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Phytochemical and phytomedicinal approaches for disease management in seed propagated horticultural crops

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Abstract

Seed borne and soilborne diseases pose major challenges to the sustainable production of horticultural crops. Conventional fungicides, although effective, often result in chemical residues, resistance development, and ecological imbalance. Phytochemicals, derived from plants and their secondary metabolites, have emerged as promising eco-friendly alternatives for disease management in seed-propagated crops. This review consolidates current knowledge on the utilisation of phytochemical-based treatments, including seed soaking, coating, and priming, to mitigate pathogen infection while enhancing germination and vigour. It further highlights the mechanisms of phytochemical action, involving inhibition of spore germination, membrane disruption, and induction of systemic resistance. Recent advances in nanoformulation, encapsulation, and green extraction technologies have improved the stability and bioavailability of active compounds. Integration of phytochemicals with microbial biocontrol agents and precision delivery systems offers new opportunities for sustainable seed health management. Despite their potential, challenges remain regarding standardisation, formulation optimisation, and field validation. This review emphasises the need for multidisciplinary research to overcome current limitations and enhance the practical adoption of phytochemicals within integrated disease management frameworks for horticultural crops. This review also highlights pharmacological significance, toxicological considerations and nano-delivery parallels of major phytochemicals, bridging agronomic applications with phytomedicine.

1. Introduction

Seed propagated horticultural crops (vegetables, ornamentals, culinary herbs and spices) are central to nursery production and commercial horticulture because sowing healthy seeds ensures uniform establishment and rapid dissemination of improved cultivars. Seed and seedling stage infections by fungi, oomycetes, bacteria and nematodes reduce germination, compromise seedling vigour and serve as important routes of long-distance pathogen dissemination, creating significant agronomic and phytosanitary challenges for growers and the seed industry. Seed treatments that reduce seedborne inoculum therefore play a fundamental role in protecting early crop stages and avoiding downstream epidemic development (Moumni *et al*., 2023; Arora *et al*., 2022).

For decades, chemical fungicides and fumigants have been the primary tools for seed disinfection and early disease control. Although, often effective, reliance on synthetic treatments is increasingly constrained by regulatory restrictions, environmental and human health concerns, and the evolution of pathogen resistance; these pressures have motivated the search for safer, sustainable alternatives and integrated seed-health strategies (Moumni *et al*., 2023; Terziæ *et al*., 2023). In this context, natural plant-derived compounds collectively termed phytochemicals are attractive because many exhibit broad antimicrobial activity, multiple modes of action and relatively rapid environmental degradation compared with persistent synthetic chemicals (Arora *et al*., 2022; Ahmed *et al*., 2023).

Phytochemicals encompass several major classes (essential oils and terpenoids, phenolics, flavonoids, alkaloids, glucosinolates, saponins) and can be applied at the seed stage by soaking, priming, coating/pelleting, fumigation or substrate incorporation (Moumni *et al*., 2021; Chrapaèienë *et al*., 2022). Laboratory and greenhouse studies have demonstrated that many botanical extracts and essential oils reduce spore germination and mycelial growth of common seedborne pathogens (*e.g.*, *Fusarium*, *Rhizoctonia*, *Alternaria*, *Pythium*), and in some systems improve germination and seedling vigour when properly dosed and formulated (Moumni *et al*., 2021; Ahmed *et al*., 2023; Oðuz *et al*., 2023).

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Nevertheless, translation to routine commercial use faces several hurdles. Crude botanical extracts often show batch-to-batch variability in chemical composition and activity, volatile phytochemicals can be phytotoxic at high doses, and many reports remain limited to in vitro or small-scale greenhouse trials with few long-term or large-scale field validations (de Almeida *et al*., 2021; Terziæ *et al*., 2023). Formulation technologies (micro-/nano-encapsulation, controlled-release coatings) and rigorous chemical standardization are therefore essential for reproducible efficacy and for minimizing negative effects on seed physiology and beneficial seed-associated microbiota (Arora *et al*., 2022; Moumni *et al*., 2023).

This review synthesizes current evidence on phytochemical approaches targeted at the seed and seedling stages of horticultural crops. We examine phytochemical classes and extraction/formulation strategies, compare application methods (soaking, priming, coating, fumigation, substrate amendment), summarizes efficacy against major seedborne pathogens, outline known mechanisms of action and physiological impacts, and identify research gaps and practical pathways for integrating phytochemical seed treatments into sustainable integrated disease-management programmes.

2. Phytochemicals in plant disease management

Phytochemicals are biologically active secondary metabolites produced by plants that play diverse ecological roles, including defence against pathogens and pests. Broadly, they include terpenoids (and essential oils), phenolics and flavonoids, alkaloids, glucosinolates/isothiocyanates, saponins, and other low-molecular-weight compounds (Gupta *et al*., 2023; Rahim *et al*., 2023). Their chemical diversity underpins a wide range of antimicrobial activities and makes them attractive candidates for protecting seeds and seedlings from disease.

2.1 Major classes and sources

2.1.1 Essential oils (EOs) and terpenoids

Volatile mixtures dominated by monoterpenes and sesquiterpenes (*e.g*., thymol, carvacrol, eugenol) that are extracted by steam-distillation or cold-pressing from aromatic plants. EOs are widely reported to inhibit fungal and bacterial growth *in vitro* and in planta and have been trialled as seed treatments and fumigants (Moumni *et al*., 2021; Gupta *et al*., 2023).

2.1.2 Phenolics and flavonoids

Non-volatile polyphenolic compounds (*e.g*., catechins, tannins) that often act as antioxidants and may have direct antimicrobial effects or function as elicitors of host defence (Gonelimali *et al*., 2018; Rahim *et al*., 2023).

2.1.3 Alkaloids and glucosinolates

Nitrogen-containing compounds and sulphur-containing glucosinolate derivatives (*e.g*., isothiocyanates) have demonstrated biocidal activity against microbes and nematodes in several studies (Gupta *et al*., 2023).

2.1.4 Saponins and other glycosides

These can disrupt cellular membranes of pathogens or function synergistically with other compounds (Gonelimali *et al*., 2018).

These phytochemicals are obtained from diverse plant sources are medicinal herbs, spices, crop residues and seeds by extraction methods ranging from simple aqueous/ethanolic extraction to steam distillation and advanced methods such as supercritical CO_2 extraction (Rahim *et al*., 2023).

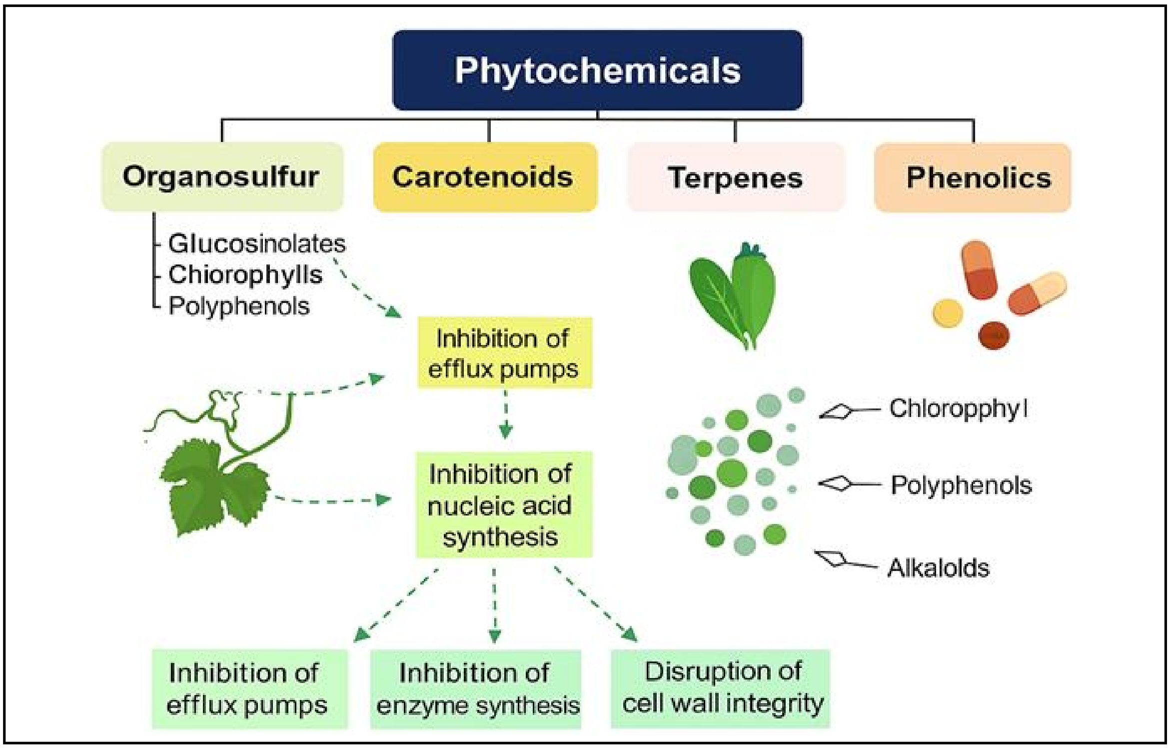

Figure 1: Classification and mechanistic pathways of major phytochemicals in disease suppression and microbial inhibition.

These naturally occurring secondary metabolites act synergistically to defend plants against bacterial, fungal, and viral pathogens through multifaceted biochemical interactions. The major classes of phytochemicals, their biosynthetic origins, and their antimicrobial targets are depicted in Figure 1, highlighting their relevance in sustainable disease management strategies for seed-propagated horticultural crops.

3. Phytomedicinal and pharmacological significance of key phytochemicals

Phytochemicals that play pivotal roles in plant disease management such as thymol, eugenol, carvacrol, allicin, catechins, isothiocyanates and saponins also possess diverse pharmacological activities in mammalian systems. These bioactive compounds exhibit antimicrobial, antioxidant, anti-inflammatory and cytoprotective properties that are mechanistically aligned with their functions in plants. Thymol and carvacrol, the principal monoterpenoids in thyme and oregano oils, disrupt lipid membranes of microbial cells, leading to leakage of intracellular contents; this mechanism explains their broad-spectrum antibacterial and antifungal activity in both plant and human pathogens. Similarly, eugenol from clove and basil demonstrates strong antioxidant and anti-inflammatory potential through modulation of cyclooxygenase and lipoxygenase pathways. Allicin, a sulfur compound from garlic, reacts with thiol groups of vital enzymes, exerting potent bactericidal and antifungal effects.

Catechins and other flavonoids scavenge reactive oxygen species (ROS), stabilize cellular membranes and influence redox signaling pathways, contributing to enhanced host tolerance against oxidative stress.

Recognizing the pharmacological relevance of these compounds not only strengthens understanding of their biochemical efficacy but also promotes safer formulation strategies and regulatory acceptance for agricultural use. Figure 2 illustrates the sequential process through which phytochemical compounds contribute to disease suppression in seed-propagated horticultural crops. The approach begins with the identification of plant sources rich in bioactive metabolites, followed by extraction, formulation, and application to seeds or seedlings. Once applied, these phytochemicals act at cellular and molecular levels to inhibit pathogenic enzymes, disrupt membrane integrity, and induce host resistance. The integration of such eco-sustainable formulations ensures pathogen inhibition and promotes healthier plant growth under field and protected conditions.

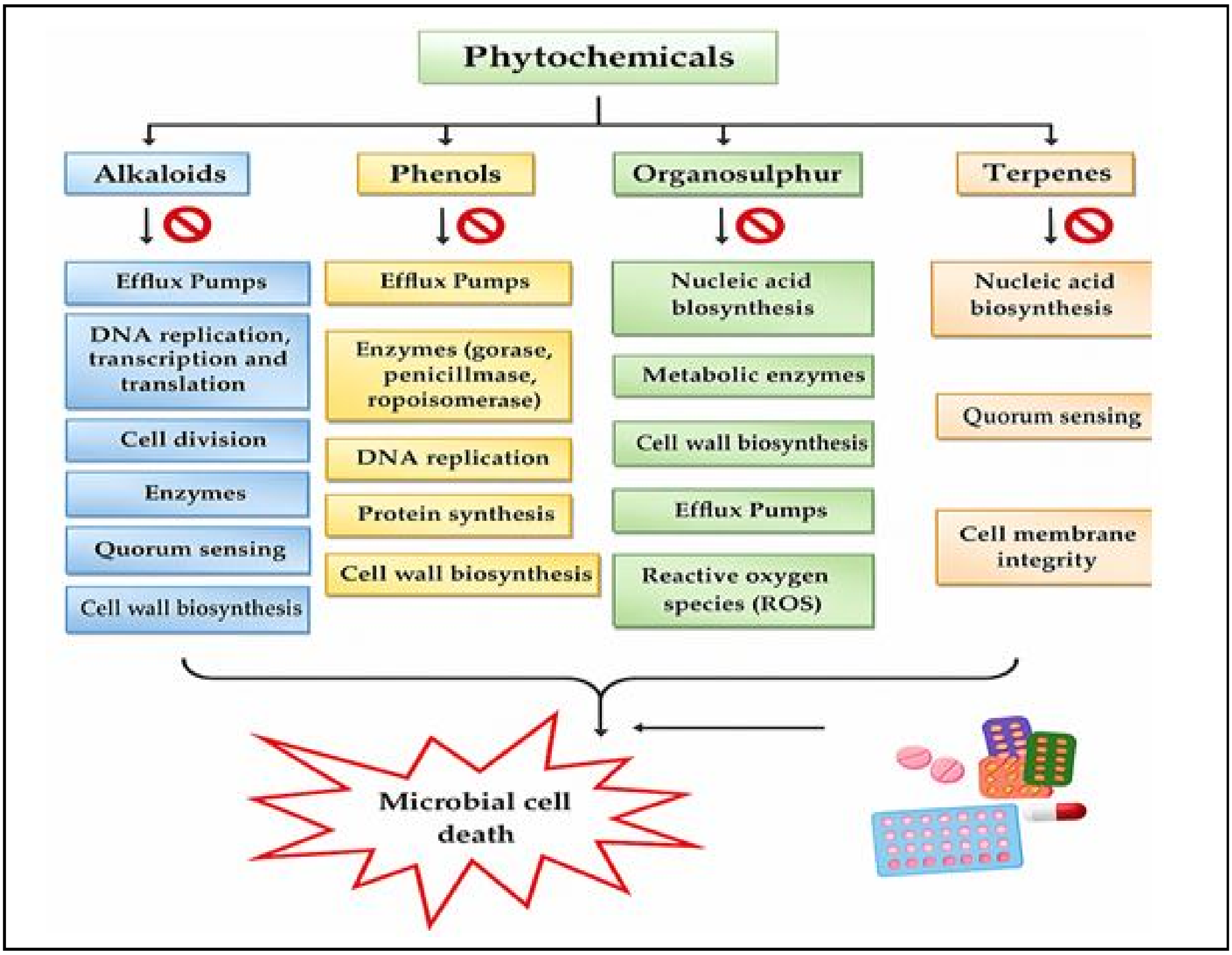

Figure 2: Sequential process of phytochemical-based disease management in seed-propagated horticultural crops.

4. Mechanisms of antimicrobial action

Phytochemicals act through multiple, often complementary mechanisms. A dominant mode of action for many essential-oil components and lipophilic phytochemicals is disruption of microbial membranes, causing increased permeability, leakage of cytoplasmic contents and loss of homeostasis (Chouhan *et al*., 2017;). Other reported mechanisms include inhibition of enzyme systems, interference with respiration, impairment of cell wall synthesis, and inhibition of spore germination or zoospore mobility in oomycetes (Gonelimali *et al*., 2018). Additionally, certain phenolics and flavonoids can act as elicitors, priming host defences and enhancing antioxidant responses in seedlings (Gupta *et al*., 2023). The multiplicity of targets contributes to reduced risk of rapid resistance development compared with single-site synthetic fungicides, although standardization and sublethal dosing must be managed to avoid selection pressures (Gupta *et al*., 2023).

5. Mechanistic parallels between plant pathogen control and pharmacological actions

Many phytochemicals exert comparable biochemical effects in both plant and animal systems, underscoring conserved molecular targets across biological domains. Lipophilic constituents such as thymol, carvacrol and eugenol integrate into microbial membranes, causing depolarization and leakage of ions; this same mechanism underlies their recognized antibacterial activity in pharmacological studies. Phenolic compounds and flavonoids enhance antioxidant enzyme activities in plants while regulating oxidative stress and inflammation in mammalian tissues through Nrf2 and NF-κB signalling pathways.

Isothiocyanates and saponins, known for eliciting systemic acquired resistance in plants, also modulate immune responses in mammals by activating detoxifying enzymes and enhancing macrophage function.

These mechanistic overlaps reinforce the dual relevance of phytochemicals as eco-friendly protectants for crops and as therapeutically valuable compounds in pharmacology.

6. Application approaches at seed and seedling stage

Phytochemicals may be applied to seeds and seedlings through several practical methods adapted from conventional seed-treatment technology:

6.1 Seed soaking and priming

Seeds are soaked in aqueous or solvent-based extracts or EO emulsions for short periods (dips) or for controlled hydration (priming). Such treatments can suppress seedborne pathogens while sometimes improving germination and vigour when concentrations are optimized (Moumni *et al*., 2021).

6.2 Seed coating/pelleting

Phytochemicals (crude extracts, purified compounds or encapsulated EOs) are incorporated into polymeric seed coatings or pellets to provide controlled release and protect the seed during sowing (de Almeida *et al*., 2021).

6.3 Fumigation/vapor exposure

Volatile phytochemicals can be applied as short fumigations in closed systems to reduce surface inoculum or to penetrate porous seed coats (Moumni *et al*., 2021).

6.4 Substrate incorporation

Phytochemical-amended media or potting substrates can protect emerging seedlings from soil-borne pathogens (Arora *et al*., 2022).

Each method requires attention to dose–response and phytotoxicity, since concentrations that are antimicrobial *in vitro* may impair germination or seedling growth if not properly formulated (Terziæ *et al*., 2023).

7. Evidence of efficacy and practical considerations

Numerous laboratory and greenhouse studies report suppression of common seedborne pathogens (*e.g*., *Fusarium*, *Rhizoctonia*, *Alternaria*, *Pythium*) by essential oils and plant extracts (Moumni *et al*., 2021; Ahmed *et al*., 2023; Parikh *et al*., 2021). For example, trials with clove, cinnamon and thyme EOs often show strong *in vitro* inhibition of fungal mycelial growth and reduced disease incidence when applied to seeds or seedlings. However, the literature also highlights important caveats: many studies are limited to controlled conditions, extract composition and activity vary with plant chemotype and extraction method, and formulations that maintain efficacy without phytotoxicity or adverse non-target effects are still under development (de Almeida *et al*., 2021; Terziæ *et al*., 2023).

Formulation advances (microencapsulation, nano-carriers) and integration with beneficial microbes or reduced-dose synthetic protectants are active areas of research aimed at improving stability, controlling release rates and preserving beneficial seed microbiota (Hosseini-Moghaddam *et al*., 2024; Arora *et al*., 2022).

8. Synthesis: role in integrated disease management

Given their multi-target activity and biodegradability, phytochemical seed treatments are promising components of integrated disease-management strategies for horticultural crops especially where residue-free production is desired. However, for reliable adoption they must be standardized, supported by dose-response data across crops and seed lots, and validated in larger field or nursery trials that assess efficacy, seed quality and non-target effects (Moumni *et al*., 2023; Rahim *et al*., 2023).

9. Application of phytochemicals in seed-propagated horticultural crops

Phytochemical application at the seed stage represents an eco-friendly strategy for managing seed-borne and early seedling diseases in horticultural crops. Because seeds often act as carriers of pathogens, their treatment with plant-derived compounds can protect both seed and emerging seedlings (Spadaro *et al*., 2017; Moumni *et al*., 2021). Several methods including soaking, coating, and fumigation have been evaluated to enhance seed health and germination performance.

10. Methods of application

10. 1 Seed soaking or priming

It involves immersing seeds in aqueous or ethanolic phytochemical solutions before sowing. For instance, treating squash (*Cucurbita maxima*) seeds with essential oils of *Cymbopogon citratus* and *Origanum majorana* significantly reduced fungal incidence while maintaining germination rates (Moumni *et al*., 2021). Similarly, priming wheat seeds with essential oils improved germination and reduced pathogen load under semi-arid conditions (Oðuz *et al*., 2023).

10.2 Seed coating

It enables controlled release of phytochemicals on the seed surface. Coatings containing botanical extracts or essential-oil microcapsules protect against early infections while maintaining seed quality (Moumni *et al*., 2023). Such delivery systems are increasingly explored in both vegetable and ornamental crops as eco-friendly alternatives to synthetic fungicidal dressings (de Almeida *et al*., 2021).

10.3 Fumigation or vapor exposure

This along with volatile phytochemicals such as thymol, eugenol, and citral also reduces surface contamination. In cereals and vegetables, vapour exposure has been reported to suppress *Aspergillus* and *Fusarium* spp. infections (Mishra *et al*., 2003).

10.4 Substrate amendment

When it is used with plant extracts in seedbeds, can further suppress soil-borne pathogens. Organic seed-treatment trials in vegetable nurseries demonstrated the potential of phytochemical amendments as components of integrated seed-health management (Spadaro *et al*., 2017).

11. Evidence of efficacy

Numerous studies have validated the biological effectiveness of phytochemical treatments in seed-propagated horticultural crops. Moumni *et al*. (2021) reported that essential oils applied at 0.5 mg ml^{-1} reduced seedborne fungi by up to 84 % in squash. de Almeida *et al*. (2021), summarized evidence showing plant extracts and natural compounds as viable substitutes for chemical fungicides in vegetable seed protection. Similar conclusions were drawn by Parikh *et al.* (2021), who documented broad antifungal spectra of essential oils against major phytopathogens. Advanced seed-treatment technologies, including encapsulated or biopolymer-based coatings, have been shown to maintain viability while delivering botanical actives efficiently (Paulikienë *et al*., 2025). These innovations illustrate how phytochemical seed treatments can complement integrated disease-management systems across horticultural crops.

12. Formulation and compatibility considerations

The efficacy of phytochemical seed treatments depends on dose, formulation, and crop specificity. Excessive concentrations may induce phytotoxicity or reduce radicle elongation (Moumni *et al*., 2021). Variations in chemical composition between plant chemotypes or extraction methods can alter biological activity, highlighting the need for chemical standardization and quality control (Rahim *et al*., 2023). Compatibility with seed physiology and processing machinery is another consideration - coatings should not affect seed flowability or mechanical performance during sowing (Paulikienë *et al*., 2025). Finally, phytochemical use should be integrated with cultural and biological strategies rather than serve as a stand-alone approach (de Almeida *et al*., 2021). The use of phytochemical-based seed treatments has been widely investigated across various horticultural crops to manage seedborne and soilborne pathogens. Numerous studies have demonstrated the antifungal and growth-promoting potential of essential oils and plant extracts when applied through seed soaking, priming, or coating (Moumni *et al*., 2021; de Almeida *et al*., 2021). Representative examples are summarized in Table 1, highlighting crop-specific phytochemicals, target pathogens, and major outcomes under experimental conditions.

13. Advantages and limitations of phytochemical approaches

Phytochemical based disease management strategies offer multiple advantages compared to synthetic fungicides. They are biodegradable, eco-friendly, and often exhibit broad-spectrum activity against seedborne and soilborne pathogens (Singh *et al*., 2025). Unlike synthetic chemicals, most plant-derived compounds possess complex molecular structures, reducing the likelihood of pathogen resistance development. Furthermore, their application in seed treatments and priming enhances seed vigour and induces systemic resistance, contributing to sustainable crop protection under integrated pest management (IPM) frameworks. Many phytochemicals such as neem, clove, lemongrass, and garlic extracts have shown dual benefits suppressing pathogens while promoting early seedling growth and metabolic activity (de Almeida *et al*., 2021).

However, despite these promising attributes, the practical use of phytochemicals faces significant limitations. Variability in the concentration and stability of active ingredients due to plant source, harvest stage, and extraction methods often leads to inconsistent efficacy. Phytochemicals are also susceptible to degradation under high temperature, light, or storage conditions, which limits their shelf life and commercial viability (Oðuz *et al*., 2023). Moreover, standardization in formulation, dosage, and mode of application remains inadequate, creating difficulties in field adoption and registration as biopesticides (Jena *et al*., 2025). In some cases, phytochemicals may exert phytotoxic effects at higher concentrations, affecting germination or seedling vigour (Moumni *et al*., 2021).

Thus, while phytochemicals represent a valuable and sustainable alternative for disease management in seed-propagated horticultural crops, their large-scale adoption requires further refinement in formulation technology, field validation, and regulatory approval pathways. Integrating these natural compounds with microbial biocontrol agents or nano-carrier systems may enhance efficacy and stability in future seed health management strategies (Jena *et al.*, 2025). While phytochemicals are generally considered safer than synthetic pesticides, their toxicological evaluation is essential for sustainable use. Many essential oils and phenolic compounds display low acute mammalian toxicity and rapid biodegradability, yet concentration-dependent irritant or cytotoxic effects have been reported.

For instance, high levels of eugenol or thymol may cause dermal sensitization, while certain isothiocyanates can irritate mucosal tissues. Nano-formulated phytochemicals further necessitate biocompatibility assessments, as encapsulation alters absorption, persistence and toxicokinetic. Regulatory authorities such as the European Food Safety Authority (EFSA) and the World Health Organization (WHO) recommend standardized residue, ecotoxicity and worker-exposure testing for botanical pesticides. Comprehensive risk assessment should therefore include human exposure pathways (operators, consumers), non-target organisms (beneficial soil microbes, pollinators) and environmental fate. Integration of pharmacological safety data into agricultural risk models can guide formulation optimization and ensure compliance with international safety standards.

14. Recent advances and future perspectives

Recent advancements in analytical chemistry, formulation science, and molecular biology have significantly enhanced the application potential of phytochemicals in horticultural disease management. Modern extraction techniques, including supercritical fluid extraction and microwave-assisted extraction, allow the recovery of bioactive compounds with higher purity and stability, minimizing solvent residues and environmental impact. In addition, nano formulations such as nano emulsions, nano capsules, and polymeric nanoparticles have emerged as innovative delivery systems for phytochemicals, improving their solubility, controlled release, and photostability (Maharana *et al.*, 2025; Jena *et al.*, 2025). These nano-enabled carriers facilitate uniform seed coating and longer residual activity, addressing one of the major limitations of conventional phytochemical applications.

15. Nanodelivery: Parallels between agricultural and pharmacological systems

Recent innovations in nanotechnology bridge the gap between agricultural and pharmacological applications of phytochemicals. Encapsulation techniques like polymeric nanoparticles, nano emulsions, liposomes, and biopolymer matrices enhance stability, solubility and controlled release of volatile or labile compounds such as allicin and eugenol.

Table 1: **Selected phytochemical treatments for disease management in seed-propagated horticultural crops and their key active compounds**

Source/extract	Target crop/ pathogen	Application method	Observed effect on disease management	Major active component/ compound	References
Clove oil (*Syzygium aromaticum*)	Tomato-*Fusarium oxysporum* f.sp. *lycopersici*	Seed treatment (EO 0.05-0.1%)	Inhibited mycelial growth and spore germination; enhanced seed vigor	Eugenol	Sharma *et al.*, 2018
Thyme oil (*Thymus vulgaris)*	Cucumber-*Pythium aphanidermatum*	Seed coating (nanoemulsion)	Controlled damping-off and improved germination rate	Thymol, Carvacrol	Attia *et al.*, 2024
Garlic extract (*Allium sativum*)	Lettuce-*Rhizoctonia solani*	Aqueous extract dip (2-5%)	Suppressed root-rot incidence	Allicin	Ankri, and Mirelman, 1999
Neem seed-kernel extract (*Azadirachta indica*)	Chilli-*Alternaria solani*	Seed priming (1%)	Reduced early-blight severity	Azadirachtin, Nimbin	Sushma *et al.*, 2024
Green-tea polyphenols (*Camellia sinensis*)	Capsicum-*Colletotrichum capsici*	Seed soak/foliar spray	Delayed lesion development; enhanced antioxidant enzymes	Catechins (EGCG)	Yang, and Zhang, 2019
Mustard seed extract (*Brassica juncea*)	Spinach-soil-borne fungi complex	Soil amendment	Acted as natural biofumigant reducing pathogen inoculum	Isothiocyanates (Allyl-, Benzyl-)	Pavana *et al.*, 2025
Licorice root extract (*Glycyrrhiza glabra*)	Tomato-*Sclerotinia sclerotiorum*	Seed dip (0.5%)	Inhibited sclerotia [germination and mycelial growth	Saponins (Glycyrrhizin)	Yadav *et al.*, 2011
Cinnamon oil (*Cinnamomum zeylanicum*)	Okra-*Macrophomina phaseolina*	Seed coating (EO 0.05%)	Reduced seed-borne infection and improved seedling vigor	Cinnamaldehyde	Khaledi *et al.*, 2015

Note: EO = Essential oil; EGCG = Epigallocatechin gallate

The same design principles underpin drug-delivery systems aimed at improving bioavailability and minimizing systemic toxicity. In agricultural use, nano-carriers enable gradual diffusion of active molecules around seed surfaces or rhizospheres, maintaining effective antimicrobial concentrations while reducing phytotoxicity. These parallels highlight opportunities to adapt well-characterized biomedical carriers for field applications, ensuring efficient and environmentally benign disease management.These studies indicate that phytochemicals not only suppress pathogens but also prime plant defense systems, enhancing antioxidant activity and stress tolerance (Jena *et al.*, 2025). The integration of phytochemicals with microbial biocontrol agents, such as *Trichoderma* spp. and *Pseudomonas fluorescens*, has shown synergistic effects in reducing seedborne infection while improving plant vigour and yield (Deresa *et al.*, 2023). Future research on phytochemical-based disease management should adopt a multidisciplinary approach linking plant pathology, pharmacology and nanotechnology.

1. **Dual purpose formulations:** Develop bioformulations that safeguard crops and possess ancillary therapeutic or antioxidant benefits for humans and livestock.
2. **Safety standardization:** Incorporate pharmacological toxicology and regulatory frameworks (LD_{50}, NOAEL, biocompatibility indices) into agricultural risk evaluation.
3. **Valorization of agro-waste:** Extract phytochemicals from crop residues for sustainable and circular bioeconomy models.

4. **Molecular modeling and *in silico* prediction:** Employ docking and QSAR studies to identify target interactions across plant and animal systems, improving efficacy prediction.

5. **Interdisciplinary collaboration:** Strengthen networks among plant scientists, pharmacologists and formulation chemists to design integrated bio-protection products

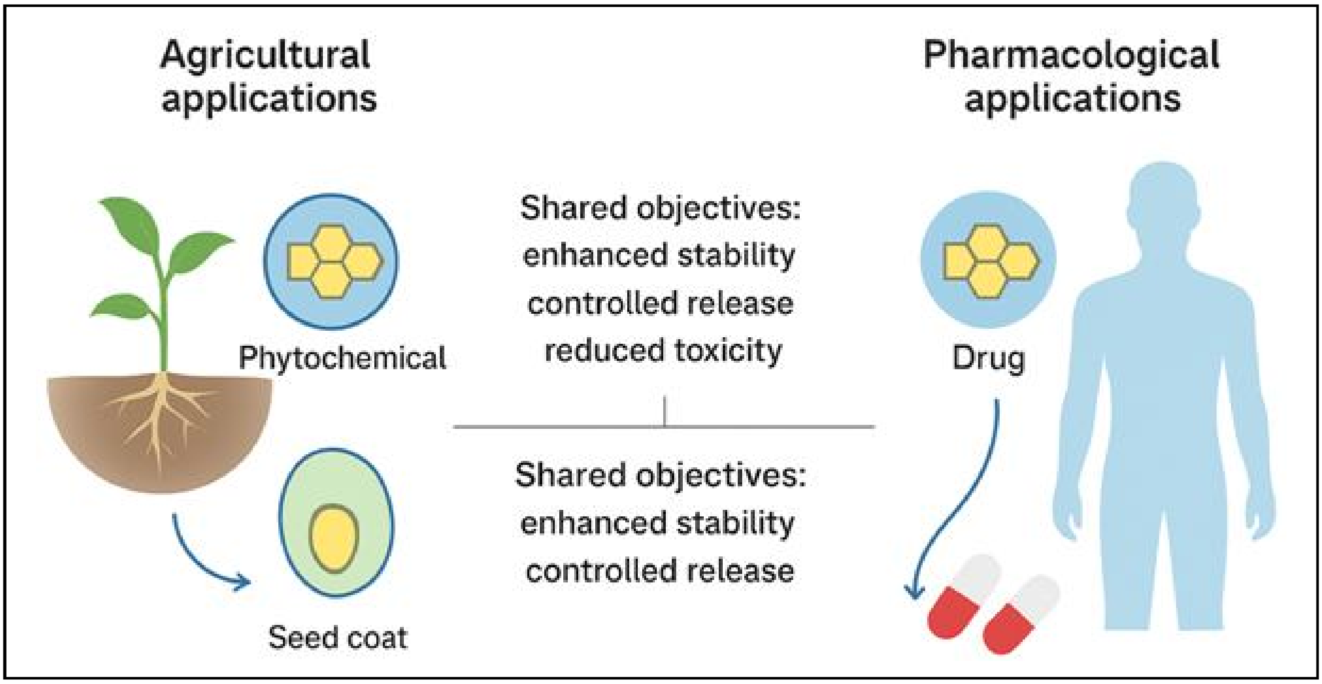

Figure 3: Conceptual representation of the integration of phytochemical-based formulations with nanotechnology and biocontrol systems for sustainable seed and seedling disease management in horticultural crops.

Overall, future efforts should align phytochemical research with human health, regulatory safety and sustainable production systems, fostering the transition toward integrated Phyto-based disease management technologies. The integration of phytochemical formulations with advanced delivery systems and microbial biocontrol agents represents a holistic approach to seed health management. These interactions are summarized in Figure 3, which illustrates the linkages between phytochemical sources, technological innovations, and synergistic strategies leading to improved seed germination, pathogen suppression, and sustainable horticultural productivity.

16. Conclusion

Phytochemical based disease management strategies hold immense promise for promoting sustainable production in seed-propagated horticultural crops. These naturally derived compounds not only suppress seedborne and soilborne pathogens but also enhance seed vigour and plant defence responses. With the advent of nanotechnology and green formulation techniques, the stability, efficacy, and delivery of phytochemicals can be significantly improved. However, challenges related to standardisation, formulation optimisation, and field validation remain critical barriers to large-scale adoption. Future research should focus on integrating phytochemical treatments with microbial biocontrol agents and precision application methods to achieve reliable, eco-friendly seed health management systems. Such integrative approaches will advance sustainable horticulture and contribute to safer, residue-free crop production.

Conflict of interest

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

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