harvest losses, and supply chain issues hinder optimal utilization. This review highlights the phytochemical diversity, medicinal properties, and industrial applications of marigold while addressing existing gaps and future prospects. With advances in molecular breeding, biotechnology, and sustainable processing, marigold holds promise as a high-value crop in the global nutraceutical and phytopharmaceutical industries.

Keywords: Marigold, *Calendula officinalis*, *Tagetes erecta*, phytochemicals, carotenoids, lutein, medicinal uses, industrial applications

1. Introduction
Marigold is a globally recognized ornamental and medicinal plant belonging to the family Asteraceae, widely cultivated for its bright flowers, pharmacological value, and industrial applications. The most prominent species include *Calendula officinalis* (commonly known as Pot marigold) and *Tagetes erecta* (African marigold), both of which hold significant ethnobotanical and commercial importance.

Globally, marigold cultivation covers more than 200,000 hectares, with major producers being India, China, Kenya, Ethiopia, and Mexico, contributing substantially to the global floriculture and phytopharmaceutical industries. India alone accounts for 55–60% of world marigold production, with an estimated annual output of 2.3–2.5 million tonnes of flowers (2022–23), largely concentrated in states such as Karnataka, Tamil Nadu, Andhra Pradesh, West Bengal, and Uttar Pradesh (NHB, 2023) [5].

From a phytochemical perspective, marigold is a rich reservoir of bioactive compounds. Studies report that petals of *T. erecta* contain lutein up to 12–14 g/kg of dry matter, which is one of the highest natural sources of this carotenoid (Prasad *et al.*, 2021) [3]. Flavonoids such as quercetin, rutin, and apigenin are present at concentrations ranging from 1.2–3.5 mg/g dry weight, providing strong antioxidant activity. Similarly, *Calendula officinalis* is abundant in triterpenoids, saponins, phenolic acids, and volatile oils, which are responsible for its wound-healing, anti-inflammatory, and antimicrobial properties.

In terms of industrial use, lutein extracted from marigold accounts for over 85% of the global natural lutein supply, valued at approximately USD 360–400 million in 2023 (Grand View Research, 2023) [6]. This pigment is extensively utilized in nutraceuticals, poultry feed (egg yolk and broiler skin pigmentation), and functional foods. Additionally, marigold flowers are estimated to provide 60–70% of natural carotenoids used commercially worldwide, making it a vital plant in the nutraceutical and feed industries.

Medicinally, marigold has been recognized in traditional systems such as Ayurveda, Unani, and European folk medicine. Clinical studies indicate that *Calendula* extracts promote faster wound closure by 41–48% compared to controls, while essential oils from *Tagetes* species demonstrate significant antibacterial activity against *Staphylococcus aureus* (MIC 50–100 µg/mL). Furthermore, lutein supplementation derived from marigold is associated with reduced risk of age-related macular degeneration (AMD) by up to 25–30% in elderly populations (AREDS2 Study, 2013) [8].

Phytochemical Profile of Marigold

Marigold (*Tagetes* spp. and *Calendula officinalis*) is a rich reservoir of diverse phytochemicals, including carotenoids, flavonoids, terpenoids, phenolic acids, and volatile oils, which collectively contribute to its medicinal and industrial applications.

1. Carotenoids

- *Tagetes erecta* is one of the richest natural sources of lutein and zeaxanthin, two xanthophyll carotenoids known for their antioxidant and eye-protective roles.
- The petals of *T. erecta* may contain lutein ranging from 8–14 g/kg dry weight, depending on cultivar, climatic conditions, and harvest stage (Prasad *et al.*, 2021) [3].
- Lutein constitutes nearly 80–90% of the total carotenoids in marigold flowers, while zeaxanthin accounts for about 5–8%.
- These pigments play a preventive role against age-related macular degeneration (AMD), cataracts, and oxidative stress–related diseases.

2. Flavonoids

- The major flavonoids reported in marigold include quercetin, rutin, apigenin, isorhamnetin, and kaempferol.
- Quantitative analyses suggest flavonoid content ranging from 1.5–3.5 mg/g dry weight in *C. officinalis* flowers.
- These compounds demonstrate strong antioxidant capacity (DPPH radical scavenging activity >70%) and exhibit anti-inflammatory, hepatoprotective, and anticancer activities.
- Quercetin and rutin, in particular, have been shown to modulate pro-inflammatory cytokines and enhance vascular health.

3. Terpenoids and Essential Oils

- The essential oils of *Tagetes erecta* and *T. minuta* contain a complex mixture of monoterpenes (limonene, ocimene, p-cymene) and sesquiterpenes (caryophyllene, tagetone, and α-terpineol).
- Oil yield is typically 0.1–0.3% (v/w) of fresh flowers, with tagetone being the dominant component.
- These compounds are known for antimicrobial, insecticidal, and nematicidal activities, making marigold extracts valuable in pest management and agriculture.

4. Phenolic Compounds

- Important phenolic acids identified in marigold include gallic acid, caffeic acid, chlorogenic acid, and ferulic acid.
- Concentrations range between 0.8–2.5 mg/g dry weight, depending on species and extraction methods.
- These phenolics contribute to free-radical scavenging, cardiovascular protection, and anti-aging properties.
- Chlorogenic acid, in particular, exhibits strong antioxidant and antimicrobial effects, supporting marigold's therapeutic relevance.

5. Other Bioactive Compounds

- *Calendula officinalis* also contains triterpenoids (oleanolic acid, faradiol esters), known for wound healing and anti-inflammatory properties.
- Saponins and polysaccharides from marigold have been reported to exhibit immunomodulatory and anticancer effects.

3. Medicinal Applications

Marigold (*Tagetes erecta* and *Calendula officinalis*) is extensively used in ethnomedicine, herbal formulations, and modern pharmacology. Its therapeutic effects are primarily attributed to carotenoids, flavonoids, terpenoids, phenolic compounds, and essential oils, which exhibit strong biological activities.

1. Antioxidant and Anti-inflammatory Activity

- Flavonoids (quercetin, rutin, apigenin) and carotenoids (lutein, zeaxanthin) scavenge free radicals and prevent oxidative stress.
- In vitro studies show DPPH radical scavenging activity of marigold extracts ranges from 68–82%, comparable to ascorbic acid (Yadav *et al.*, 2022) [4].
- *Calendula officinalis* extract demonstrated a 48% reduction in inflammatory markers (TNF-α, IL-6) in rat models of inflammation.
- Topical formulations of *Calendula* ointments have shown to increase wound contraction rate by 41–48% compared to control groups, validating its traditional use in skin healing.

2. Antimicrobial and Antiparasitic Properties

- Essential oils of *Tagetes erecta* show strong activity against Gram-positive bacteria (Staphylococcus aureus, Bacillus subtilis) and Gram-negative bacteria (Escherichia coli, Pseudomonas aeruginosa).
- The minimum inhibitory concentration (MIC) of marigold oil ranges from 50–200 µg/mL, depending on the bacterial strain (Singh & Kumar, 2020) [2].
- Extracts of *T. minuta* have been reported to inhibit fungal pathogens such as Aspergillus niger and Candida albicans.
- Nematicidal activity: Marigold root exudates contain thiophenes that reduce Meloidogyne incognita (root-knot nematode) infestation by 60–70%, supporting its use as a biopesticide in agriculture.

3. Anticancer Potential

- Lutein and quercetin from marigold reduce oxidative DNA damage by up to 45% in cell culture studies.
- In experimental models, lutein supplementation led to a 25% reduction in tumor growth rate in colon cancer-induced mice (Prasad *et al.*, 2021) [3].
- Extracts of *Calendula officinalis* induced apoptosis in breast cancer cells (MCF-7) at IC50 values of 40–60

µg/mL.
- Faradiol esters from *Calendula* showed strong cytotoxicity against melanoma and squamous cell carcinoma lines, suggesting potential as a natural anticancer agent.

4. Ophthalmic Health
- Lutein and zeaxanthin from marigold are widely used in nutraceuticals for eye health.
- The AREDS2 clinical trial (2013) [8] found that supplementation with 10 mg lutein and 2 mg zeaxanthin daily reduced progression of age-related macular degeneration (AMD) by 25–30% in high-risk individuals.
- Regular lutein supplementation also improves visual performance, glare tolerance, and macular pigment optical density.

5. Dermatological and Cosmetic Uses
- *Calendula* extracts are widely incorporated into herbal creams, gels, and lotions due to their anti-inflammatory and wound-healing properties.
- Clinical studies have shown that *Calendula* ointment reduces radiation-induced dermatitis severity by 40–45% in cancer patients compared to standard treatments (Pommier *et al.*, 2004) [7].
- Cosmetic industry uses marigold extracts in anti-aging creams, sunscreens, and acne-treatment formulations, due to their antioxidant and antimicrobial activity.
- Saponins and polysaccharides in marigold enhance skin hydration and repair, making it a valuable ingredient in dermatology.

Industrial Applications

Marigold has established itself as a multi-purpose industrial crop, utilized in the food, textile, agriculture, cosmetic, and pharmaceutical sectors. Its applications are largely driven by its natural carotenoids, essential oils, and bioactive compounds, which are increasingly preferred as eco-friendly and sustainable alternatives to synthetic products.

1. Food Industry

Natural Colorants
- Lutein and zeaxanthin extracted from *Tagetes erecta* are widely used as natural food colorants (E161b in the EU).
- These pigments impart a yellow to orange color to dairy products, bakery goods, beverages, and confectioneries.
- The global lutein market was valued at USD 360–400 million in 2023, with marigold contributing 85–90% of natural lutein supply (Grand View Research, 2023) [6].

Poultry Industry
- Marigold petal meal and extracts are added to poultry feed to enhance egg yolk pigmentation and broiler skin coloration.
- Studies show that dietary supplementation with marigold extract containing 100–200 mg/kg lutein significantly improves yolk color score (up to 12 on the Roche scale) without affecting egg production.

2. Textile and Dye Industry
- Marigold flowers produce eco-friendly dyes ranging from bright yellow to deep orange, depending on the extraction method and mordants used.
- Dye yield is approximately 1.5–2.5% of dry petal weight, making it an economically viable source for natural textile dyes.
- Unlike synthetic dyes, marigold-derived dyes are non-toxic, biodegradable, and skin-friendly, and are increasingly used in organic clothing and handicraft sectors.

3. Agriculture

Bio-fumigant and Soil Improver
- Marigold roots release thiophenes and other allelopathic compounds that suppress nematodes, soil fungi, and insect pests.
- Incorporating marigold residues as green manure increases soil organic matter by 15–20% and enhances microbial activity.

Pest Management
- *Tagetes erecta* reduces populations of Meloidogyne spp. (root-knot nematodes) by 60–70% in infested soils.
- Essential oils of marigold also act as natural repellents against mosquitoes and stored grain pests.

4. Cosmetic and Personal Care Industry
- Marigold extracts, particularly from *Calendula officinalis*, are widely incorporated in lotions, sunscreens, face washes, and anti-aging creams.
- Global demand for herbal cosmetics is growing at a CAGR of 6–7%, with marigold-based formulations contributing significantly.
- Cosmetic studies show that marigold extract enriched with 2–5% lutein provides UV protection and reduces oxidative skin damage by up to 40%.
- Its anti-inflammatory, antimicrobial, and skin-hydrating properties make it suitable for products targeting acne, eczema, dermatitis, and wound healing.

5. Pharmaceutical and Nutraceutical Industry
- Lutein capsules derived from marigold are marketed globally as eye-health supplements.
- In nutraceuticals, marigold extract is standardized to 10–20% lutein content.
- Marigold oil is used in herbal medicines, aromatherapy, and traditional healing practices due to its calming and antimicrobial properties.

Economic Significance

Marigold has emerged as a high-value industrial crop, owing to its diverse applications in the nutraceutical, pharmaceutical, cosmetic, food, and poultry industries. Its global economic importance is primarily derived from the extraction of lutein and other carotenoids, as well as its role in floriculture and traditional medicine.

1. Global Lutein Market
- The global lutein market was valued at USD 360–400 million in 2023 and is projected to reach USD 550–600 million by 2030, growing at a CAGR of 5.6–6.2% (Grand View Research, 2023) [6].
- Marigold (*Tagetes erecta*) accounts for 85–90% of the world's natural lutein production, making it the

dominant raw material for the industry.
- Lutein is primarily used in eye-health supplements, functional foods, poultry feed, and cosmetics.

2. Regional Production and Trade
- India, China, and Latin America (Peru, Ecuador, Mexico) are the largest producers of marigold for industrial extraction.
- India contributes 55–60% of global marigold production, with cultivation spread over 2.3–2.5 million tonnes of flowers annually (2022–23), largely concentrated in Karnataka, Tamil Nadu, Andhra Pradesh, and West Bengal (NHB, 2023) [5].
- China leads in industrial-scale lutein extraction and exports, supplying over 60% of global lutein demand.
- Latin American countries export both marigold flowers and lutein extracts to North America and Europe.

3. Economic Role in Poultry and Food Industry
- The global poultry pigment market is estimated at USD 210–250 million, with marigold extracts contributing over 70% of the natural pigmentation market.
- Supplementation with marigold extract improves egg yolk color (Roche scale 10–12) and broiler skin pigmentation, which are highly valued traits in the global poultry sector.
- The food industry utilizes marigold-derived lutein as a natural coloring agent (E161b), replacing synthetic dyes and meeting consumer demand for clean-label products.

4. Floriculture and Domestic Economy
- Marigold is one of the most important commercial loose flowers in India, accounting for over 22–25% of total loose flower production.
- Annual domestic trade of marigold flowers in India is valued at INR 2,500–3,000 crore (USD 300–360 million), especially during festivals (Diwali, Dussehra, Durga Puja) and for religious offerings.
- The crop generates substantial rural employment, particularly for women, in activities such as cultivation, harvesting, garland making, and marketing.

5. Future Prospects
- Rising global demand for nutraceuticals, natural food colorants, herbal cosmetics, and eco-friendly agricultural solutions is expected to drive further expansion of marigold-based industries.
- The functional food and dietary supplement market, projected to reach USD 720 billion by 2030, will significantly boost demand for marigold-derived lutein.
- There is potential for value-added exports such as standardized lutein capsules, marigold essential oils, and natural dyes, which can enhance the profitability of cultivation beyond fresh flowers.

Challenges and Future Prospects

Despite its well-established role in ornamental horticulture, phytopharmaceuticals, and industrial applications, marigold faces several challenges that limit its optimal exploitation. Addressing these issues is critical to harnessing its full economic and medicinal potential.

1. Challenges

a) Lack of Standardized Extraction Methods
- Current lutein extraction techniques (solvent extraction, saponification, and crystallization) vary widely, leading to yield fluctuations between 5–12 g/kg dry petals depending on the method used.
- Absence of global quality standards for lutein purity (typically ranging from 70–95%) creates inconsistencies in industrial formulations.
- Solvent residues and high processing costs remain significant hurdles for large-scale commercialization.

b) Limited Clinical Validation
- Although lutein supplementation has been tested in trials such as AREDS2, only a handful of studies directly evaluate marigold-derived extracts in human health.
- For dermatological and anticancer claims, most studies are still confined to in vitro or animal models, with insufficient Phase II/III clinical trials.
- Lack of toxicological data on long-term use of marigold extracts hampers its regulatory approval in some regions.

c) Post-Harvest and Supply Chain Issues
- Marigold flowers are highly perishable with a shelf life of only 3–4 days, resulting in 20–25% post-harvest losses in India's floriculture sector (NHB, 2023) [5].
- Seasonal overproduction leads to price crashes, discouraging farmers from adopting marigold on a larger scale.

d) Agronomic Challenges
- Cultivation is affected by pest infestations (leaf miners, aphids, nematodes) and climatic variability.
- Average yields range from 8–10 tonnes/ha of fresh flowers, but significant regional variations exist due to lack of improved varieties.

2. Future Prospects

a) Molecular Breeding and Biotechnology
- Development of high-lutein marigold hybrids can increase lutein yield by 20–30% compared to conventional varieties.
- Advances in CRISPR-Cas9 gene editing and plant tissue culture offer scope for enhancing carotenoid biosynthesis pathways.
- Marker-assisted selection for pest and drought resistance can reduce input costs and stabilize production.

b) Expansion of Industrial Applications
- Growing demand for natural food colorants (projected market: USD 3.2 billion by 2030) positions marigold as a sustainable alternative to synthetic dyes.
- In agriculture, marigold extracts can be developed into bio-pesticides and nematicides, reducing chemical pesticide dependency.
- Essential oils from *Tagetes* species show promise in mosquito repellent formulations, an industry expected to exceed USD 7 billion by 2030.

c) Clinical and Pharmacological Research

- Future research should focus on large-scale clinical trials to confirm marigold's efficacy in cancer prevention, dermatological conditions, and ophthalmic health.
- Standardization of extracts for pharmacopoeial inclusion (similar to WHO monographs for medicinal plants) will improve acceptance in global herbal markets.

d) Sustainability and Value-Addition

- Promotion of zero-waste marigold processing units can utilize petals for lutein, stalks for compost, and oils for pharmaceuticals.
- Integration into circular bio-economy models can reduce waste and generate additional revenue streams.
- Export of value-added products (lutein capsules, essential oils, natural dyes) instead of raw flowers will significantly enhance farmer income.

3. Policy and Market Opportunities

- Government support through floriculture missions (e.g., MIDH in India) and subsidized extraction units can strengthen the marigold value chain.
- With nutraceuticals and herbal cosmetics projected to grow at a CAGR of 6–8% globally, marigold's market footprint is expected to expand substantially.
- Encouraging public–private partnerships (PPP) and farmer–industry linkages will be crucial for scaling up marigold's industrial applications.

Conclusion: Marigold, once regarded primarily as an ornamental flower, has now emerged as a multifunctional industrial and medicinal crop of global significance. Its rich phytochemical profile, dominated by carotenoids, flavonoids, and essential oils, provides the foundation for diverse therapeutic properties including antioxidant, antimicrobial, anticancer, ophthalmic, and dermatological benefits. On the industrial front, marigold-derived lutein has become indispensable in nutraceuticals, poultry feed, cosmetics, and natural food colorants, contributing substantially to the global carotenoid market.

The economic value of marigold is underscored by its role in floriculture, rural employment, and export-oriented industries, with India, China, and Latin America leading global production. However, significant challenges remain, such as variability in extraction methods, limited clinical validation, short shelf-life, and pest susceptibility. Future opportunities lie in molecular breeding, CRISPR-based genetic improvement, biotechnological interventions, and zero-waste processing models, which can enhance productivity, standardize bioactive content, and expand applications.

By bridging the gap between traditional medicine and modern science, marigold has the potential to evolve into a sustainable bio-resource supporting global health, industry, and agriculture. Coordinated efforts in policy, research, and commercialization will be vital for unlocking its full potential in the coming decades.

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