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Review Article

Agroecological alternatives for disease management in *Capsicum* crops

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ABSTRACT

Justification. *Capsicum* spp. fruits are widely recognized and marketed worldwide due to their relevance in gastronomy and the pharmaceutical industry. The five most important species are *C. annuum, C. baccatum, C. chinense, C. frutescens* and *C. pubescens*; however, more than 43 wild species have been reported to date. Pepper plants and fruits are susceptible to diseases caused by phyopathogenic bacteria and fungi which are routinely controlled with synthetic products. These compounds generate serious side effects for both the environment and human health. Similarly, their use promotes increased microbial resistance and more severe diseases in crops. For this reason, the present review addresses the main diseases affecting pepper crops as well agroecological alternatives for controlling using antagonistic microorganisms and plant-based bioproducts to reduce the incidence and severity of diseases.

Theoretical and Experimental framework. An updated literature review was conduced regarding the diseases affecting different *Capsicum* species, as well as the agroecological alternatives available for their management.

Conclusions and Perspectives. Pepper production faces challenges due to diseases and the excessive use of agrochemicals which promote microbial resistance and environmental damage. Antagonistic microorganisms, plant extracts and essential oils offer a viable agroecological alternative to control phytopathogens without negative impacts. Although these strategies provide medium- and long-term benefits further research is required to control viral diseases and achieve sustainable production.

Keywords: Essential oils, Natural extracts, Antagonism, Microorganism

INTRODUCTION

All chili plants belong to the genus *Capsicum*, within the Solanaceae family. Around 43 native species have been recorded in tropical regions of the Americas. The domesticated species with economic importance include *C. annuum*, *C. baccatum*, *C. chinense*, *C. frutescens*, and *C. pubescens* (Ali *et al.*, 2016; Banya *et al.*, 2020). The fruits of *Capsicum* spp. are consumed worldwide for their nutritional and nutraceutical value (Kulkarni *et al.*, 2017; Coyotl-Pérez *et al.*, 2025).

Global *Capsicum* production is approximately 25.7 million tons, with an annual growth rate of 3.2% due to its use as a spice in gastronomy and the food industry, as well as the active compound capsaicin in the pharmaceutical industry (Kulkarni *et al.*, 2017). The leading producers are China, accounting for 50% of global production, followed by Mexico (9%), Turkey (7%), Indonesia (7%), and Spain (3.5%) (Shisia, 2017). However, production of this crop is affected by various diseases, resulting in yield losses ranging from 10% to 50%, depending on the disease. The main problems are of fungal, bacterial, viral, nematological, and physiological origin (Shahid *et al.*, 2017; Anjum *et al.*, 2020; Pérez-Vásquez *et al.*, 2022).

In recent years, synthetic pesticides such as triazoles, strobilurins, phenylamides, pyrethroids, and others have been used to control plant diseases (Esyanti *et al.*, 2020). However, the excessive and prolonged use of these products has caused environmental problems, including contamination of soil, groundwater, and air (Khatun *et al.*, 2023). This, in turn, negatively affects beneficial organisms such as insects and soil microorganisms, disrupting agroecosystems and harming the health of a wide range of animals, including humans. Alarmingly, increased resistance of disease-causing agents to these synthetic products has also been observed. Given this problem, there is a need for improved, environmentally friendly products and strategies to regulate these diseases. In the search for effective, sustainable, and safer alternatives for humans and the environment, essential and volatile oils are considered a potential source of plant protection products (Abdelhamaid *et al.*, 2020; Chacón *et al.*, 2021).

General aspects of the genus *Capsicum*

Capsicum belongs to the Solanaceae family and includes chili varieties distinguished by their size, shape, color, and pungency (Pérez-Castañeda *et al.*, 2015). This genus is characterized by having alternate leaves, either entire or divided. Floral leaves or bracts are often joined to the floral axis, which favors the paired arrangement of leaves and the extra-axillary position of flowers and inflorescences. The reproductive structures are hermaphroditic and regular, consisting of five sepals, five petals, and five stamens. The fruit is a fleshy, hollow berry shaped like a capsule, containing seeds located in the locules.

Main commercial species of the genus *Capsicum*

C. annuum, C. chinense, C. pubescens, C. frutescens and *C. baccatum* are the five most important commercial species worldwide (Figure 1). However, the biodiversity of this genus extends to 43 species reported in tropical regions of the Americas (Coyotl-Pérez *et al.*, 2025).

Chili fruit production generates significant economic revenue worldwide. In 2022, China allocated 759,817 ha to produce 16,837,404.78 t, yielding profits of approximately 3.16 billion USD. In Mexico, 156,718 ha were used to produce 3,113,244.27 t, generating around 1.047 billion USD. Turkey cultivated 76,398 ha and produced 3,018,775 t, with profits of 161 million USD. India produced 74,292.01 tons 8,714 ha, earning about 1.2 billion USD. In Spain, 22,260 ha were allocated to production, reaching 1,533,280 t and generating approximately 170 million USD (Odepa, 2024).

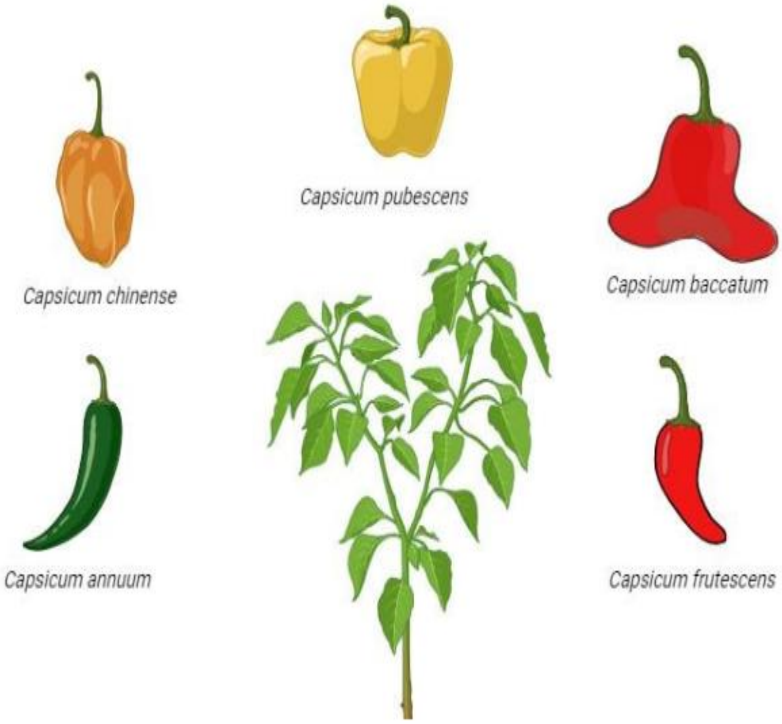

Figure 1. Fruit phenotypes of domesticated *Capsicum* species.

Phytosanitary problems in the commercial species of the genus *Capsicum*

Phytosanitary problems can be caused by diseases associated with microorganisms or viruses, as well as insect pests. These issues can affect both yield and fruit quality, as well as the plant's lifespan. It is estimated that 40% of the diseases affecting chili plants are of fungal origin, followed by bacterial, viral, and nematode diseases (Landa, 2012; Kulkarni *et al.*, 2017). Chili crops require high water input and relative humidity, the latter being a favorable factor for the growth of phytopathogenic fungi. Research indicates that the main pathogens associated with chili crops are *Fusarium*, *Pythium*, and *Botrytis* (Schroeder *et al.*, 2015; Romero-Arenas *et al.*, 2022; Wang *et al.*, 2022). However, other pathogenic microorganisms with high incidence include *Phytophthora capsici*, *Xanthomonas campestris*, *Alternaria* spp., *Verticillium* spp., *Rhizoctonia* spp., *Leveillula taurica*, *Ralstonia solanacearum*, *Erwinia carotovora*, among others (Klosterman *et al.*, 2009; Pérez-Acevedo *et al.*, 2017; Esyanti *et al.*, 2020; Canseco, 2023).

In addition, several viruses have been reported that infect leaves, stems, and fruits, such as *Tobamovirus tabaci* (Tobacco mosaic virus–TMV), *Tombusvirus lycopersici* (Tomato bushy stunt virus–TBSV), *Potyvirus capsimaculae* (Pepper mottle virus–PepMoV), *Potyvirus potato virus Y* (Potato virus Y–PVY), *Begomovirus capsicumhuastecoense* (Pepper huasteco yellow vein virus–PHYVV), and *Begomovirus capsicummusivi* (Pepper golden mosaic virus–PepGMV) (Rentería-Canett *et al.*, 2011; Landa, 2012; Velásquez-Valle *et al.*, 2013; González-Franco *et al.*, 2014).

Fungal diseases in *Capsicum* spp.

***Fusarium* spp.** Some species of this genus are considered saprophytic fungi, as they reduce chili crop yields (Mejía-Bautista *et al.*, 2016). These microorganisms cause diseases such as soft rot and wilt or blight. These pathologies are associated with symptoms including rot of primary and secondary roots, leaf spots, chlorosis, defoliation, vascular wilt, stem and root necrosis, and reduced fruit yield (Villanueva-Arce *et al.*, 2013; Mejía-Bautista *et al.*, 2016; Verma *et al.*, 2020). Fruit rot is characterized by lesions that progress rapidly until the fruit collapses with a foul odor (Figure 2A) (Pérez-Vázquez *et al.*, 2022; Romero-Arenas *et al.*, 2022). This disease mostly affects ripe fruits that are present in areas with high humidity, warm temperatures, and with mechanical wounds or insect damage (Chacón *et al.*, 2021; Coyotl-Pérez *et al.*, 2024).

***Pythium* spp.** Species of this genus of oomycetes (false fungi) inhabit water and soil and are known as pathogens affecting crops of high economic value such as eggplant (*Solanum melongena*), mustard (*Sinapis alba*), papaya (*Carica papaya*), tobacco (*Nicotiana tabacum*), chili (*Capsicum annuum*), among others (Verma *et al.*, 2020). *Pythium* spp. cause loss of vigor in chili seedlings and roots. Symptoms include seed, root, and fruit rot, loss of leaf turgor, and chlorotic shoot tips (Figure 2B); infected plants also show stunted growth leading to foliar wilt (Schroeder *et al.*, 2006). The species *P. ultimum* and *P. aphanidermatum* have high incidence and cause problems in both open-field and greenhouse crops. As a result, they increase the rate of fruit softening or rot (Verma *et al.*, 2020).

***Botrytis* spp.** The main symptom caused by this genus is gray rot. This disease is difficult to eradicate, with *Botrytis cinerea* being the primary species responsible for severe postharvest losses in chili fruits (Figure 2C). Symptoms include small spots on leaves and flowers that develop into brown necrotic lesions, which may eventually cover the entire leaf and cause wilting. In addition, the stem may show elongated, sunken necrotic lesions that are brown to black in color (Wang *et al.*, 2022).

***Alternaria* spp.** These fungi cause small concentric leaf spots ranging from green to dark brown. Symptoms on stems appear as sunken, elongated, dark lesions that lead to wilting or dieback. On fruits, they cause lesions with dark mold sporulation that develop into sunken, concentric necrotic spots (Figure 2F) (Canseco, 2023). In addition, these fungi can damage seeds, reducing their viability, and induce severe defoliation that leaves fruits exposed to UV radiation. This, in turn, significantly reduces the quality and yield of chili fruits (Cambiagro, 2021; Canseco, 2023).

***Phytophthora* spp.** The genus *Phytophthora* is classified as an oomycete that causes wilt and death in chili plants, with *P. capsici* being the main species involved (Esyanti *et al.*, 2020). This pathogen causes seed rot, leaf blight, and wilting, mainly in young seedlings, as they are more susceptible (Verma *et al.*, 2020). During the growth stage, seedlings may show root and stem rot, general wilting, stunting, and canker formation. In mature plants, infection by this pathogen primarily results in root, stem, and fruit rot, as well as wilting (Figure 2D) (Esyanti *et al.*, 2020; Quispe-Quispe *et al.*, 2022).

***Rhizoctonia* spp.** *Rhizoctonia* is composed of a group of adelomycete fungi, classified as imperfect fungi because they lack reproductive structures such as spores. They reproduce through fragmentation of mycelium and sclerotia (Vaishnav and Meena, 2014). These microorganisms cause stem blight and root rot, leading to necrosis (Figure 2H) (Pérez-Acevedo *et al.*, 2017). A study indicates that *Rhizoctonia solani* shows greater aggressiveness in *C. annuum* due to its higher affinity and faster infection rate. Based on this, the competitive ability of these fungi in open-field crop soils allows for greater survival and dissemination of this microorganism compared with others such as *Pythium* or *Phytophthora* (Verma *et al.*, 2020).

***Verticillium* spp.** This group of fungi promotes plant wilting, with the infection process beginning in the lower leaves due to factors such as excess water, high temperatures, and others. The leaves develop a pale-green coloration that progresses to necrosis surrounded by an orange-yellow halo (Figure 2G). In addition, complete plant loss occurs as a result of root rot (Klosterman *et al.*, 2009).

Leveillula taurica. This microorganism belongs to the Ascomycetes and causes powdery mildew, producing chlorotic spots on the leaves (Figure 2I). This disease symptom is associated with powdery mildew that begins on the abaxial side of the leaf as a white to grayish powder, gradually weakening the leaf until defoliation occurs under relative humidity below 40% (Field, 2020).

***Colletotrichum* spp.** This genus of filamentous fungi is highly aggressive in agriculture and primarily affects fruits, causing postharvest losses ranging from 10% to 80% (Ali *et al.*, 2016; Banya *et al.*, 2020). The disease caused by these fungi is known as anthracnose, which is favored by high humidity in ripe chili fruits (Sonawane and Shinde, 2021). The main species associated with chili crops are *C. coccodes*, *C. dementium* (leaves), *C. gloeosporioides*, *C. capsici*, *C. acutatum* (fruit), and *C. truncatum* (ripe fruits) (Than *et al.*, 2008; Ali *et al.*, 2016; Sonawane and Shinde, 2021). Infected fruits develop dark red sunken lesions with concentric rings containing spore clusters (Banya *et al.*, 2020). Another characteristic is the presence of brown, black, or even salmon-colored spots where pathogen signs can be observed (Ali *et al.*, 2016). However, symptoms vary depending on the *Colletotrichum* species present.

Bacterial diseases in *Capsicum* spp.

Xanthomonas campestris. Infection caused by *X. campestris* appears as necrotic spots surrounded by chlorotic halos. Another characteristic symptom of this bacterium is severe defoliation of chili plants. Lesions are highly prevalent on leaves and fruits, including the peduncle and calyx, and are influenced by environmental factors such as high relative humidity (>80%), high temperatures, or water stress (Figure 2E) (López-Vielma *et al.*, 2016; Fasio *et al.*, 2001).

Ralstonia solanacearum. Chili plants infected by *R. solanacearum* show a marked reduction in growth. In addition, the leaves develop chlorosis and wilt, while interveinal chlorosis and foliar epinasty occur in the stems (DGS, 2013). This bacterium is present in the soil, from where it enters through the roots and colonizes the plant's vascular system, producing an internal abscess that blocks the transport of water and nutrients. This physiological disruption induces rapid wilting (Figure 2J) (Conesa, 2020).

Erwinia carotovora. This bacterium is known to cause soft rot in various chili species, primarily affecting fruits, stems, and roots (Figure 2K) (Kunstmann *et al.*, 2006). The disease appears as watery, soft, foul-smelling spots, especially in previously damaged tissues. Its development is favored by warm temperatures between 28 and 35 °C, high relative humidity above 85%, and excess water conditions such as heavy rainfall or over-irrigation (López-Pérez and Sáenz, 2018).

Viral diseases in *Capsicum* spp.

***Tobamovirus tabaco* (TMV).** Tobacco mosaic virus belongs to the genus *Tobamovirus* and can cause yield losses of up to 70% in chili plants (Velásquez-Valle *et al.*, 2013). It is also the most prevalent, as it is transmitted through mechanical damage caused by handling seedlings during growth (Figure 2L) (González-Franco *et al.*, 2014). Contamination of chili seeds with TMV can occur endogenously or exogenously. Exogenously contaminated seeds can result in up to 64% of seedlings carrying the virus, while endogenous contamination affects only about 15% (Velásquez-Valle *et al.*, 2013). In addition, chili seedlings may become infected through the presence of vectors such as the grasshopper (*Sphenarium purpurascens*) or the leaf miner (*Liriomyza trifolii*), and transmission can also occur through the roots in hydroponic systems.

***Tombusvirus lycopersici* (TBSV).** Tomato bushy stunt virus has high incidence in chili crops in northern Mexico. It infects chili and other solanaceous plants, causing stunting, excessive branching, chlorosis, and reduced fruit size (CABI, 2024). This virus is transmitted through seeds or via mechanical damage caused by infection with *Olpidium* spp. (González-Franco *et al.*, 2014).

***Potyvirus capsimaculae* (PepMoV).** Pepper mottle virus is transmitted by aphids such as *Myzus persicae* or *Aphis gossypii*, which feed on the phloem of chili plants (Velásquez-Valle *et al.*, 2013). In the first stage of infection, symptoms include systemic necrosis, apical fruit dieback, severe stunting, and small, deformed leaflets. In the second stage, along with systemic chlorosis, chili fruits develop blisters and malformations (Bayer, 2025).

***Potato virus Y* (PVY).** Potato virus "Y" is a *Potyvirus* present in chili crops in Puebla, Coahuila, Estado de México, and Nuevo León. This virus is transmitted through previously infected seeds and by aphids such as *Myzus persicae*, *Aphis gossypii*, and *Macrosiphum euphorbiae* (González-Franco *et al.*, 2014). It is considered one of the most aggressive viruses, as it causes necrosis of veins, petioles, and stems, leading to plant defoliation. Other problems resulting from infection include stunted plants, flower abortion, and the production of small or deformed fruits (Velásquez-Valle *et al.*, 2013).

***Begomovirus capsicumhuastecoense* (PHYVV).** Pepper huasteco yellow vein virus belongs to the *Begomovirus* group. The whitefly (*Bemisia tabaci*) is a vector that simultaneously transmits PHYVV and PepGMV. Chili plants infected with this virus show mosaic-like chlorosis on the leaves, yellow-colored veins, deformed and yellowing foliage, and reduced fruit production (Velásquez-Valle *et al.*, 2013).

***Begomovirus capsicummusivi* (PepGMV).** Pepper golden mosaic virus has been reported in *C. annuum* var. *glabriusculum*, *C. pubescens*, and *C. chinense* (Landa, 2012). It can cause production losses of up to 43% in these species. The foliar mosaic it induces may appear as dull yellow or golden, accompanied by leaf wrinkling, deformation, and interveinal chlorosis, depending on the cultivar. PepGMV also intensifies infections by other viruses, leading to severe problems such as early senescence. Infected plants often develop distorted and yellowing leaves within 14 days, caused by severe co-infection with PHYVV (Rentería-Canett *et al.*, 2011; Velásquez-Valle *et al.*, 2013).

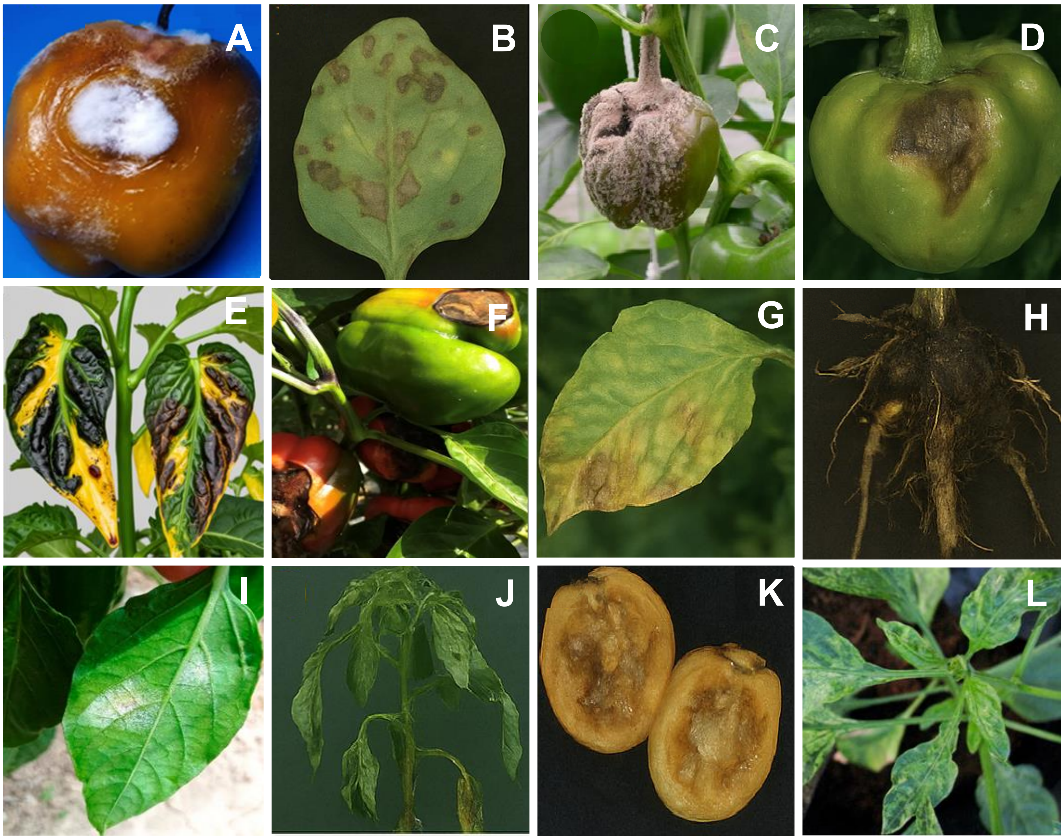

Figure 2. Symptoms of diseases caused by A) *Fusarium*, B) *Pythium,* C) *Botrytis*, D) *Phytophtora*, E) *Xanthomonas*, F) *Alternaria*, G) *Verticillium,* H) *Rhizoctonia*, I) *Leiveillula*, J) *Ralstonia*, K) *Erwinia* and L) TMV in *Capsicum* species.

Strategies for disease management in chili

The control of phytopathogens in the genus *Capsicum* has become a major global challenge (Kim and Lee, 2022). As mentioned earlier, *Capsicum* plants are susceptible to various diseases caused by fungi, bacteria, and viruses. However, certain symptoms can help identify the possible causal agent, which can be further confirmed by observing its reproductive structures (Figure 3); nonetheless, pathogenicity tests are always necessary to verify the causal agent. The main methods for disease management rely on the use of synthetic fungicides, which address a wide range of diseases, are easy to apply, and relatively inexpensive. However, they significantly pollute the environment and pose serious risks to public health, causing acute intoxication, organ damage, and, in extreme cases, an increased risk of cancer (Mejía-Bautista *et al.*, 2016).

The adverse effects of agrochemicals promote the emergence of resistant microbial species that worsen diseases, making it essential to gradually replace them with new agroecological agents (Cruz-Cerino *et al.*, 2020; Shcherban, 2023). In this context, a promising strategy is biocontrol through the use of beneficial organisms or antagonists of phytopathogens. Another method involves the design and formulation of natural chemical fractions capable of inhibiting the growth of human pathogens and phytopathogens. This latter alternative leads to safer foods while protecting the nutritional and nutraceutical quality of a wide range of agricultural products (Abdelhamid and El-Dougdoug, 2020; Pérez-Vázquez *et al.*, 2022). Therefore, essential oils and standardized plant extracts play an important role as natural antimicrobials that help preserve food quality and safety (Kim and Lee, 2022; Pérez-Vázquez *et al.*, 2022; Wang *et al.*, 2022).

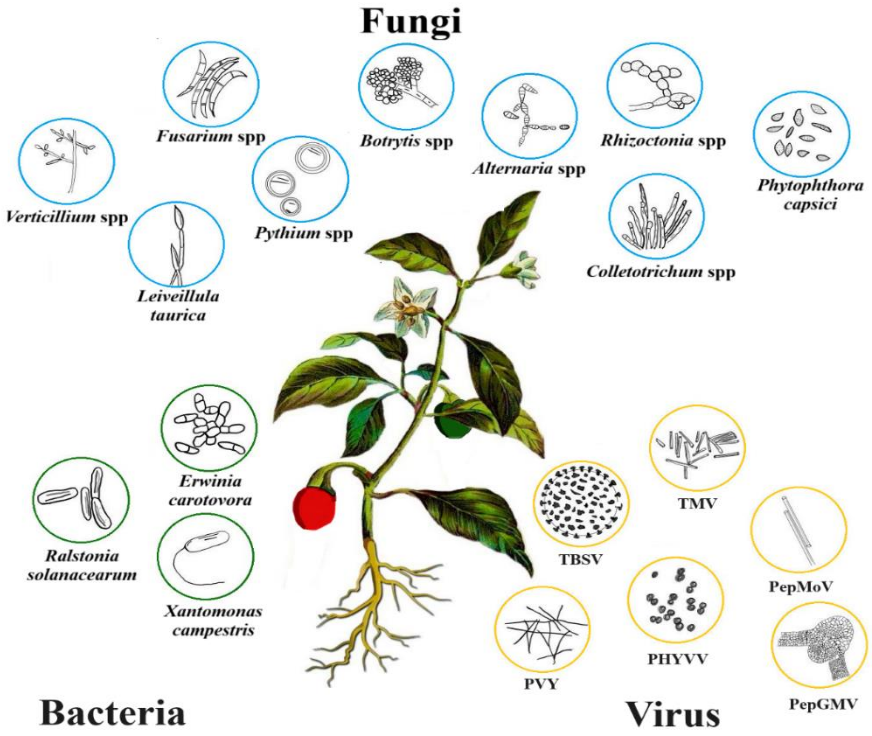

Figure 3. Main pathogens causing diseases in pepper crops.

Antagonism strategies. Antagonistic methods have revolutionized agriculture due to their ease of application and low environmental risk. These methods use microorganisms that control bacteria and fungi in chili plants. Antagonistic microorganisms synthesize secondary metabolites to inhibit the growth of phytopathogens (Mejía *et al.*, 2016). At times, individual antagonistic microorganisms may not have sufficient activity to suppress phytopathogen growth, which has led to the use of synergistic consortia that enhance the range of inhibition.

The main antagonistic microorganisms include *Trichoderma* spp., *Pseudomonas* spp., *Rhizobium* spp., *Bacillus subtilis*, and *B. amyloliquefaciens*. *Bacillus* species directly inhibit phytopathogen growth in plants and stimulate systemic resistance in the host. They can also suppress zoospore germination and fungal germ tube elongation in host tissues. *Bacillus* inhibits phytopathogen growth through several mechanisms, including the production of antimicrobial compounds (oligopeptides and enzymes), competition for nutrients and space, stimulation of plant natural defenses (systemic resistance), production of siderophores that limit iron availability to pathogens, and formation of protective biofilms on roots (Valenzuela-Ruiz *et al.*, 2024).

It has been documented that *Bacillus* spp. are highly effective in reducing leaf blight caused by different phytopathogenic fungi (Quispe-Quispe *et al.*, 2022). Against fungi of the genus *Fusarium*, this group of bacteria produces lipopeptides that alter the hyphal cell wall, inhibiting their growth (Radzhabov and Davranov, 2010; Gond *et al.*, 2015).

In a way, antagonists compete with phytopathogens for nutrients and space (Anjum *et al.*, 2020). These strategies contribute to ecological sustainability; however, as soil conditions, climate, and agricultural practices change, antagonists may lose effectiveness (Jayapala *et al.*, 2019). Although they are excellent inhibitors of phytopathogens, their action is slower compared with agrochemicals. For this reason, farmers often choose conventional agrochemicals, seeking a quick, efficient, and low-cost solution, despite the long-term damage they cause (Abdelhamid and El-Dougdoug, 2020).

In general, biological control strategies remain an excellent natural alternative for managing diseases in chili crops, improving sustainability, and reducing the excessive use of agrochemicals (Liotti *et al.*, 2019; Anjum *et al.*, 2020). However, it is necessary to improve their effectiveness in terms of viability and response time under changing environmental conditions. In this regard, the use of new biodegradable materials represents an area of opportunity that should be explored with particular emphasis.

Application of essential oils. Essential oils are complex mixtures of low-molecular-weight organic compounds that are harmless and possess diverse biological properties (Shahid *et al.*, 2017; Kim and Lee, 2022). These compounds accumulate as a result of secondary metabolite biosynthesis in plants (Pandey *et al.*, 2017). The production of secondary metabolites functions as a plant defense mechanism under stress conditions, such as disease control (Kulkarni *et al.*, 2017; Kim and Lee, 2022; Coyotl-Pérez *et al.*, 2024). This property can be harnessed for biotechnological purposes.

The mechanism of action of essential oils lies in their ability to alter membrane permeability, reducing bacterial viability (Hyldgaard *et al.*, 2012). In fungi, essential oils interfere with conidial germination and affect mycelial growth due to the presence of terpenes, alcohols, phenols, and ketones. In addition, conidiophores have been reported to develop deformities as a result of changes in the electrochemical gradients of Ca^{2+}, K^{+}, and Mg^{2+} (Kadogliou *et al.*, 2011; Pandey *et al.*, 2017). Essential oils also reduce the production of ergosterol, the main sterol in the cell membrane of filamentous fungi. This weakens the lipid bilayers and disrupts osmotic balance, leading to the rupture of cellular organelles (Arora *et al.*, 2024). Another mechanism of action is related to hydroxyl groups present in certain compounds, which can disrupt membrane lipids (Kadogliou *et al.*, 2011). However, the mechanism of action varies depending on the phytochemical composition of the essential oil and the type of microorganism.

The use of essential oils is an agroecological alternative with broad effectiveness against various phytopathogens. Among the most commonly used are thyme (*Thymus vulgaris*), peppermint (*Mentha piperita*), turmeric (*Curcuma longa*), eucalyptus (*Eucalyptus globulus*), cinnamon (*Cinnamomum verum*), and clove (*Syzygium aromaticum*), among others (Table 1) (Ragab *et al.*, 2012; Pérez-Vázquez *et al.*, 2022; Arora *et al.*, 2023; Arora *et al.*, 2024). These oils are composed of diverse volatile compounds such as terpenes, with different relative abundances, and the major compounds are generally responsible for their antimicrobial properties (Ragab *et al.*, 2012). Although they are harmless, essential oils may rarely cause allergic reactions in sensitive individuals (Arora *et al.*, 2023). The application of essential oils is considered a preventive strategy, since once the plant shows severe symptoms, their activity is usually ineffective (Pérez-Vázquez *et al.*, 2022).

Therefore, it is advisable to apply these chemical fractions at the early stages of infection to counteract disease spread. Despite their agroecological advantages, the use of essential oils is costly due to extraction methods such as steam distillation, hydrodistillation, or solvent use. In addition, their low yields and photosensitivity limit large-scale application. For this reason, new biotechnological methods are needed for large-scale production of volatiles, which could potentially be combined with new biodegradable hybrid materials to enhance and extend their biological effectiveness.

Application of natural extracts. Plant-derived extracts naturally possess antimicrobial, antioxidant, antiparasitic, and aromatic properties. For this reason, they are considered promising bioproducts for managing biotic stress factors in crops, including chili (Shafique *et al.*, 2015; Arora *et al.*, 2023). They also provide an agroecological pathway to support sustainable food production (Cruz-Cerino *et al.*, 2020). In agriculture, their use enhances yield and quality of horticultural products, reduces reliance on agrochemicals, improves soil nutrition, and helps preserve environmental integrity (Godlewka *et al.*, 2021).

Table 1. Agroecological strategies to control major pathogens causing diseases in *Capsicum* plants.

	Strategy	Disease	Phytopathogen	***Capsicum* specie**	Location	Reference
ANTAGONIST	*Bacillus* sp.	Anthracnose	*Colletotrichum capsici* UOM-02	*C. annuum* cv.G-4	Seed-Seedling	Jayapala *et al.*, 2019
	Trichoderma koningii *Glomus mosseae*	Wilting	*Fusarium oxysporum*	*C. annuum*	Plant	Oyetunji y Salami, 2011
	Streptomyces griseocarneus R132 (11 cepas)	Anthracnose Wilting	*Colletotrichum gloeosporioides* MPU99 *Fusarium oxysporum* 46.7	*C. annuum* cultivar Ikeda	Fruit	Liotti *et al.*, 2019
	Trichoderma asperellum cepa T34		*Phytophthora capsici*	*C. annuum* cv. *Dulce Italiano*	Plant	Segarra *et al.*, 2013
	Trichoderma harzianum *T. viride* *T. aureiviride* *Bacillus subtilis* *Pseudomonas fluorescens*	Wilting	*Fusarium oxysporum*	*C. annuum*	*In vitro*	Ragab *et al.*, 2012
	T. hamatum	Wilting	*Fusarium oxysporum* f. sp. *capsici*	*Capsicum* variedad LCA334	Root	Anjum *et al.*, 2020
	B. subtilis (EPCO 16 y EPC5) *Pseudomonas fluorescens*		*Fusarium solani*	*C. annum* cv. CO3	Plant	Sundaramoorthy *et al.*, 2012
	Bacillus, *Staphylococcus* sp. *Pseudomonas* sp. *Sphingomonas* sp. *Achromobacter* sp.		*F. oxysporum* f.sp. *pisi* *F. oxysporum* f.sp. *capsici* *F. proliferatum* *F. udum* *R. solani* *C. capsici*	*C. annuum*	Seedling	Passari *et al.*, 2018
	Bacillus sp. LBF-01	Rot	*Fusarium oxysporum*	*C. annuum*	Plant	Chowdhury *et al.*, 2020

	Bacillus subtilis *Saccharomyces cerevisiae*	Anthracnose Rot	*Colletotrichum capsici*	*Capsicum* spp.	Plant	Banya *et al*., 2020
	Bacillus spp.	Anthracnose	*Phytophtora capsici*	*Capsicum*	Plant	Quispe-Quispe *et al*., 2022
NATURAL EXTRACT	*Murraya koenigii* *Glycyrrhiza glabra* *Anethum graveolens* *Polyalthia longifolia* *Melia azedarach* *Cassia fistula* *Thevetia peruviana*	-	*Fusarium oxysporum* *Colletotrichum capsici* *Pythium aphanidermatum*	*C. annuum* cv. *Pusa Jwala*	Seed	Arora *et al*., 2023
	Eucaliptus citriodora	Wilting	*Fusarium oxysporum* f.sp *capsici*	10 variedades: *Golden hot, Revival, Hot chili, Saim hot, Sky red, P6, Neelam, Sitara, Anchal, Kundri*	Plant	Shafique *et al*., 2015
	Mosannona depressa, *Parathesis cubana*, *Piper neesianum*	Wilting	*Fusarium equiseti* strain FCHE *Fusarium oxysporum* strain FCHJ	*C. chinense*	*In vitro*	Cruz-Cerino *et al*., 2020
	Azadirachta indica *Swietenia mahagoni* *Allium sativum*	Anthracnose	*Colletotrichum capsici*	*C. annuum*	Plant	Rashid *et al*., 2015
	Abrus precatorius	Fruit rot	*Colletotrichum capsici*	*C. annuum* cv. K2	Plant and fruit	Ali *et al*., 2016
ESSENTIAL OIL	*Anethum graveolens* *Thymus vulgaris* *Curcuma longa* *Eucalyptus globulus*	Wilting, Anthracnose	*Fusarium oxysporum* *Colletotrichum capsici* *Pythium aphanidermatum*	*C. annuum* cv. *Pusa Jwala*	Seed Leave Rot Flower	Arora *et al*., 2023
	Zanthoxylum limoncello	Soft rot	*Fusarium temperatum*	*C. pubescens*	Fruit	Romero-Arenas *et al*., 2022
	Thymus	Anthracnose	*Colletotrichum capsici*	*C. annuum*	Seed Plant	Arora *et al*., 2024
	Mentha piperita	Rot	*Fusarium sambucinum*	*C. pubescens*	Fruit	Pérez-Vázquez *et al*., 2022
	Cinnamomum verum *Syzygium aromaticum* *Thymus vulgaris* *Citrus* ^{x} *limon* *Mentha* ^{x} *piperita* *Brassica juncea*	Wilting	*Fusarium oxysporum*	*C. annuum*	*In vitro*	Ragab *et al*., 2012
	Cymbopogon citratus	Anthracnose	*Phytophthora capsici*	*C. annuum*	Fruit	Ali *et al*., 2015
	Piper auritum Kunth		*Fusarium oxysporum* *Fusarium equiseti*	*C. chinense*	*In vitro*	Chacón *et al*., 2021

One of the main advantages of using plant extracts is that they can be as effective, or even more effective, than synthetic products for controlling the onset of diseases, while having minimal impact on the environment and on the health of both farmers and consumers (Cruz-Cerino *et al.*, 2020; Kim and Lee, 2022). A major challenge for achieving reproducibility in the use of plant extracts is standardization, since obtaining bioactive extracts from wild material raises several issues, including variation in secondary metabolites within the extract and the risk of violating conservation regulations for wild species.

The terms "natural extract" and "essential oil" are often confused because both are derived from plants. However, they differ in their extraction methods and chemical composition. Natural extracts are obtained through solvent extraction, whereas essential oils are mainly obtained by steam distillation. Their composition also differs: extracts contain a broad spectrum of chemical compounds, while essential oils are composed primarily of terpenes and volatile compounds.

CONCLUSIONS AND PERSPECTIVES

The production of chili fruits (*Capsicum* spp.) faces significant challenges due to the emergence of both chronic and new diseases. Traditionally, control has relied on the use of pesticides and insecticides. However, the indiscriminate application of synthetic agrochemicals has led to resistant microorganisms, greater plant susceptibility to pathogens, and serious environmental and human health concerns.

Findings from the studies reviewed here show that antagonistic microorganisms and plant extracts are viable agroecological alternatives for inhibiting the growth of phytopathogens (fungi and bacteria) in chili without causing environmental harm. These strategies offer medium- and long-term benefits for producers, although more progress is needed in the management of viral diseases. Strengthening antagonistic activity against phytopathogens and advancing the use of plant-derived products remain key challenges, particularly in terms of process standardization and controlled production within sustainable systems.

In this context, the future of phytosanitary management in *Capsicum* will depend on overcoming current limitations such as variability in compound efficacy, stability of active ingredients, and the performance of antagonists under field conditions. Innovation in formulations, the design of microbial consortia, and the integration of emerging technologies such as omics tools and applied biotechnology open new opportunities to optimize these alternatives.

At the same time, the transition to more sustainable cropping systems depends not only on scientific research but also on economic incentives and training programs that bring these practices closer to producers. Only through the integration of science, technology, and social commitment will it be possible to advance toward a model of chili production that is more competitive, safe, and environmentally responsible. The challenge and opportunity of modern agriculture is to move toward sustainable phytosanitary management that ensures productivity and resilience without compromising health or natural resources.

Limitations

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Conflict of interest

The authors declare no conflict of interest.

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Author contributions

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