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CURCUMIN AND ITS POTENTIAL APPLICATION AS ANTIMICROBIAL AGENT IN AGRICULTURE: A PRELIMINARY REVIEW

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ABSTRACT

Soil conservation is a critical aspect of sustainable agriculture. Damage to the physical, chemical, and biological structures of the soil decreases its fertility and disrupts native microbiota, leading to reduced nutrient availability, disruption of biological cycles (nitrogen and carbon), and a lack of protection against infections caused by fungal and bacterial pathogens. Therefore, the development of natural-origin fertilizers that are compatible with the soil microbiota and provide protective effects is essential. This work aimed to review the antifungal and antibacterial mechanisms of curcumin, a lipophilic bioactive compound of the *Curcuma longa* (turmeric) plant, and its potential application as a natural antimicrobial agent in agriculture. In general, the background information collected suggests that cell membrane weakening could allow the release of cellular material from microbial agents, through cell membrane rupture due to the inhibition of ergosterol synthesis, a key compound that allows maintaining the structure, fluidity, and permeability of the cell membrane. The review demonstrated that curcumin could have a potential practical application in agriculture due to its antifungal and antibacterial properties, with a more pronounced effect against fungi. This is attributed to the ability of curcumin to disrupts the fungal cell membrane and indirectly affect the proteins associated with it. Overall, this work highlights the promise of curcumin as a

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green alternative to conventional agrochemicals, while emphasizing the need for further research to develop and expand its agricultural applications.

Keywords: Turmeric, natural-origin fertilizer, agricultural soil, fungal cell membrane, ergosterol.

INTRODUCTION

The control of agricultural infections using chemical pesticides is not recommendable due to the associated risks of environmental contamination and harm to human health, highlighting the need to develop greener, more sustainable solutions. The ecological management of pathogenic infections is important in crops, as most agricultural products are intended for direct consumption (Mishra and Singh, 2012). Soils with low fertility are a common problem in many regions of the world. According to the Food and Agriculture Organization of the United Nations (FAO, 2021), 25% of the world's agricultural land shows signs of erosion. Intensive agricultural practices can exacerbate soil degradation, leading to nutrient depletion and a reduction of the natural soil microbiota. Consequently, the soil becomes more susceptible to harboring pathogens that cause plant infections, resulting in the decline of many commercially important crops (Antoniadis et al., 2017). Fungi are filamentous pathogens causing infections in plants and crops (Almeida et al., 2019). In general, these soil pathogens grow within the internal tissues of plant roots and can have negative effects on their growth. Plants with simple and poorly lignified roots may be more susceptible to pathogen attack. In addition, there are asymptomatic plant species that can serve as a source of inoculum for susceptible species (Malcom et al., 2013).

The use of natural ingredients as an alternative to synthetic antimicrobial agents represents a promising strategy, particularly considering the growing global resistance to synthetic antimicrobials commonly used in plants protection. Polyphenols, found in various plants, offer a potential solution to this challenge (Alalwan et al., 2017). Specifically, curcumin, which is a polyphenol extracted from the rhizomes of the *C. longa* plant, is an interesting active plant ingredient (Mahmood et al., 2015). In fact, it is a lipophilic compound with recognized biological activities such as anti-inflammatory, antioxidant, and anti-proliferative effects, as suggested by animal studies (Gupta et al., 2012). Additionally, it serves as an important source of macro-, meso-, and micronutrients (Jabborova et al., 2021). Curcumin has exhibited a broad spectrum of antimicrobial properties, including antibacterial (Adamczak et al., 2020) and antifungal effects (Murugesh et al., 2019), as well as the ability to decrease adhesion properties (O´Mahony et al., 2005). In general, the mechanisms underlying the antimicrobial activity of curcumin is not fully understood; however, it has been suggested that the presence of methoxyl and hydroxyl groups could be responsible for its antimicrobial activity (Han and Yang, 2005). However, the low water solubility and chemical instability of curcumin make its application difficult. A study reported the development of a natural fertilizer enriched with turmeric to evaluate its effects on tomato plants and soil properties; the formulation had positive effects on the metabolic processes of soil quality, and key fruit characteristics (Carvajal-Mena et al., 2023). Additionally, it has been found that curcumin can enhance its solubility and stability in emulsion systems (Leiva-Vega et al., 2020).

The use of curcumin represents a feasible and promising approach for the development and application of natural pesticides. Therefore, this work aims to review the antifungal and antibacterial mechanisms of curcumin to evaluate its potential application as a natural antimicrobial agent in agriculture.

Improvement of the solubility and bioavailability of curcumin for agricultural applications

In the context of human health, the application of curcumin is challenging due to its poor water solubility and low bioavailability, which result from its hydrophobic nature. Therefore, several studies have aimed to address these inherent limitations through the development of nanoparticles (Peng et al., 2018), nanosuspensions (Leiva-Vega et al., 2020) or complexes with cyclodextrins (Arya and Raghav, 2021).

However, the use of nanoparticles, nanosuspensions, or cyclodextrin complexes may not represent a viable alternative for improving the solubility and bioavailability of curcumin when the final application is on agricultural soils. Soil conditions are not necessarily favorable for the release of active compounds, and the preparation of these formulations requires complex laboratory equipment that is typically unavailable on farms.

A proposed solution to address the inherent limitations of curcumin is the search for new polymorphic varieties (Górnicka et al., 2023), which could show real applications in the agricultural area. These varieties could be developed as powder products for direct application on soils and require simple laboratory equipment for their preparation. According to Pandey and Dalvi (2019), polymorphism is the potential of a substance to exist in two or more crystalline forms with different molecular conformation. A polymorphic substance can exhibit different physical properties such as porosity, structure, density, and texture, which are key factors that may affect root development, water retention capacity, aeration, drainage, and soil workability, thereby directly affecting crop yield and plant health.

Turmeric powder exhibits polymorphism, a phenomenon in which its active compound, curcumin, can crystallize into different crystalline forms. Polymorphic substances share a similar chemical composition but possess distinct crystal structures characterized by differences in their crystallographic parameters. These differences can lead to changes in solubility, bioavailability, and release profiles, all of which may influence the half-life and efficacy of the active compounds (Prasad et al., 2020).

The most common polymorphic form of curcumin found in commercial products is form I. In contrast, the polymorphic form II can be obtained through the crystallization of the commercial product using the following methods: (i) crystallization with 4-hydroxypyridine in ethanol at room temperature, (ii) crystallization with dimethyl sulfoxide (DMSO) at room temperature, and (iii) crystallization from a saturated solution of the active compound in ethanol kept at 10°C for two days. Additionally, polymorphic form III can be obtained by crystallization from 4,6-dihydroxy-5-nitropyrimidine (Górnicka et al., 2023; Sanphui et al., 2011).

A curved or slightly twisted conformation in curcumin form I was detected. On both sides of its molecule, hydrogen bonds are formed between the phenolic groups of curcumin and adjacent molecules, resulting in the combination with a fourth curcumin molecule, to form a macrocyclic hydrogen-bonding ring. However, in forms II and III, this ring is absent due to their linear molecular conformation (Wan et al., 2020). In this regard, a study on the stability of polymorphic forms by crystallization in ethanol at room temperature for 24 h demonstrated the following: (i) in the case of form I, the chemical structure of the active compound remains stable and exhibits poor water solubility, and (ii) for the other polymorphism forms, the polymorphs are less stable; however, their water solubility can improve up to three times compared to form I (Sanphui et al., 2011).

Soil pathogens

Agricultural activities have led to significant environmental impacts, altering natural vegetation, disrupting biogeochemical cycles, and reducing soil biodiversity. These modifications caused by agricultural practices have resulted in species extinction rates that are 100 to 1,000 times higher than natural rates (Lewis and Maslin, 2015), primarily due to the increased prevalence of soil pests and pathogens (De Carvalho Mendes et al., 2012). Soil diseases are commonly referred to as "microbiome diseases", characterized by a loss of microbial diversity in the soil and, consequently, in the rhizosphere and endosphere of plants (Van Elsas et al., 2012). The synergistic interaction of pathogenic bacteria and fungi in the soil results in significant agricultural yield losses, increased production costs, and the overuse of synthetic antimicrobial agents, all of which contribute to soil degradation (Oerke, 2006; Bennett et al., 2012).

The most common soil pathogens found in agricultural systems are presented in Tables 1 and 2. Fungi are the main filamentous pathogens responsible for plant and crop diseases. Fungal diseases cause significant losses in agricultural harvest and food production. To colonize the plant and cause disease, some fungi kill their hosts and feed on dead material (necrotrophs), while others colonize living tissue (biotrophs) (Almeida et al., 2019).

Oomycetes are filamentous eukaryotic microorganisms that exhibit both saprophytic and pathogenic lifestyles. They can develop resistance to chemical treatments and/or overcome plant resistance genes, complicating disease management strategies (Larousse and Galiana, 2017).

Among soil bacteria, a small subset can colonize and infect plant roots. These include unicellular pathogenic bacteria whose survival and virulence depend on environmental conditions such as soil moisture, temperature, and carbon substrate availability. Certain bacterial species are highly sensitive to environmental fluctuations and can be inactivated by minor changes in soil conditions. In contrast, other species are remarkably resilient, tolerating extreme temperatures, desiccation, or nutrient scarcity. Additionally, some bacteria exhibit host specificity, selectively colonizing particular plant species or crops (Dion, 2010).

In general, soil pathogens typically colonize root tissues, where they disrupt plant growth and development. Plants with simple root systems and poorly lignified root structures are particularly prone to pathogen colonization. Furthermore, asymptomatic plant species (those harboring pathogens without displaying symptoms) can act

Table 1. Fungal pathogens found in agriculture.

Species	Symptoms	Affected product	References
Fungal pathogens:			
• *Blumeria graminis*	Wheat powdery mildew	Wheat	Zhao et al. (2020)
• *Botrytis cinerea*	Grey mould	Grapes	Williamson et al. (2007)
• *Colletotrichum gloeosporioides*	Anthracnose	Citrics	Ashwini et al. (2013)
• *Fusarium graminearum*	Fusarium head blight	Grain cereals	Brown et al. (2017)
• *Fusarium oxysporum*	Fusarium wilt	Tomato	Singh et al. (2020)
• *Fusarium solani*	Rot	Strawberry	De La Lastra et al. (2018)
• *Magnaporthe oryzae*	Rice blight	Rice	Wang et al. (2018)
• *Melampsora lini*	Flax rust	Linseed	Lawrence et al. (2007)
• *Mycosphaerella graminícola*	Leaf blight	Wheat	Suffert and Sache (2011)
• *Puccinia graminis*	Stem rust	Grain cereals	Gruner et al. (2020)
• *Rhizoctonia solani*	Root rot	Soybean	Rahman et al. (2020)
• *Sclerotinia sclerotiorum*	White mold	Lettuce	Young et al. (2004)
• *Ustilago maydis*	Corn smut	Corn	Redkar et al. (2017)
• *Verticillium dahlia*	Wilting	Pepper	Veloso et al. (2015)
Oomycetes pathogens:			
• *Albugo candida*	White rust	Corn	Cevik et al. (2019)
• *Hyaloperonospora arabidopsidis*	Downy mildew	Sunflower	Mestre et al. (2016)
• *Phytophthora capsici*	Blight, rot	Tomato	Syed-Ab-Rahman et al. (2019)
• *Phytophthora cinnamomi*	Root rot	Avocado	Andrade-Hoyos et al. (2020)
• *Phytophthora infestans*	Blight	Potato	Goss et al. (2014)
• *Phytophthora parasitica*	Root and stem rot	Tomato	Larousse et al. (2017)
• *Phytophthora sojae*	Root and stem rot	Soybean	Kang et al. (2019)
• *Plasmopara vitícola*	Downy mildew	Grape	Chitarrini et al. (2017)
• *Pythium ultimum*	Water rot	Potato	Tsror (Lahkim) et al. (2021)

Table 2. Bacterial pathogens found in agriculture.

Species	Symptoms	Affected product	References
Erwinia carotovora	Rot	Potato	Salem et al. (2018)
Erwinia amylovora	Fire blight, ooze production, necrosis	Apple	Schröpfer et al. (2021)
Erwinia stewartii	Wilt	Corn	Doblas-Ibáñez et al. (2019)
Rasoltonia solanacearum	Vascular wilt	Tomato	Aslam et al. (2017)
Xanthomonas campestris	Foliar spots and blight	Cabbage	Vicente and Holub (2013)
Pseudomonas syringae	Foliar spots and blight	Stone fruits	Popović et al. (2021)

as reservoirs of inoculum, facilitating the spread of infection to susceptible species (Malcom et al., 2013). In this regard, turmeric could be used in agriculture as a natural fertilizer that improves soil structure, water retention, and nutrient availability for plants, while it can also act as a natural insecticide and repellent against some pests. Its use as a natural fertilizer can contribute to sustainable agricultural production, reducing the use of hazardous chemicals (Fig. 1).

Antifungal mechanism of curcumin

Fungal infections and mycotoxin contamination pose a global threat to food and feed safety. Current hypotheses suggest that the antifungal activity of curcumin, the primary bioactive compound in turmeric, may be associated with alterations in fungal cell membrane properties and indirect effects on membrane-bound proteins (Lee and Lee, 2014), as observed in Fig. 2. Specifically, these effects arise from disruption

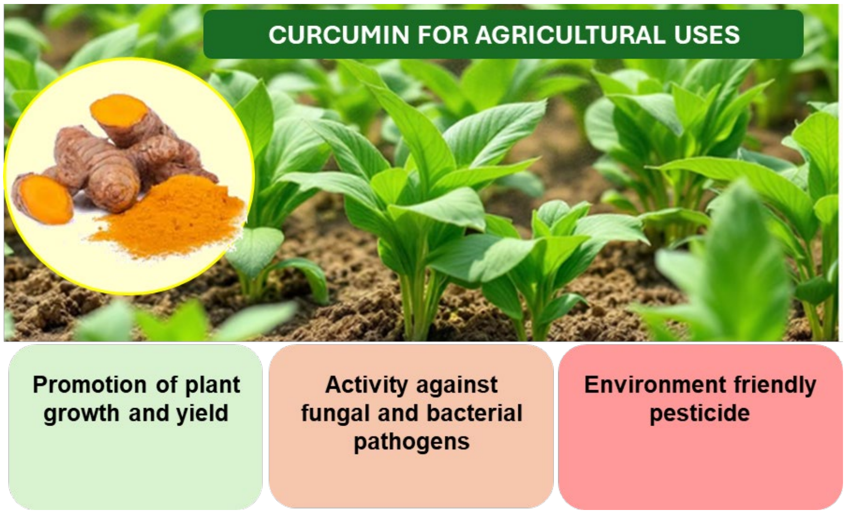

Fig. 1. Agricultural application of turmeric and its active compound, curcumin.

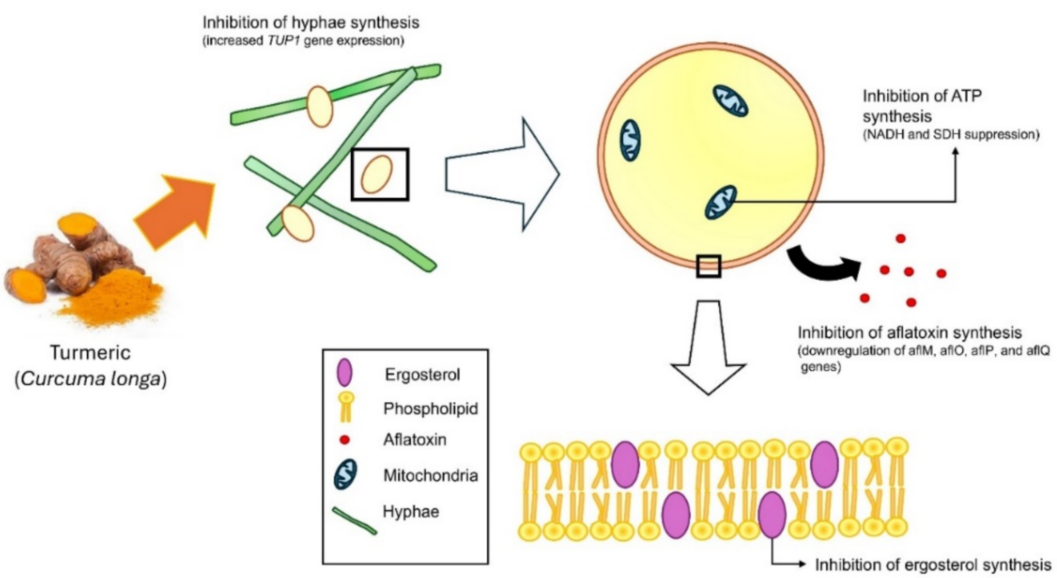

Fig. 2. Schematic representation of the proposed mechanisms for fungal inhibition by curcumin (Sources: Hu et al., 2017; Chen et al., 2018; Amminikutty et al., 2023).

of fungal endomembrane systems (Hu et al., 2017), and inhibition of ergosterol biosynthesis. As a critical sterol in fungal cell membranes (Chen et al., 2018), ergosterol plays a key role in maintaining membrane structure, fluidity, and permeability, while supporting essential cellular functions such as nutrient transport, environmental stress response, and cellular detoxification (Rodrigues, 2018). Additionally, turmeric essential oil might suppress mycotoxin production by modulating gene expression in the aflatoxin biosynthetic pathway, specifically by downregulating the expression of *aflM*, *aflO*, *aflP*, and *aflQ* genes (Amminikutty et al., 2023).

A study in *F. graminearum* culture demonstrated that the antifungal mechanism of curcumin involves the enzymatic downregulation of ergosterol biosynthesis. This disruption leads to the accumulation of ergosterol precursors, triggering oxidative stress via reactive oxygen species (ROS) generation and reduced ergosterol levels, which compromise membrane integrity and cellular transport. Furthermore, the study revealed that *C. longa* extract inhibits NADH oxidase and superoxide dismutase activity, thereby disrupting mitochondrial electron transport and ATP synthesis in the respiratory process (Chen et al., 2018).

Multiple studies have demonstrated the antifungal potential of incorporating turmeric powder (0.8 to 1.0 g L^{-1}). Furthermore, methanol extracts of turmeric exhibited antifungal activity against *Cryptococcus neoformans* and *Candida albicans*, with minimum inhibitory concentrations (MIC) of 128 and 256 ◎g mL^{-1}, respectively (Ungphaiboon et al., 2005).

In other investigations, *n*-hexane and ethyl acetate extracts of turmeric at concentrations of 1,000 mg L^{-1} and 500 mg L^{-1}, respectively, demonstrated antifungal activity against *B. cinerea*, *P. infestans*, *R. solani*, *Erysiphe graminis*, and *Puccinia recondita* (Kim et al., 2003). Moreover, turmeric oil showed inhibitory effects against *F. solani* and *Hirschmanniella oryzae* with IC50 values of 19.7 and 12.7 µg mL^{-1}, respectively (Chowdhury et al., 2008).

Studies across *Candida* species have demonstrated that curcumin exerts a dose-dependent inhibitory effect on (i) proteinase secretion, and (ii) plasma membrane P-type ATPase activity, significantly reducing intracellular pH levels (Khan et al., 2012). Additionally, curcumin suppresses hyphal development in *Candida spp.* under both liquid and solid culture conditions by targeting the *TUP1* gene, a global transcriptional repressor of hyphal development (Sharma et al., 2010), with analogous antifungal effects observed in *F. solani* (Akter et al., 2019).

Another study on *C. albicans* showed that curcumin induces fungal cell death by modulating the expression of 348 genes involved in various cell death pathways, including cell cycle regulation, signal transduction, cell wall integrity, cellular metabolic processes, stress response, cytoskeletal organization, DNA synthesis/repair, hyphal development, mitochondrial function, and transcriptional/translational machinery. Notably, several genes linked to virulence, transport, and uncharacterized functions were also implicated (Kumar et al., 2014). Furthermore, the study demonstrated that curcumin disrupts membrane permeability, alters fungal cell morphology, and compromises cell wall integrity by targeting the MAP kinase pathway and calcineurin-dependent signaling cascades.

Antibacterial mechanisms of curcumin

Current evidence suggests that the antibacterial mechanism of curcumin involves a combination of factors, including disruption of bacterial membrane integrity, inhibition of biofilm formation, and induction of oxidative stress (Suryanarayana et al., 2007; Tyagi et al., 2015; Hamzah et al., 2020). Curcumin has also demonstrated efficacy against diverse bacterial pathogens, including multidrug-resistant strains. These properties position it as a potential adjuvant, with studies proposing its use in combination therapy to synergistically enhance the activity of conventional antibiotics (Odo et al., 2023).

Specifically, Gram-negative bacteria exhibit lower susceptibility to curcumin compared to Gram-positive species, because of structural differences in their cell walls, particularly the lipopolysaccharide-rich outer membrane (Shlar et al., 2017). However, it has been demonstrated in *Escherichia coli* and *Bacillus subtilis* models that curcumin directly targets the catalytic domain of the filamenting temperature-sensitive mutant Z (FtsZ) protein, inhibiting its polymerization and disrupting prokaryotic cell division (Kaur et al., 2010). Structural analyses reveal that curcumin's α-terminal keto-enol group and terminal phenolic hydroxyl groups form hydrogen bonds with FtsZ's catalytic site, which is critical for its inhibitory activity (Kaur et al., 2010). These findings aligned with another study that reported that curcumin: (i) suppresses cytokinetic Z-ring assembly in *B. subtilis*, (ii) destabilizes FtsZ protofilaments, (iii) alters FtsZ's secondary structure, and (iv) hyperactivates FtsZ's GTPase activity—mechanisms collectively lethal to bacterial proliferation (Rai et al., 2008).

Curcumin exhibits potent antibacterial activity by suppressing key virulence factors in *Pseudomonas aeruginosa*, including pyocyanin production, protease activity, and elastase secretion. Furthermore, it disrupts the quorum sensing (QS) system (a cell-cell communication mechanism mediated by autoinducer molecules), specifically reducing the synthesis of 3-oxo-N-dodecanoyl-L-homoserine lactone (3-oxo-C12-HSL) and N-butyryl-L-homoserine lactone (C4-HSL). These QS autoinducers are essential for bacterial cell communication and regulation of gene expression (Rudrappa et al., 2008).

Current uses of turmeric in agricultural and heavy metal-contaminated soils

Applications of turmeric and its active compound, curcumin, in agricultural settings and heavy metal-contaminated soil remediation are summarized in Table 3.

Existing research indicates that the

Table 3. Current uses of turmeric in agricultural applications and soil remediation for heavy metals.

Agricultural applications	Soil remediation	Pesticide and herbicide	References
Tomato crops	Reduction of the toxic effect of nickel (II) chloride on garlic	Synergistic effects with avermectin, diflubenzuron, and lambda-cyhalothrin against *Spodoptera litura*	Carvajal-Mena et al. (2023) Kalefetoğlu Macar et al. (2022) Cui et al. (2022)
Plant growth and productivity improvement	Phytoremediation	Inhibitor of *Bidens pilosa* germination and growth in a dose-dependent way	Khan et al. (2023) Ru et al. (2014) Ejeh et al. (2025)
Soil properties and productivity	Adsorption and immobilization of copper	-	Bhupenchandra et al. (2022) Hu et al. (2019)
Soil quality	-	-	Srinivasan et al. (2016)

antimicrobial properties of curcumin effectively protect plants against phytopathogens, thereby reducing disease incidence and enhancing crop resilience (Rai et al., 2020). Curcumin has also been used to promote plant growth and yield in agricultural systems (Anas et al., 2024), and to remediate heavy metal-polluted soils, mitigating issues such as stunted growth, reduced biomass production, and excessive heavy metal uptake/accumulation in plants (Ru et al., 2014). Additionally, curcumin has shown potential as an insecticide in mosquitoes, termites, ticks, and other insects. Reported effects include synergistic effect with known biopesticides against *S. litura*, a destructive agricultural pest that infests more than 120 host plant species (Veeran et al., 2017; Veeran et al., 2019; Cui et al., 2022). Furthermore, turmeric has shown potential as a plant growth inhibitor to treat widely distributed weeds like *B. pilosa* (Akter et al., 2018), thereby avoiding the use of synthetic herbicides.

Challenges in agricultural soil product formulation

Limitations in formulating agricultural soil products include the development of stable multi-ingredient formulations. Additional difficulties involve ensuring compatibility with other biological and chemical products and tailoring formulations to specific soil types and climate conditions (Fadiji et al., 2024).

Challenges related to the biologically active natural ingredients

- Biological viability: For microbial products, the primary challenge is keeping the beneficial organisms alive and robust during storage and after application.
- Stability: Biological ingredients can be degraded by natural enzymes in the soil or other components in the formulation, reducing their effectiveness over time.
- Multi-active formulations: Combining multiple active ingredients, both chemical and biological, can increase complexity and create compatibility issues.

Challenges related to formulation and delivery

- Physical stability: Solid formulations may exhibit slow release rates, potentially delaying benefits, and achieving a homogeneous distribution of natural ingredients can be challenging.
- Environmental sensitivity: Product efficacy can be heavily influenced by local environmental factors, such as soil type, temperature, humidity, and the existing microbial population, all of which vary significantly across different regions.

Challenges related to soil complexity

- Environmental variability: A single formulation may not perform consistently across different geographical locations due to variations in climate, soil chemistry, and ecology.

- Intrinsic soil properties: The effectiveness of any product is limited by the existing soil conditions, such as compaction, erosion, or salinity, which can impact its ability to perform its intended function.

CONCLUSIONS

In this review, the antifungal and antibacterial mechanisms of curcumin, a lipophilic bioactive compound derived from *C. longa* were examined to establish a theoretical background for its potential application in agricultural soils as a sustainable strategy to mitigate pathogenic infections in plants and crops.

Based on the evidence analyzed, curcumin demonstrates significant agricultural potential, primarily due to its antifungal properties, which include disruption of fungal cell membranes, inhibition of ergosterol biosynthesis, and modulation of mycotoxin production. While its antibacterial activity is also notable, it appears less pronounced, as curcumin primarily targets bacterial membrane integrity and indirectly affects membrane-bound proteins. These findings highlight curcumin's promise as a natural alternative to conventional agrochemicals; however, further research is needed to optimize its efficacy and application under greenhouse conditions.

Future research on turmeric and its bioactive compounds for agricultural and heavy metal remediation applications should prioritize:

1. Developing turmeric-based holistic biocontrol strategies to reduce reliance on synthetic pesticides and fertilizers, targeting integrated pest and disease management.
2. Enhancing crop resilience to abiotic/biotic stressors (e.g., drought, salinity, pathogens) through curcumin-mediated modulation of stress-responsive pathways.
3. Quantifying the phytoremediation potential of turmeric in heavy metal-contaminated soils, with particular emphasis on rhizosphere microbial interactions and metal chelation mechanisms.
4. Evaluating the climate mitigation co-benefits of curcumin-enhanced crops, as improved plant health and metal-free biomass could foster carbon sequestration in agricultural systems.

Author contributions

Javier Leiva-Vega: Conceptualization, Bibliographic review, Methodology, Writing – original draft, Writing – review & editing. Constanza Flores-Soto: Writing – review & editing. Carolina Herrera-Lavados: Writing – original draft, Writing – review & editing. Daniela Pino-Acuña: Writing – review & editing. Diana Correa-Otero: Writing – review & editing. Lucía De La Fuente-Jiménez: Methodology, Writing – review & editing. Patricio Mejías-Barrera: Writing – review & editing. Keyla Tortoló-Cabañas: Writing – review & editing.

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Declaration of conflicts of interest

The authors declare no conflicts of interest.

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