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REVIEW ARTICLE

Multifunctional Applications of *Tagetes* Species: From Phytochemistry to Sustainable Crop Protection and Human Health

Deepa Rani,[1,2] Vipin Saini,[2] Sarita Sharma,[3] Tarun Nangia[4]

1. MM College of Pharmacy, Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala, Haryana, India.
2. Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala, Haryana, India.
3. Amity Institute of Pharmacy, Amity University, Gwalior, Madhya Pradesh, India.
4. Swami Vivekanand Multispeciality Hospital, Yamunanagar, Haryana, India.

Abstract

Tagetes spp (marigolds) is a genus of multifunctional plants that has been recognised to have ornamental, cultural, agricultural and therapeutic value. In the last ten years, the complex phytochemical profile of the genus, including thiophenes, flavonoids, terpenoids, carotenoids and essential oils, explaining a range of biological activities, has been characterised by intensive scientific research. These pharmacological activities include antifungal, antimicrobial, nematocidal, insecticidal, allelopathic, antioxidant, anti-inflammatory, hepatoprotective and wound-healing activities. As a result, *Tagetes spp* have been put at the centre of bioresources at the nexus of sustainable agriculture, pharmacology and biotechnology. The recent advances in nanotechnology, synthetic analogues and agro-waste valorisation have expanded their functional use. However, most of the available research is limited to *in vitro* experiments with limited evidence on field experiments, *in vivo* models and clinical settings. Moreover, lack of standardised extraction methods, optimal dose schedules and the tiring ecological safety studies restrain the translational capacity of these plants. The current review is a synthesis of phytochemical, ecological and biomedical knowledge between 2015-2025, hence, provides a consistent framework of the rational utilisation of *Tagetes spp* in crop protection and human health.

Key words: *Tagetes*; Phytochemicals; Diversity; Crop protection, sustainable; Biological control agents; Nanotechnology; Ecology; Humans; Health.

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Corresponding author:
VIPIN SAINI
E: vipinsaini2020@gmail.com

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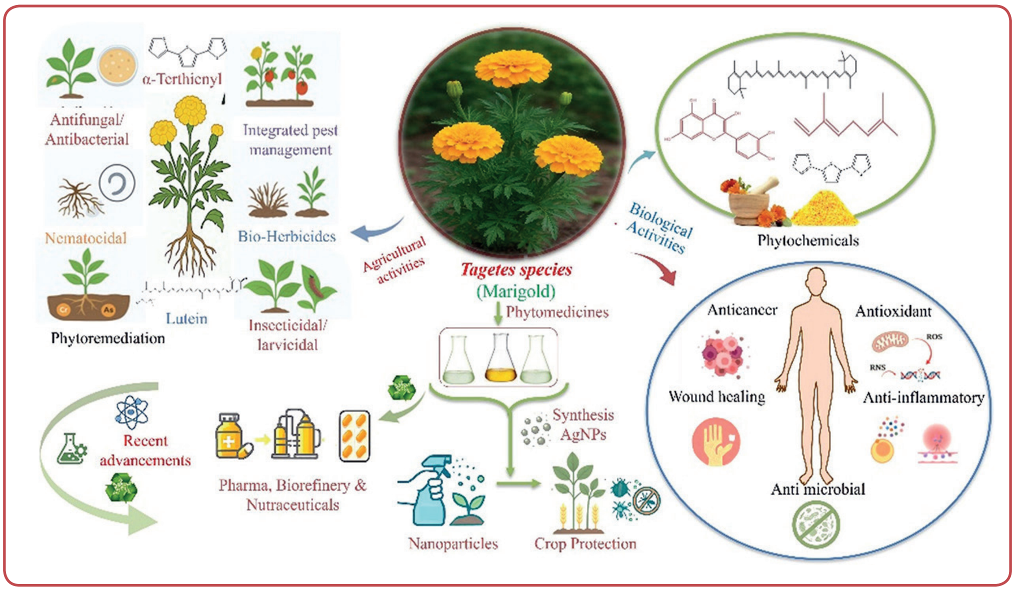

Graphical abstract

Introduction

Marigolds, which are plants of the genus *Tagetes* (family Asteraceae), have historically been used as decorative and ritual plants.[1] Over time, *Tagetes* species have acquired scientific attention as good sources of bioactive phytochemicals, such as thiophenes, flavonoids, carotenoids, terpenoids and essential oils.[2] These metabolites help provide a broad range of biological activities, placing *Tagetes* at the crossroads of plant science, sustainable agriculture and human health.[3]

In the past ten years, the application of *Tagetes spp* in eco-friendly crop protection methods and therapeutic development has become the subject of increasing research.[4] In agricultural systems, thiophenes, especially α-terthienyl, show strong nematocidal, antifungal and insecticidal properties, which are commonly mediated by light-dependent photodynamic processes.[5, 6] Such properties offer environmentally safe substitutes for synthetic pesticides and complement integrated pest management (IPM) practices through intercropping, allelopathy and soil enrichment.[7]

Simultaneous pharmacological studies indicate that *Tagetes* extracts and essential oils possess antioxidant, anti-inflammatory, antibacterial and wound-healing effects, facilitating their use in nutraceutical, cosmeceutical and therapeutic products.[8] Current developments in nanobiotechnology and circular bioeconomy strategies have further increased the functional range of *Tagetes*, such as plant-mediated nanoparticle synthesis and the valorisation of floral waste.[9, 10]

Despite these advances, there remains a gap in existing research, which is mostly disjointed and responds to isolated activities rather than providing a comprehensive insight into phytochemistry, ecological functions and biotechnological uses.[9] This review combines current research published between 2015-2025 to present *Tagetes* spp as multifunctional bioresources connecting sustainable crop protection with human health.

Phytochemical constituents and multifunctional roles of *Tagetes spp*

Tagetes spp are chemically diverse plants whose phytochemicals underpin their medicinal and agricultural significance.[11] Flavonoids such as quercetagetin, quercetin, kaempferol, rutin, patuletin and laricitrin predominantly present in flowers, leaves and seeds of *T erecta, T lucida* and *T patula* exhibit strong antioxidant and anti-inflammatory activities.[12] Carotenoids, including lutein, zeaxanthin, antheraxanthin and α/β-carotene, are abundant in the floral tissues of *T erecta* and contribute to nutritional and therapeutic benefits.[13-15]

Terpenoids and volatile constituents (eg, ocimene, limonene, myrcene, tagetone and dihydrotagetone), prevalent in the essential oils of *T erecta, T minuta and T lucida*, display antibacterial, insecticidal and pesticidal properties.[16, 17] Thiophenes, particularly α-terthienyl and related bithiophene derivatives are characteristic metabolites of *T patula, T minuta* and *T lucida* and are closely associated with nematocidal and antifungal activity.[18, 19] Additional constituents including phenolic acids, saponins, sterols, fatty acids, vitamins and polysaccharides further expand the bioactive spectrum.[20]

Collectively, this diverse phytochemical composition establishes *Tagetes spp* as valuable sources of nutraceutical, pharmaceutical and environmentally sustainable biocidal compounds. The major phytochemical classes, representative compounds, plant part distribution and associated biological functions of *Tagetes spp* are summarised in Table 1. The major phytochemical classes and their structure–activity relationships are summarised in Figure 1.

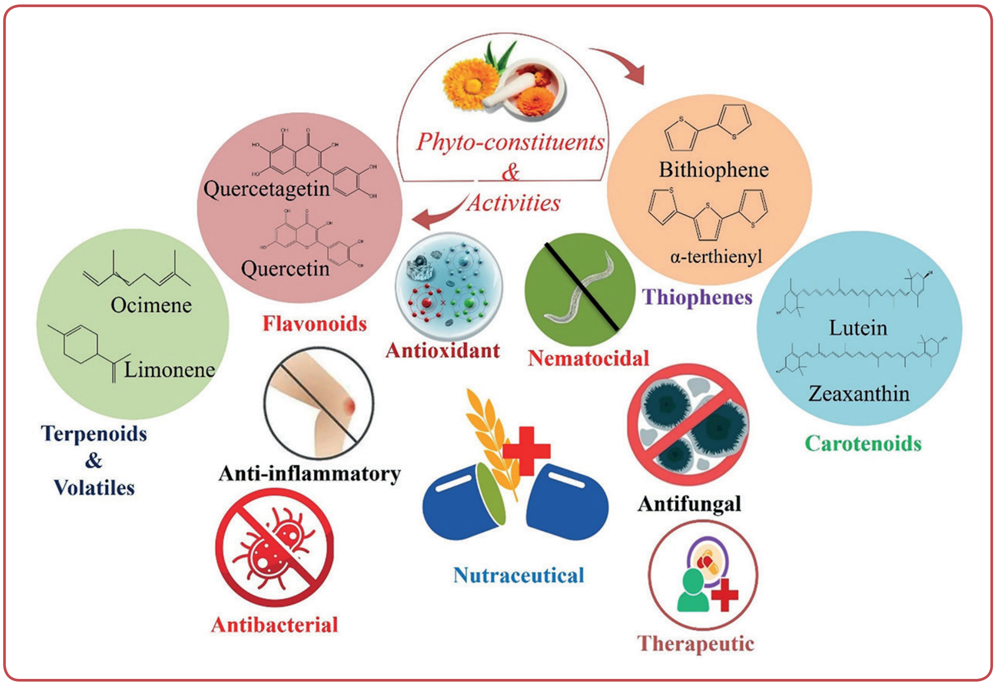

Figure 1: Bioactive compounds of Tagetes spp and their multifunctional applications

Table 1: Major phytochemicals of Tagetes spp and their biological activities

Phytochemical class	Major compounds	Species / plant part	Documented biological activities	Ref.
Sterols and triterpenes	Β-sitosterol, ß-daucosterol, 7-hydroxysitosterol, lupeol, erythrodiol, erythrodiol-3-palmitate	*T erecta* (flowers)	Antioxidant, anti-inflammatory	[11, 20, 21]
Phenolics and flavonoids	Kaempferol, syringic acid, gallic acid, rutin, kaempferitrin, quercetagetin, patuletin, patuletrin, quercetin, isoquercitrin, apigenin, laricitrin	*Tagetes spp* (flowers, leaves, seeds)	Antioxidant, anti-inflammatory	[12, 22-25]
Fatty acids and other lipids	Tetradecanoic acid, N-hexadecanoic acid, 15-hydroxypentadecanoic acid, hexadecanoic acid, palmitin, norolean-12-ene, vitamin E	*T erecta* (flowers)	Antioxidant, anti-inflammatory	[20, 26]
Carotenoids and xanthophylls	Lutein, antheraxanthin, α-cryptoxanthin, β-carotene, α-carotene, zeaxanthin, lutein esters	*T erecta* (petals, inflorescences)	Nutritional, antioxidant, therapeutic	[13–15]
Hydroxycinnamic acids	Chlorogenic acid, rosmarinic acid, caffeic acid, ferulic acid	*Tagetes spp* (leaves)	Antioxidant, antimicrobial	[20, 27]
Amino acids	Aspartic acid, glycine, histidine, valine	*T erecta, T patula* (leaves)	Nutritional, metabolic	[28]
Vitamins	Vitamin c, vitamin e	*T patula* (inflorescences), *Tagetes spp*	Antioxidant, nutritional	[20, 29]
Thiophenes and steroidal compounds	α-terthienyl, bithiophene derivatives, steroidal compounds	*T patula, T minuta, T lucida* (whole plant)	Nematocidal, antifungal, antimicrobial	[18, 19, 30]
Saponins and benzofurans	—	*Tagetes spp*	Cytotoxic, antimicrobial	[20]
Terpenoids and volatile terpenes	Ocimene, limonene, terpinene, myrcene, tagetenone, dihydrotagetone	*T erecta, T minuta, T lucida*	Antibacterial, insecticidal, pesticidal	[16, 17]

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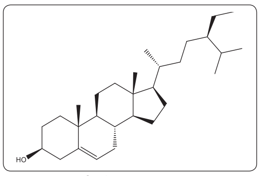
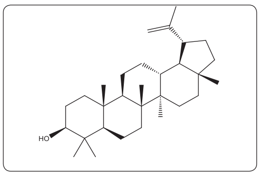
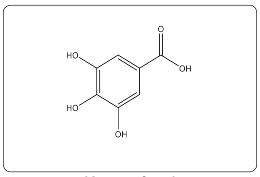
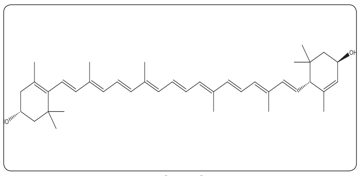
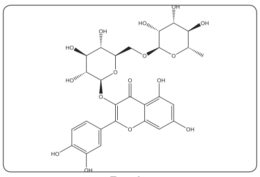
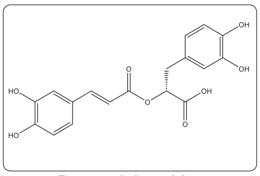
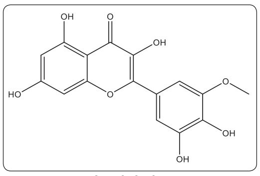
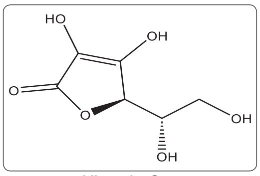
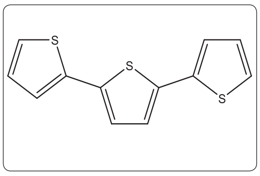
Solvent-dependent phytochemical variation in *Tagetes spp*

The qualitative and quantitative phytochemical composition of *Tagetes spp* is strongly influenced by the extraction solvent. Non-polar solvents predominantly extract lipophilic constituents such as sterols and terpenoids, whereas polar solvents are more effective in enriching flavonoids, phenolic acids, vitamins and thiophenes. These solvent-dependent variations allow optimisation of extraction strategies for obtaining targeted biological activities.[11] Detailed solvent-wise phytochemical profiles of *Tagetes spp* are provided in Table 2.

Table 2: Solvent-dependent phytochemical composition

Species	Extraction solvent / extract type	Predominant phytochemical classes	Major compounds with structure	Ref.
Tagetes spp	Ether / ethereal extracts	Lipophilic metabolites	 β-Sitosterol  Lupeo  Kaempferol	[11]
T erecta, *T patula*	Ethanolic extracts	Carotenoids, flavonoids, phenolic acids	 Lutein  Rutin	[13, 22, 31-33]

T erecta	Methanolic extracts	Fatty acids, sterols, vitamins, phenolics	 Rosmarinic acid  Laricitrin	[25, 26]
T patula, T minuta	Aqueous extracts	Amino acids, vitamins, thiophenes	 Vitamin C  α-Terthienyl	[26]

Essential oil composition and geographic variation

The essential oil composition of *Tagetes spp* exhibits considerable interspecific and geographic variation. Monoterpenes such as ocimenes, tagetones, tagetenones and dihydro-tagetone commonly dominate the volatile profiles; however, their relative abundance varies with species and region of origin, influencing biological efficacy and application potential.[34] A comparative overview of essential oil constituents across different *Tagetes spp* and geographic regions is summarised in Table 3.

Table 3: Geographic variation in essential oil composition

Species	Plant part / region	Dominant volatile constituents	Ref.
T patula	Aerial parts (India, Egypt, South Africa, Zambia)	Ocimenes, tagetones, tagetenones, dihydrotagetone, limonene, β-caryophyllene (regional dominance of Z-β-ocimene, Z/E-tagetone)	[16, 17, 34]
T lucida	Aerial parts, fruits	Ocimenes, tagetones, tagetenones, dihydrotagetone, sabinene, methyl chavicol	[35]
T filifolia	Mexico, Argentina	(E)-Anethole, methyl chavicol; minor: menthone, pulegone, germacrene D, cumin aldehyde	[36, 37]
T terniflora	Leaves (Argentina)	(E)-β-ocimene, Z/E-tagetone, Z/E-tagetenone	[34]
T tenuifolia	Aerial parts	Ocimenone, dihydrotagetone, tagetones, limonene	[38, 39]
T mandonii / T maxima	Aerial parts	(Z)-Tagetone, dihydrotagetone, (E)-tagetenone; minor terpenes	[40]
T multiflora	Aerial parts	Tagetone, tagetenone, β-ocimene, dihydrotagetone	[40]
T lemmonii	Flowering stems	Dihydrotagetone, tagetone, tagetenone, alloocimene	[41]

T rupestris	Aerial parts (Argentina)	Ocimenes, tagetones, tagetenones	[42]
T subulata	Capitula, leaves	Terpinolene, piperitenone, limonene	[43]
T caracasana	Venezuela	(E)- and (Z)-tagetone	[43]
T pusilla	Venezuela, Bolivia	(E)-Anethole, α-pinene	[44]
T mendocina	Argentina	Ocimenes, tagetones, ocimenone, α-pinene	[34]

Various benefits of *Tagetes spp* in health and agriculture

Tagetes spp (marigolds) are adaptable plants with agricultural and therapeutic use valued for their aesthetic appeal and numerous phytochemical elements such as flavonoids, thiophenes, carotenoids and essential oils.[1]

Agricultural benefits: These metabolites support their diverse bioactivities, making them effective plant pesticides with confirmed insecticidal, nematocidal and antifungal properties.[45] These characteristics make them more suitable for use in sustainable agricultural approaches such as organic farming and integrated pest management (IPM) systems.[46]

Health and therapeutic benefits: Simultaneously, *Tagetes*-derived compounds exhibit strong antioxidant and anti-inflammatory capabilities with prospective applications in dermatological treatment, immunological modulation, including the therapeutic management for reactive oxygen species stress-related diseases.[8]

Dual agro-pharmacological significance: Collectively, these dual agro-pharmacological benefits position *Tagetes spp* as valuable candidates for advancing both ecological crop protection strategies and plant-based therapeutic development.

Antifungal activity of *Tagetes spp* against crop pathogens

Tagetes spp exhibit strong and broad-spectrum antifungal activity making them promising botanical alternatives to synthetic fungicides in crop protection. Extracts and essential oils obtained from *T erecta, T patula, T minuta* and *T pusilla* have shown inhibitory effects against several economically important plant pathogenic fungi, including *Alternaria alternata, Botrytis cinerea, Fusarium spp*, *Trichoderma viride, Pythium ultimum* and *Candida albicans*, as summarised in Table 4.

Table 4: Antifungal activity of Tagetes spp extracts and essential oils against crop-associated fungal pathogens

Species	Plant part / region	Pathogen(s) tested	Method	Results	Ref.
T erecta, T patula	Petals; hexane and methanol	*Ganoderma lucidum, Alternaria alternata*	Disc diffusion; MIC	Inhibition zones 6.4–8.5 mm; MIC 7.5–13.3 mg/mL; *T patula* more active	[47]
T patula	Flowers; essential oil	*Penicillium digitatum, Botrytis cinerea*	*In vitro* inhibition assay	Complete inhibition; MIC 1.25 µL/mL (*P digitatum*), 10 µL/mL (*B cinerea*)	[48]
T patula	Whole biomass; hydroalcoholic	*Trichoderma viride*	Growth inhibition	Mycelial growth reduced by 50–54 %	[49, 50]
T minuta	Aerial parts; various solvents	*Fusarium verticillioides, F proliferatum, Aspergillus flavus, A parasiticus*	MIC	Fungistatic activity; MIC 0.02–2.5 mg/mL; aqueous extract inactive	[51]
T pusilla	Essential oil	*Candida albicans*	Cavity diffusion	Inhibition halo > 20 mm	[52]
T minuta	Leaves; essential oil	*Candida albicans*	Cavity diffusion	Inhibition halo 26 mm	[53]
T patula	Leaves; essential oil	*Candida albicans*	Disc diffusion; MIC	Inhibition zone 7.7 mm; MIC 3180 µg/mL	[54]

T minuta	Essential oil	*Aspergillus niger, Candida albicans*	MIC determination	MIC 115–135 μg/mL	[55]
T patula	Aerial parts; 70 % ethanolic	*T rubrum, T mentagrophytes, M canis*	MIC	MIC 195–625 μg/mL; no effect on *Metarhisium*, *Beauveria*	[56]
T patula	Whole plant; methanolic	*B cinerea, F moniliforme, P ultimum*	Solid medium assay (solar / UV-A)	Growth inhibition 50.9–72.6 %	[49]

MIC: minimum inhibitory concentration; EO: essential oil;

Table 5: Antibacterial activity of Tagetes spp extracts against agricultural pathogens

Species	Extract type	Target microorganisms	Inhibition / MIC	Ref.
T minuta	Essential oil	*Vibrio spp, E coli, E cloacae, S aureus, S uberis, S typhi, B subtilis*	Disc diffusion; MIC	[55–57]
T minuta	Hydroalcoholic extract	*P aeruginosa, E coli, S aureus*	Moderate–strong inhibition	[58]
T minuta	Crude / aqueous / butanolic	*P pickettii, B subtilis, S aureus*	Inhibition halos 5–7.6 mm	[59]
T patula	Methanolic extract	*Multiple bacterial strains*	Zones 12.4–20.2 mm; MIC 0.19–4.05 mg/mL	[47]
T patula	Methanolic extract	*Multiple bacterial strains*	Zones 10–17.5 mm; MIC 0.63–7.6 mg/mL	[47]

The antifungal efficacy of *Tagetes* varies depending on the species, plant part used, extraction solvent and experimental conditions. Several studies have demonstrated that light or UVA exposure significantly enhances antifungal activity. In light-assisted assays, methanolic extracts of *T patula* caused 50–70 % growth inhibition of *Pythium ultimum* and *Fusarium moniliforme*,[47–51] further supporting the data presented in Table 4. Overall, these findings clearly indicate that *Tagetes spp* possess effective antifungal properties and can be exploited as eco-friendly and sustainable agents for the management of fungal diseases in agricultural systems.

Antibacterial activity of *Tagetes spp*

Several studies have consistently demonstrated the antibacterial potential of *Tagetes spp* against a wide range of crop- and livestock-associated bacterial pathogens, as summarised in Table 5. Essential oils of *T minuta* exhibit strong inhibitory activity against both Gram-positive and Gram-negative bacteria, including *Vibrio spp*, *Escherichia coli, Enterobacter cloacae, Staphylococcus aureus, Streptococcus uberis* and *Salmonella typhi.* [55–57]

Hydroalcoholic extracts prepared from the aerial parts of *T minuta* were particularly effective against *Pseudomonas aeruginosa, E coli* and *S aureus*, in some cases showing higher activity than the corresponding essential oil.[58] In addition, crude, aqueous and butanolic fractions of *T minuta* suppressed the growth of *Pseudomonas pickettii, Bacillus subtilis* and *S aureus*.[59]

Other marigold species also display notable antibacterial effects. Methanolic extracts of *T patula* petals produced broad-spectrum inhibition against multiple bacterial strains, whereas *T erecta* extracts showed moderate antibacterial activity.[47] Collectively, these findings indicate that *Tagetes spp*, particularly *T minuta*, represent promising sources of plant-based antibacterial agents for agricultural and livestock pathogen management.

Mechanistic basis of antimicrobial activity

The antimicrobial effects of *Tagetes* spp arise from multiple bioactive metabolites that act on diverse microbial cellular targets. These complementary mechanisms are summarised below and schematically illustrated in Figure 2.

Cell membrane disruption

The essential oils of *Tagetes,* containing ter-

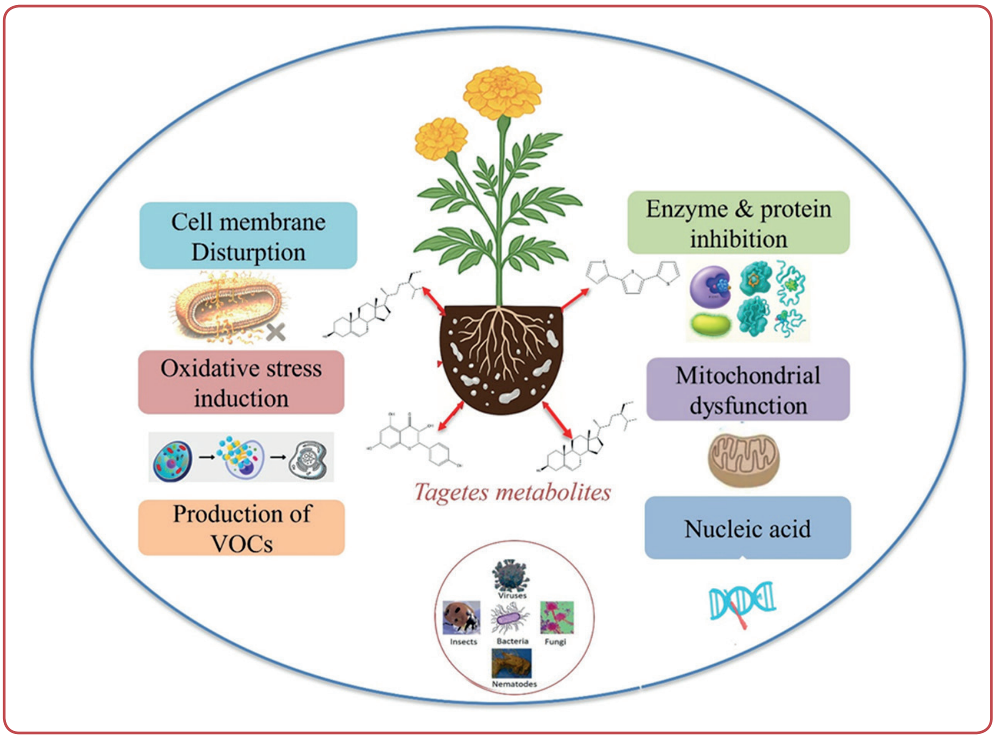


Figure 2: Mechanisms of antimicrobial activity of Tagetes-derived metabolites; VOCs: volatile organic compounds;

penoids, enter the lipid bilayers of microbes, making the membranes more permeable with the consequence of leakage of ions and intracellular substances. The damage to the integrity of the cell membranes interferes with cellular homeostasis, leading to the disruption and death of pathogens.[60]

Oxidative stress induction

Thiophenes and flavonoids in *Tagetes* cause an excess of ROS production in bacterial cells. The ROS component of oxidative stress leads to oxidative reactions and damages lipids, proteins and nucleic acids in bacterial cells that overwhelm bacterial antioxidants, causing irreparable damage to cells and bacterial death.[61]

Production of volatile organic compounds (VOCs)

Volatile organic compounds are emitted by the roots and above-ground portions of the plants of the species *Tagetes* and directly inhibit the growth of the pathogens. In addition, these compounds have the ability to stimulate the systemic defence signalling pathways of the plants such as jasmonates, salicylic acid and ethylene-induced signalling pathways, hence increasing the ability of the plants to indirectly inhibit the growth of the pathogens.[60]

Enzyme and protein inhibitors

Flavonoids and phenolic acids present in *Tagetes* act on major microbial enzymes and proteins, thereby inhibiting enzymatic function. Inhibition of enzymes responsible for cell wall synthesis and metabolic control limits the growth and pathogenicity of microbes.[60]

Mitochondrial dysfunction

Certain *Tagetes*-derived compounds disrupt microbial pathogen mitochondrial electron transport chains and ATP production. Such disruptions of microbial metabolism result in an imbalance of microbial cell energies, ultimately leading to growth inhibition and cell death.[61]

Nucleic acid interaction

Certain metabolites of *Tagetes* interact with the DNA/RNA of microorganisms, thereby inhibiting the process of replication/translation. Further, ROS-induced damage causes instability of nucleic acids, thus enhancing antimicrobial activity.

In summary, various metabolites in *Tagetes* act against diverse microbial targets, such as cell membranes, redox cycles, signal transduction, enzymes, mitochondria and nucleic acids, thus displaying a broad-spectrum effect. This versatility makes way for the increasing use of botanicals of the plant species *Tagetes* for pest control and protection.[60-62]

Applications of *Tagetes spp* in sustainable agriculture

Nematocidal activity

The nematocidal activity of the genus *Tagetes* has been well documented since the pioneering work of Uhlenbroeck and Bijloo (1958), who demonstrated that root extracts of marigold suppress nematodes such as *Heterodera rostochiensis*, *Ditylenchus dipsaci* and *Anguina tritici*.[63] Subsequent studies confirmed that roots of *T erecta* significantly reduce populations of *Meloidogyne javanica* and *M arenaria*.[64] whereas *T halisciencis* has been reported to be effective against *M incognita*.[65] *Tagetes patula* has also been shown to exhibit activity against soil nematodes including *Caenorhabditis elegans* and *Pratylenchus penetrans*.[66] The nematocidal effects of *Tagetes spp* are primarily attributed to thiophene derivatives, particularly α-terthienyl, which is considered the principal bioactive compound responsible for nematode suppression. Marigolds are most effective when used as cover crops, intercrops, green manures as continuous release of root exudates enables nematode suppression throughout the plant growth period.

Insecticidal and larvicidal properties

Marigold species, beyond their nematocidal effects, also exhibit significant insecticidal and larvicidal activities. Extracts from *Tagetes erecta* have demonstrated activity against pests from various groups including *Tribolium spp* (stored cereal pests), aphids (*Aphidoidea*) and *Spodoptera frugiperda* (fall armyworm).[67–70] In addition, extracts from both *T erecta* and *T patula* have been reported to be active against *Sitophilus zeamais* (rice weevil), indicating their potential application in the protection of stored grains.[71, 72] Essential oils from *Tagetes minuta* have demonstrated efficacy against disease-vector mosquitoes such as *Anopheles gambiae*, showing comparable effectiveness under experimental and field conditions to commercial insecticides.[73] Overall, these studies highlight the potential of marigold species as botanical alternatives to synthetic pesticides within integrated pest management strategies.

Potential of bioherbicides

Certain species of the *Tagetes* genus exhibit bioherbicidal activity against a range of weed species. Essential oils and extracts of *Tagetes minuta* have shown phytotoxic effects against *Amaranthus viridis*, *A tricolor*, *Bidens pilosa*, *Phalaris minor*, *Chenopodium murale* and *Echinochloa crus-galli*, primarily through the reduction of seed germination and early seedling growth.[74] These findings support the use of marigold as a natural weed suppressor, helping to reduce dependence on chemical herbicides and promote sustainability in crop management.

Phytoremediation

Tagetes spp have important roles in phytoremediation through the tolerance and accumulation of heavy metals from polluted soils facilitating soil detoxification. *Tagetes erecta* is capable of efficient absorption of Zn and Cd with exclusion of Pb to prevent contamination in the food chain.[75] *Tagetes patula* tolerates fly ash contaminated soils.[76] while up to 94 % Cr accumulation could be obtained within 35 days in *T erecta* inoculated with rhisobacteria.[77] These characteristics highlight the potential of marigolds to rehabilitate contaminated agricultural lands.

Intercropping, companion planting and green manuring

Tagetes erecta and *Tagetes patula* cultivars, when used as preplant crops, have been reported to satisfactorily suppress *Meloidogyne spp* galling and juvenile populations in tomato, often superior to fallow controls.[78] Intercropping with *T minuta* also reduces root-knot nematode development in a range of vegetables and has the added benefit of promoting plant growth.[79] The inclusion of *T erecta* into rotation and intercropping systems has been shown to decrease nematode densities and increase yields, a function attributed to the production of α-terthienyl from roots.[80] While less documented green manuring with *Tagetes* positively impacts soil health through increased organic matter content and nutrient cycling.

Integration into integrated pest management

Tagetes spp serve as multifunctional biocidal agents within integrated pest management systems. Through intercropping, crop rotation, companion planting and other cultural practices they leverage their nematocidal, insecticidal and allelopathic properties reducing dependence on synthetic agrochemicals. This holistic approach promotes ecological intensification by enhancing soil health, suppressing pests and weeds and improving agroecosystem resilience. The ability of *Tagetes* to enhance soil microbial diversity and contribute to phytoremediation further supports sustainable farming systems.[81, 82]

Pharmacological and medicinal applications

The rich phytochemical profile of *Tagetes spp* including carotenoids, flavonoids and other bioactive compounds underpins their considerable therapeutic potential. Numerous *in vitro/in vivo* studies have demonstrated significant antioxidant, anti-inflammatory and wound healing activities of *Tagetes* extracts highlighting their medicinal relevance.

Antioxidant properties

Extracts from *Tagetes spp* are well recognised for their strong antioxidant properties primarily attributed to their high carotenoid and flavonoid content. *In vitro* studies have shown that extracts from *T erecta* and *T patula* possess significant free radical scavenging activity effectively inhibit lipid peroxidation, thereby reducing oxidative damage.[83] Complementary *in vivo* investigations support these findings demonstrating that oral administration of *T erecta* extracts in experimental rat models enhances the activity of endogenous antioxidant enzymes while simultaneously reducing oxidative stress markers.[84] These results underline the potential of *Tagetes* derived phytochemicals as natural therapeutic agents for the prevention and treatment of oxidative stress related diseases and age-associated degenerative processes. *In vivo* experimental studies have demonstrated that topical application of marigold extracts exhibits significant anti-inflammatory effects, which are mediated through inhibition of key pro-inflammatory enzymes and mediators, particularly inducible nitric oxide synthase (iNOS) and cyclooxygenase-2 (COX-2).[85, 86]

Anti-inflammatory effects

Tagetes spp exhibit notable anti-inflammatory activity which is mediated through the inhibition of key pro-inflammatory enzymes and mediators, particularly cyclooxygenase-2 and inducible nitric oxide synthase.[85] *In vivo* studies have shown that topical application of *T patula* extracts significantly reduces ear oedema in mice with effects comparable to those of standard anti-inflammatory drugs.[86] These findings suggest that marigold extracts may serve as effective natural therapeutic agents potentially with fewer adverse effects than conventional medications, for inflammatory conditions such as arthritis and dermatitis.

Wound healing

There is a long history of marigold use in wound care within traditional medicine, which has been substantiated by modern experimental evidence. In vivo studies using *T erecta* extracts have reported accelerated wound healing, enhanced collagen deposition and increased epithelialisation in rat models.[87] These findings indicate a significant role in tissue repair and regeneration. Marigold-mediated wound healing is a multifactorial process involving antibacterial, anti-inflammatory and antioxidant activities, as well as stimulation of fibroblast proliferation and collagen synthesis. Collectively, these actions reduce infection risk, limit inflammation and promote efficient tissue regeneration, supporting the application of marigold extracts in topical wound-care and dermatological formulations.

Antimicrobial efficacy

Marigold extracts, particularly those rich in thiophenes and essential oils, exhibit broad-spectrum antimicrobial activity. Essential oils of *T erecta* show notable antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*.[88] Similarly, essential oils of *T minuta* demonstrate pronounced antifungal activity against *Candida spp* and dermatophytes.[19, 89] These findings highlight the potential application of marigold extracts in the management of infectious diseases.

Anticancer properties

The anticancer potential of *Tagetes spp* has been investigated in several studies. *In vitro* studies have shown that flower extracts of *T patula* exert cytotoxic effects against breast, colon and lung cancer cell lines. Cytotoxic activity has been reported against multiple cancer cell lines, including HeLa, MCF-7, PC-3 and NCI-H460.[90, 91] These effects are attributed to phenolic constituents such as patuletin, patulitrin and methyl protocatechuate, which are known to induce apoptosis and disrupt cancer cell proliferation.[92]

Traditional medicinal uses of *Tagetes spp*

Tagetes spp have an important role in traditional medicine across different cultures. They are used for the treatment of skin problems and wounds, as well as digestive and respiratory issues, neurological or mental health conditions and for combating infections and parasites. These uses are widely reported.

In South Asia, people use *T patula* and *T erecta* extensively for skin troubles, fevers, swelling, kidney problems and muscle aches. Usually, they are prepared as topical applications or boiled as decoctions.[93, 94] In Latin America, *T minuta* and *T filifolia* are used for stomach and lung disorders, menstrual problems and wound healing. *T lucida* is used for neurological and psychiatric conditions, as well as for eliminating parasites.[95–97] In Africa and Europe, *T erecta* is also reported, especially for malaria, fever reduction and external applications.[98, 99]

When the patterns are examined, skin and wound care emerge as the most common uses. After that, digestive and respiratory applications are frequently reported, followed by neurological or psychiatric uses. The genus also covers fevers, parasitic infections and muscle-related conditions, indicating its relevance to broader health concerns.[100] Infectious disease-related uses are also frequently mentioned. These applications are summarised in Table 6 and Figure 3.

Table 6: Traditional ethnomedicinal uses of Tagetes spp

Therapeutic category	Species	Plant part(s) used	Traditional uses / ailments	Region / country	Ref.
Dermatological and wound care	*T patula*	Leaves, juice	Boils, carbuncles, muscular pain, piles; earache, ophthalmia	Bangladesh	[93]
	T filifolia	Infusion	Infected wounds	Argentina	[100]
	T minuta	Leaves and flowers	Wounds, sores healing	Argentina, Bolivia, Brazil, Paraguay, Peru	[101]
		Sap (topical), leaves	Wound healing, skin diseases	Kenya	[102–105]
	T erecta	Flowers, leaves, extracts	Sores, burns, ulcers, eczema, earache	India	[106–108]
		Whole plant, petals	Wound healing, skin infections	Guatemala, Mexico	[109,110]
Digestive and respiratory	*T filifolia*	Branches (tea)	Stomach ache	Mexico	[95]
	T minuta	Leaves and flowers (decoction)	Digestive disorders, colic, stomach pain	South America, Pakistan	[111, 112]
		Decoction	Children's cough, headache	Uganda	[113, 114]
		Infusion	Sedative	Brazil	[115–117]
	T erecta	Whole plant, petals	Pneumonia, asthma, tuberculosis, colic	Guatemala, Mexico	[118, 119]
		Infusion (flowers)	Flu, fever, body pain, sore throat, arthritis	Mexico	[120]
Neurological and psychiatric	*T lucida*	Aerial parts	Epilepsy, dementia, fever	Mexico	[121, 122]
		Infusion, hydroalcoholic extracts	Anxiety, depression, irritability	Mexico	[123, 124]
		Decoctions	Nervous tonic, immune stimulant; rheumatism, inflammation	Various	[125]
Febrile, parasitic and other	*T patula*	Leaves, flowers	Antipyretic	Pakistan	[94]
	T minuta	Leaves and flowers	Antiparasitic, febrifuge, gynaecological	South America	[101]
		Flower tea	Musculoskeletal ailments	Morocco	[103]

		Infusion	Post-labour prophylaxis	Argentina	[105]
	T erecta	Whole plant, petals	Antileukemic, analgesic, immune stimulation, headache, tetanus, CNS ailments	Guatemala, Mexico	[126, 127]
Febrile, parasitic and other		—	Antimalarial	Madagascar	[128]
		Flower infusion	Fever due to infection	Rodrigues Island	[129]
	T lucida	Flower decoction	Abdominal pain, neonatal jaundice	Mauritius	[130]
	T erecta	External preparations	Detersive, vesicant, resolutive	Spain, France	[131]

CNS: central nervous system;

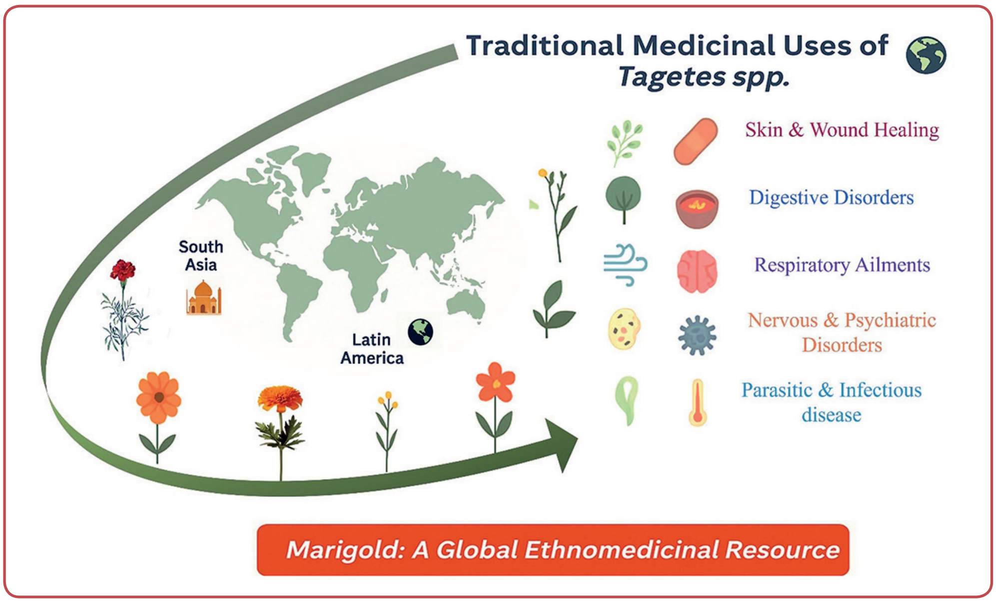


Figure 3: Traditional medicinal uses of Tagetes spp across different regions of the world

Merging therapeutic with industrial applications

Potential of *Tagetes spp* for herbal formulations

The *Tagetes spp*, especially *Tagetes erecta, T patula* and *T minuta*, exhibit considerable potential for herbal formulation development because of their diverse and rich phytochemical profiles. These taxa are rich in bioactive constituents, including flavonoids, carotenoids, essential oils, thiophenes and minor alkaloidal components, that together contribute to the therapeutic effect.[18] Pharmacological studies reveal that *T* erecta demonstrates potent anti-inflammatory and antioxidant activities, hence its use in formulae intended to alleviate conditions resulting from oxidative stress and inflammation.[126] On the other hand, the essential oils from *T patula* show high levels of antibacterial and antifungal activities; thus, they are suited for application in antimicrobial topical formulations and surface protection.[127]

Various carotenoids and flavonoids isolated from *Tagetes spp* have also shown wound healing and skin-protective effects which increases their relevance for dermatological and cosmetic products. Besides medicinal applications *Tagetes spp* produce biologically active compounds that have insecticidal and nematocidal action serving as environmentally benign alternatives for pest management in sustainable agriculture.[128] In addition, their integration into cropping systems has been found to promote soil microbial diversity and overall soil health.[18]

The flowers of marigold are rich sources of natural pigments especially lutein which finds wide applications in nutraceuticals related to ocular and skin health. Extracts from *Tagetes* spp have been increasingly incorporated into cosmetic preparations due to their protective effects against oxidative damage.[129]

To ensure the consistency of their bioactive content and therapeutic performance, advanced techniques of extraction, such as supercritical fluid extraction and ultrasound-assisted extraction, along with strict standardisation and quality control are being used.[130] Ensuring regulatory compliance will be critical for ensuring safety, efficacy and commercial viability of the products based on *Tagetes*.[8] In summary, *Tagetes spp* represent promising botanical resources for further translational research and industrial development for medicinal, agricultural and cosmetic applications.[11, 18]

Advances in biotechnological and industrial applications

Nanotechnology

Recently, *Tagetes spp*, especially *T erecta* and *T patula*, have been explored for green synthesis of AgNPs using plant-mediated methods.[131] Biosynthesised AgNPs have shown remarkable antibacterial activity, hence these might have potential applications in biomedical, agricultural and food-safety areas.[132-135] Interestingly, AgNPs prepared using *T erecta* leaf and petal extracts exhibited potent antibacterial action against *Erwinia amylovora* with implications for use in plant disease management strategies.[135]

Valorisation of industrial waste

Agro-industrial by-products arising from marigold cultivation represent an interesting opportunity for sustainable valorisation within biorefinery schemes.[136] Leaves and floral residues of *T erecta* have been used for the extraction of phenolic compounds through Soxhlet and vacuum-assisted extraction techniques for further applications in pharmaceutical and cosmetic industries.[137] Carotenoids, especially lutein can be successfully recovered from marigold waste streams for nutraceutical and functional food applications, further reinforcing circular-economy principles.[138]

Augmented efficacy via illumination

Certain species of *Tagetes*, especially *T minuta* contain thiophenic compounds whose antifungal activity is prominently enhanced by UVA illumination. Experimental tests conducted with UVA exposed *T minuta* root extracts have shown marked inhibition against *Candida spp* and dermatophytes, thus illustrating a promising photodynamic antifungal mechanism.[139] This light-activated bioactivity further extends the functional scope of *Tagetes*-derived compounds in plant disease and medical fungal management.

Challenges and future prospects

Standardisation of extracts and bioactive constituents

In the practical application of *Tagetes*-derived products a major limitation arises because of the variation in bioactive compound concentration across species, plant parts and developmental stages.[140-145] This variability complicates extract standardisation, essential for ensuring reproducible efficacy, safety and regulatory acceptance. Advanced analytical techniques and stringent quality-control protocols are indispensable.

Safety and toxicological considerations

While *Tagetes spp* are considered generally safe comprehensive toxicological studies for long term use have been scant. Certain species especially *T minuta* may produce compounds that are toxic at very high concentrations.[2, 8] Systematic toxicity studies and well-designed clinical trials are therefore essential to determine safe dosing and therapeutic windows.

Commercial viability

Large-scale commercialisation of *Tagetes*-derived products is promising due to their multifunctional bioactivities. However, challenges for large-scale cultivation, standardisation of extracts, regulatory approval and consumer awareness must be addressed to facilitate market acceptance.[9, 145]

Field-scale validation

While laboratory-scale trials appear promising, field-level efficacy, environmental impact and scalability require validation through extensive field trials and pilot-scale studies.[146, 147] Addressing these gaps will be key to translating experimental success into practical agricultural and industrial applications.

Conclusion

Tagetes spp, specifically *T erecta, T patula* and *T minuta* exhibit significant potential for the development of herbal formulations due to their diverse phytochemical profiles including flavonoids, carotenoids, essential oils and thiophenes. Pharmacological studies have highlighted their anti-inflammatory, antioxidant, antimicrobial, antifungal, wound-healing and nematocidal activities which contribute to applications in medicine, agriculture and the cosmetic industry.

Advances in biotechnology such as green synthesis of silver nanoparticles and nano-emulsions together with the valorisation of industrial by-products provide sustainable pathways to deploy marigold residues from temple and agro-industrial sources.

Particularly, enhanced efficacy under light exposure involving photodynamic antifungal mechanisms mediated by thiophenes, further expands the functional applications of *Tagetes spp*. However, challenges remain including standardisation of bioactive compounds, comprehensive safety and toxicity evaluations, large-scale field validation and regulatory compliance, which are necessary for successful commercialisation and integration into mainstream therapeutics and agricultural practices.

Addressing these gaps through collaborative research, advanced extraction, analytical techniques and strict adherence to quality control standards will facilitate the translation of *Tagetes spp* from laboratory research to industrial and clinical applications. Collectively, the multifaceted bioactivities, phytochemical richness and biotechnological adaptability of *Tagetes spp* underline their value as durable, versatile and high-potential resources for herbal formulations, food products, agricultural chemicals and cosmetic applications.

Ethics

This study was a secondary analysis based on the currently existing data and did not directly involve with human participants or experimental animals. Therefore, the ethics approval was not required in this paper.

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Conflicts of interest

The authors declare that there is no conflict of interest.

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Data access

The data that support the findings of this study are available from the corresponding author upon reasonable individual request.

Author ORCID numbers

Deepa Rani (DR):
0009-0000-8072-1163
Vipin Saini (VS):
0000-0003-2881-042X
Sarita Sharma (SS):
0000-0003-4010-1562
Tarun Nangia (TN):
0009-0005-8534-1684

Author contributions

Conceptualisation: DR
Methodology: DR
Validation: SS
Formal analysis: TN
Data curation: TN
Writing - original draft: DR
Writing - review and editing: VS, SS
Supervision: VS

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