PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.9416

eISSN 2348-1900

REVIEW ARTICLE

Study of indigenous and non-indigenous practices for disease resistance in *Capsicum*: A review

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Received: 11 May 2025; Accepted: 07 August 2025; Available online: Version 1.0: 20 February 2026

Cite this article: Shahida K, Mohammad MK, Waqar A, Ali M, Mekhled MA, Mohammad HS. Study of indigenous and non-indigenous practices for disease resistance in *Capsicum*: A review. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.9416

Abstract

Chilli pepper is a major cash crop in many countries, making a substantial contribution to export markets and national gross domestic product (GDP). The production and quality of chilli peppers is significantly affected by biotic and abiotic stresses, particularly diseases caused by fungal, bacterial and viral pathogens. This review focuses on the major diseases such as anthracnose, root rot, powdery mildew and *Fusarium* wilt that led to substantial crop losses every year. Both traditional and contemporary non-indigenous strategies for inducing disease resistance have been discussed. The article maps key practices including the adoption of proper cultural practices, use of algal extracts and raising of disease-resistant varieties, application of biological and chemical control methods aimed at enhancing disease resistance in chilli. Relevant case studies are included to assess and support the effectiveness of agricultural practices that have proven effective in reducing crop losses and improving yield quality. The economic implications of improved disease resistance for tropical regions have also been discussed. Key recommendations are provided for policymakers, farmers and exporters and the need for technical and financial support as well as modern processing facilities to meet international market demands is emphasized. Further studies are required especially from the tropical areas where chilli consumption and cultivation are increasing. Proactive measures such as sustainable nursery management, integrated approaches and cluster-based frameworks are recommended to enhance early intervention and risk mitigation to protect crop and achieve sustainability. These insights offer a foundation for developing targeted strategies to improve crop resilience and productivity in regions facing similar challenges.

Keywords: biotic and abiotic stressors; chilli; cluster-based development; disease resistance; good agricultural practices; policy framework

Introduction

The word *Capsicum* comes from the Greek word "*Kapsimo*" which means to bite (1). Christopher Columbus was the first European who discovered it in the Caribbean. On his trip to America, Columbus tasted a plant whose pungency was like black pepper. He took that plant back to Europe and introduced it to Africa and Asia. Carl Linnaeus named this plant *Capsicum* in the year 1793 (2). *Capsicum* (bell pepper) has been recognized in the Western hemisphere since the dawn of civilization. It has been a component of the human diet since 7500 BC. Between 5200 and 3400 BC, native Americans grew chilli plants. It is one of the first crops that were cultivated in America. New Mexico is considered to be the home of chilli. *C. annum* L. (chilli) is one of the most important and economically essential fruit vegetable crops in the tropics. The fruit of chilli is used in many diets as spices and has antioxidants and medicinal properties, reducing the risk of cancer (3). Chilli's high fibre content may help prevent gallstone formation, insulin resistance and heart disease (3,4). The vitamin content of chilli fruits is almost twice that of citrus fruits. Capsaicin is the main compound responsible for chilli's hot nature. The heat level of chillies is measured in Scoville Heat Units (SHU) (5). Chillies have diverse applications. Beyond culinary use, chillies are used in processed foods, as a colouring agent in salad dressings and in cosmetics and textiles (6).

Today, chilli is cultivated worldwide on ~3.8 million hectares, with the majority of production taking place in Asia (7,8). On a global scale, chilli production has gradually increased. A critical analysis of the time scale data reveals that the world's chilli production in 1970 was just 5 million tonnes and it increased to 36.0 million tonnes in 2022 (7). The increase in the harvested area also correlates well with the increasing overall production. The harvested area of chilli in 1970 was just 639 thousand ha and in 2022 it increased to 2 million hectares (8). Asia is the largest continent producing around 24.0 million tonnes of chilli followed by the America, Europe, Africa and Oceania (Fig. 1). At the country scale, China is the largest producer, cultivating chilli on more than 1.3 million hectares of land, which represents about 35 % of the global area under chilli cultivation (Fig. 2). India, while not listed in the top 10 for fresh chilli production, is a major producer of dried chillies and peppers, with ~ 1.8 million tonnes produced in 2022.

Pakistan is one of the world's key producers of chillies and most of the production comes from the southern province of Sindh. On average, ~143000 tonnes of chilli are produced annually. However, Kunri, located in Sindh province, is responsible for producing 85 % of all red chilli, hence Pakistan is referred to as "red chilli capital of Asia" (7-9). China imports 7.2 % of red chillies from Pakistan (9). According to recent data, chilli crop contributes approximately 1.5 % to Pakistan's GDP (9). Chilli production in Pakistan faces significant challenges from biotic (pests, pathogens) and abiotic (edaphic factors, climate change) factors, reducing yield, quality and export potential. Major pests include aphids, mites and thrips, while pathogens like fungi, viruses, bacteria and nematodes cause severe diseases. Climate change further exacerbates production challenges. Pakistan is now experiencing decline in chilli harvests due to these pressures.

Among other pathogens, fungi are more destructive, causing significant harm to the chilli crop as compared to other pathogens. Some of the common fungal diseases include anthracnose, *Phytophthora* root rot, powdery mildew, damping off and *Fusarium* wilt (Table 1). Above all, *Aspergillus flavus* significantly affects the chilli production by producing aflatoxins that contaminate the crop during harvest, drying and storage.

Indigenous and non-indigenous technologies are used to control various plant diseases. The most important indigenous technologies include the fungicides application (carbendazim, mancozeb, tebuconazole, chlorothalonil and copper oxychloride), biological control (using *Trichoderma*, *Pseudomonas*, *Bacillus* and *Pichia*), physical treatments (temperature control, irradiation and soil solarization) and the use of plant extracts or oils (neem extract, garlic extract, *Piper beetle* extract, *Coleus* extract and various plant essential oils) (10). Integrated pest management, seed treatments with fungicides, postharvest management (cleaning latex and debris after harvest, sorting, precooling and hot water treatment with fungicides) and nutritional management (less nitrogenous fertilizer and application of silicon-based fertilizer), also indigenous techniques are also used in plant disease control (10).

On the other hand, crop rotation, the use of disease-resistant varieties, sanitation and altering planting time are important non-indigenous disease management practices that focus on manipulating the environment to reduce pathogen infection and spread (11). Non-indigenous methods aim to create conditions less favourable to disease development and reduce reliance on chemical pesticide applications. Disease-resistant chilli varieties can be developed through selective breeding (crossing selected, desirable chilli plants), hybridization (crossing chilli plants to combine desirable traits, including disease resistance) and marker-assisted selection (utilising both selective breeding and hybridization to speed up the process) (12). Mutation breeding (exposing chilli plants to radiation or chemicals), genetic engineering (manipulating existing plant genes to introduce

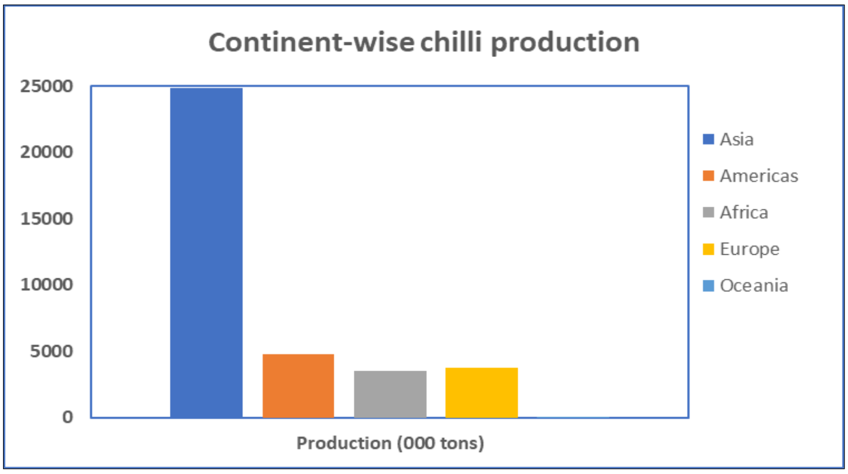

Fig. 1. Continent-wise chilli production in 2022, the largest producer of chillies was Asia, followed by the Americas, Europe, Africa and Oceania (8).

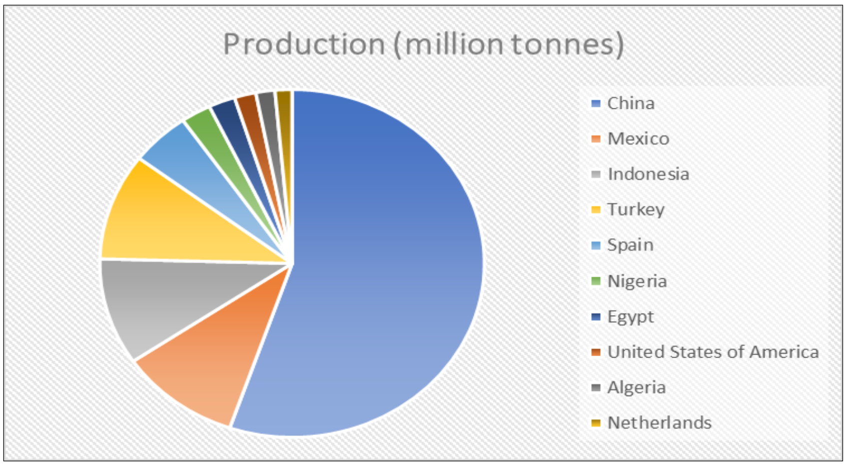

Fig. 2. Top ten chilli producing countries, the largest producer of chillies was China, followed by Mexico and Indonesia, which produced considerably less (8).

Table 1. Diseases of chilli reported from different countries and regions across the globe

S. No	Disease	*Causal organism*	Symptoms	Plant parts affected	Scale (global/region/ country)	References
1	Fusarium wilt	*Fusarium solani* var. *capsici*	Yellowing of leaves, brown vascular streaks and wilting	Leaf	Country (New Mexico)	(17)
2	Wilting	*Verticillium dahlia*	Reduced growth, premature leaf loss, limp foliage and discoloured vascular system	Whole plant	Global	(18)
3	Root rot	*Rhizoctonia solani*	Wilting and death	Lower region of stem and root	Global	(18)
4	Cercospora leaf spot/ Velvet spot	*Cercospora capsici, Cercospora unonidicola*	Small brown spots, light gray centres, dark edges	Leaf, stem	Global (severity in warm and moist conditions)	(19)
5	Phytophthora blight	*Phytophthora capsici*	Affected root and lower portion of the stem and potential wilting	Leaf, stem and fruits	South Korea and countries with high humidity and summer rainfall	(20)
6	Damping off	*Pythium spp., Fusarium* spp.*, Sclerotinia* spp.	Seedling mortality, reduced plant population, stand loss	Roots and crown of older plants	Global	(21)
7	Anthracnose (fruit rot)	*Colletotrichum truncatum (capsici), C. gleosporoides, C. acutatum*	Lesions become water soaked and sunken with ringed acervuli	Leaf, stem and fruits	Tropical and sub-tropical countries	(22,23)
8	Powdery mildew	*Leveillula taurica*	Yellow patches and spots on leaves, leading to leaf drop	Leaves	Places with warm and dry climate	(24)
9	Anthracnose	*Colletotrichum* spp.	Dark black, round and indented spots featuring layered circles of acervuli	Leaves, fruits	Country (India)	(23,25)
10	Anthracnose	*Colletotrichum* spp.	Small, dull brown, slightly depressed spots on stems and leaves; dark patches with pink or orange spore clusters on fruits; dry, decayed flowers	Stems, leaves, blooms, fruits	Country (India, USA, Brazil, Mexico, Spain, Italy, China, Malaysia) and tropical and subtropical regions Indonesia, Malaysia, Sri Lanka, Thailand and Taiwan	(23–26)
		Fungal/Oomycete				
11	Damping off and Root Rot	*Pythium* spp.	Pre- and post-emergence damping off, seed decay, root rot, drooping plants, water-soaked spots, black/brown discoloration and stunted growth	Seeds, seedlings, young roots	Global	(18,21)
		Bacterial Diseases				
1	Bacterial spot	*Xanthomonas campestris* pv. *Vesicatoria*	Lesions become water soaked on leaves	Leaves, stems, fruits	Global/regional (warm and humid)	(27)
2	Bacterial wilt	*Ralstonia solanacearum*	Browning of roots and lower part of stem leading to wilting of plant	Root, Stem	Tropical and subtropical countries with high rainfall	(28)
		Insects and Mite Infections				
1	Mite feeding injury (leaf stippling)	*Polyphagotarsonemus latus*	Inverted spoon shaped leaves, pods with rust or corky surface	Leaves, Fruits	Regions (Asia and Pacific, Africa, Europe, America)	(29)
2	Aphid feeding injury (leaf stippling)	*Myzus persicae, Aphis gossypii*	Distorted, mottled young leaves, chlorosis, leaf drop, reduced fruit size	Leaves, Fruits	Global	(30,31)
3	Thrips feeding injury (leaf stippling)	*Thrips parvispinus, Scirtothrips dorsalis*	Boat shaped curled leaves, distorted pods	Leaves, Fruits	Regional/country India, Sri Lanka, Orient and Pacific Islands, Continental USA	(32,33)

disease resistance genes from wild resistant varieties) and tissue culture (propagating plants with disease resistance traits) are also used to develop disease resistant varieties of chilli (12). Some important chilli diseases and their indigenous and non-indigenous disease management practices are described below.

Fungal and bacterial diseases affecting chilli

Anthracnose

Chilli anthracnose is one of the most devasting biotic stresses that adversely affects chilli production across the globe. Anthracnose is caused by *Colletotrichum* infestation. Despite extensive research on disease management, commercial cultivars of *C. annuum* with resistance to the pathogenic fungus causing anthracnose, have not yet been developed (13). This disease causes dark, sunken lesions on fruits, stems and leaves, leading to fruit rot. This type of fungal infection has been reported from various countries and regions across the globe (Table 1). Anthracnose disease caused by *Colletotrichum* species (*capsici* and *gloeosporoides)* results in significant reduction in yield, reaching up to 80 % in certain developing countries like Thailand (14) (Fig. 3). The main target of the fungal species is mature fruits and as a result, severe fruit losses occur during the pre- and post-harvest stages (15,16).

Pathogenic fungus (*Colletotrichum* spp.) causing anthracnose disease belongs to Phylum Ascomycota, Class Sordariomycetes and Family Phyllachoraceae (34). The morphological or molecular characteristics of *Colletotrichum* species vary for each species (Table 2). Conidia possess blunt pointed ends and are sub-cylindrical, fusiform, ellipsoid, oblong and ellipsoid.

Falcate conidia are formed that possess two pointed ends. Small, circular structures called black acervuli appear on plant surfaces in areas affected by anthracnose disease. These Black acervuli produces conidia. The mycelium is white and turns brownish orange as it matures, producing black setae from acervuli (15,35) (Fig. 3).

Control of chilli anthracnose

Colletotrichum spp. infections is a major issue in chilli production. It leads to anthracnose disease in plants and fruits. Anthracnose disease in chilli has caused production losses (pre- and post-harvest loss) up to 50 % on a global scale. About 50 % loss in Malaysia, 20-80 % in Vietnam, 10-54 % loss in India and as high as 80 % in Thailand has been reported in the year 2020 (31,38,53,62). Chilli anthracnose has been reported to be caused by at least four species of *Colletotrichum* such as *C. capsici* and C. *gloeosporioides* found in Malaysia, Thailand, Indonesia, India and Korea (36,37,47, 51,52) (Table 2). The pathogenesis of chilli anthracnose can be controlled using chemicals, biological agents, plant extracts and by other measures (Table 3). The pathogenesis of chilli anthracnose can be controlled through the application of chemical, biological, or plant-derived agents, along with other management strategies.

Chemical fungicides are widely used to control anthracnose disease in chilli due to quick response. However, the use of fungicides causes toxic effects on the environment and human health. Alternatively, plant extracts are an important way which are non-toxic and eco-friendly. Bio-elicitors are molecules of biological origin that can trigger defense responses in plants. They are typically associated with plant pests, diseases or synergistic organisms. When these molecules attach to special receptor proteins on plant cell membranes, they activate intracellular defense signalling, leading to enhanced synthesis of metabolites that increase plant resistance to pests, diseases or environmental stress (79). The use of algal extracts as bio-elicitors from marine algae to control anthracnose diseases on chilli has not been reported yet. However, the combination of *Swietenia mahagoni* and *Allium sativum* L. (garlic) extract effectively reduced the anthracnose in chilli (80). In another study, ginger extract (15 %) showed significant inhibition in the fungal mycelial growth and spore germination and showed curative and protective efficacy comparable to Antracol and Nativo (74).

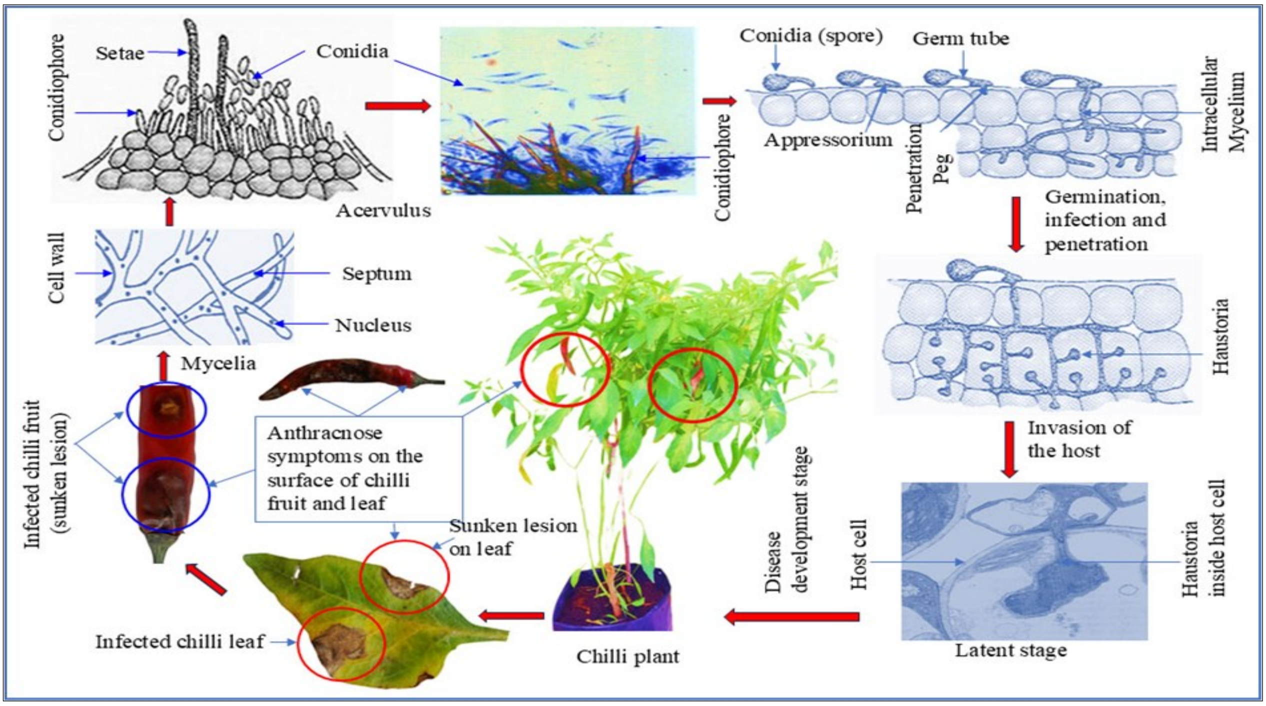

Fig. 3. Schematic diagram of anthracnose disease cycle of chilli crops.

Table 2. Species of *Colletotrichum* associated with anthracnose of chilli in different geographical locations at country, regional and global scale

S. no.	*Colletotrichum* species	Geographical location	References
1	*Colletotrichum dematium, C. acutatum*	Philippines, Australia	(36,37)
2	*C. truncatum, C. capsici*	USA, Mexico	(37)
3	*C. truncatum, C. capsici, C. gloeosporioides, C. coccodes*	USA, Mexico, India, Thailand, Brazil, Canada	(37–50)
4	*C. dematium, C. capsici, C. gloeosporioides, C. acutatum*	Canada, Brazil, Philippines, India, Thailand, Sri Lanka, USA, Korea, Australia, China	(39–50)
5	*C. gloeosporioides, C. coccodes*	Canada, Australia	(36,37)
6	*C. gloeosporioides, C. truncatum, C. capsici, C. acutatum, C. coccodes, C. scovillei, C. siamense, C. fioriniae, C. nymphaeae*	USA, Korea, Australia, Thailand, India, China, Vietnam, Sri Lanka, Bangladesh, Malaysia, Indonesia, Brazil, Pakistan, South Korea, Canada	(36,37,47, 51,52)
7	*C. capsici, C. gloeosporioides*	Vietnam, Thailand	(22,53,54)
8	*C. truncatum, C. acutatum*	Indonesia, Malaysia	(55)
9	*C. capsici, C. scovillei*	Thailand, Philippines	(56,57)
10	*C. truncatum, C. capsici, C. gloeosporioides*	India, Thailand, Sri Lanka	(38–50)
11	*C. truncatum, C. capsici, C. boninense*	India, Brazil	(38,58)
12	*C. scovillei, C. acutatum*	Thailand, Sri Lanka, China	(22,55,59,60)
13	*C. truncatum, C. acutatum*	India, Nepal	(38)
14	*C. acutatum, C. gloeosporioides, C. tainanense*	Indonesia, Taiwan	(55,61)

Table 3. A holistic view of all control measures for chilli anthracnose across geographical regions

S. No.	Control measures	Geographical location	References
1	Chemical: Fungicides (carbendazim, azoxystrobin, mancozeb, difenoconazole, propiconazole, chlorothalonil, strobilurin-based), copper-based fungicides, Bordeaux mixture.	USA, Korea, Australia, Thailand, India, China, Vietnam, Sri Lanka, Bangladesh, Malaysia, Indonesia, Brazil, Pakistan, South Korea, Canada	(63–67)
2	Biological: *Trichoderma spp.* (*T. harzianum and T. viride*), Pseudomonas fluorescens, Bacillus subtilis B298 (microencapsulated), *Paenibacillus polymyxa* C1 formulation (reduces disease incidence by 60-70 %), Pichia guilliermondii R13 (yeast antagonist), *Bacillus vallismortis* BS07.	India, Thailand, Malaysia, Brazil, Vietnam, Indonesia, South Korea	(25,68–72)
3	Botanical: Use of plant extracts such as neem extract (*Azadirachta indica*), garlic extract (*Allium sativum*), Piper betle L. extract (*Betel leaf*), Coleus aromaticus extract (*Indian borage*), *Rhinocanthus nasuta* extract (*Snake jasmine*). Essential oils are also being used for eco-friendly anthracnose control.	Thailand, Sri Lanka, India	(73,74,75)
4	Cultural: Proper drainage and irrigation management; crop rotation; removal of infected plant parts; use of disease-free seeds; maintaining plant spacing; rice straw and plastic mulches; pruning dead wood before flowering; native species restoration.	USA, Mexico, Canada, Australia, Thailand, Vietnam	(22,35,52,76)
5	Host Resistance: Breeding resistant chilli varieties for anthracnose tolerance; transgenic chilli plants expressing genes to enhance resistance.	China, India, Indonesia, Malaysia	(55,56,77)
6	Seed Treatment: Soaking seeds in fungicides like thiram (0.2 %) for up to 12 hours to prevent early-stage infection by Colletotrichum spp.	Global scale application	(64)
7	Post-Harvest Management: Removing infected fruits from storage or transportation areas; orchard hygiene practices like clearing debris after harvest; hot water treatment combined with fungicides to reduce post-harvest losses due to anthracnose infection.	Thailand, Philippines	(35,52)
8	Nutritional Management: Application of silicon-based fertilizers to enhance chilli resistance by strengthening cell walls and reducing pathogen penetration. This method has shown promising results in reducing anthracnose severity in trials.	Vietnam	(78)

Combination approaches: Many regions implement integrated management systems that combine chemical treatments with biological controls and cultural practices for sustainable disease management.

Eco-friendly trends: There is a growing shift toward using biological agents (e.g., *Trichoderma* spp.), botanicals (e.g., neem extracts) and nutritional methods (e.g., silicon fertilizers) as alternatives to chemical fungicides.

Global scale application: While some measures are region-specific (e.g., host resistance breeding in Asia), others like cultural practices and post-harvest management are universally applicable.

The chilli anthracnose disease was significantly suppressed and the plant growth traits were enhanced after application of extracts. The phytochemical profiling showed the presence of compounds such as tannins, phenols, terpenoids, flavonoids, alkaloids, reducing sugars and anthraquinones in ginger and chicory extracts confirming their antifungal potential against *C. capsici* (Fig. 4). Chilli plants may induce resistance by developing waxy cuticle, thicken cell wall, formation of higher trichomes, glands and tyloses in xylem tissue (Fig. 4). The plants also produce antifungal protein, phenols, flavonoids, terpenoids, defence enzymes, plant growth regulators and induce the expression of defence genes to combat with different pathogens (Fig. 4).

Cultivation practices such as proper drainage, crop rotation, disease-free seeds and mulching help reduce pathogen survival (Table 3). Biological control agents such as *Trichoderma harzianum*, *Bacillus subtilis* and *Pseudomonas fluorescens*, are known to suppress *Colletotrichum* spp. through competition and induced resistance. Resistant varieties of chilli can be developed through breeding to reduce dependency on chemical inputs. Several chilli varieties showing resistance to anthracnose has been developed for tropical regions. For example, in Bangladesh, Comilla-2 (V8) variety showed field resistance to *C. capsici*, with minimal infection (2.53 % on ripe fruits vs. 10–17 % in susceptible varieties like Kustia (V9) and BARI Marich-1. Research studies conducted in Thailand and Southeast Asia, *C. baccatum* lines (PBC80 × CA1316 hybrids) showed resistance in fruit bioassays (81). Daepoong-cho (Korean variety) is reported to be resistant to *C. capsici* (29).

In-vitro studies depicted antagonistic potential of bacterial endophytes against chilli anthracnose pathogen *Colletotrichum acutatum* (82). The Integrated Disease Management (IDM) strategy was reported as a fruitful option to contest Anthracnose rather than relying upon a single method. An understanding of the etiological agent of the disease is a prerequisite for management. To develop resistant varieties, breeders require comprehensive knowledge of pathogen races. However, there remains a significant lack of information regarding the early detection of pathogenic fungi and effective strategies for their management (33,83).

Root rot (Phytophthora root rot)

Symptoms of *Phytophthora* root rot: The oomycete *Phytophthora capsici* is a formidable pathogen that causes blight in chilli pepper (Fig. 5A). This disease leads to wilting, root rot and plant death. This is prevalent in the major chilli-growing districts of Pakistan. The symptoms of root rot start at the soil line and a wet environment is suitable for this disease. The affected chilli plants show brown to black discolouration in the root, stem, crown and fruits. Small or irregular spots may occur on the leaf and enlarge with time. Lesions develop by merging spots and lesions that spread around the stem and leaves result in plant death. The infected fruits become dark green and turn brown later (18,21). This disease can be managed by using resistant cultivars, proper irrigation and soil drainage.

Control of *Phytophthora* root rot : The management of root rot is mainly done through crop rotation and using comparatively more root-rot-resistant varieties of chillies. Additionally, other options have been emerged in Pakistan. In a study the genetic diversity of

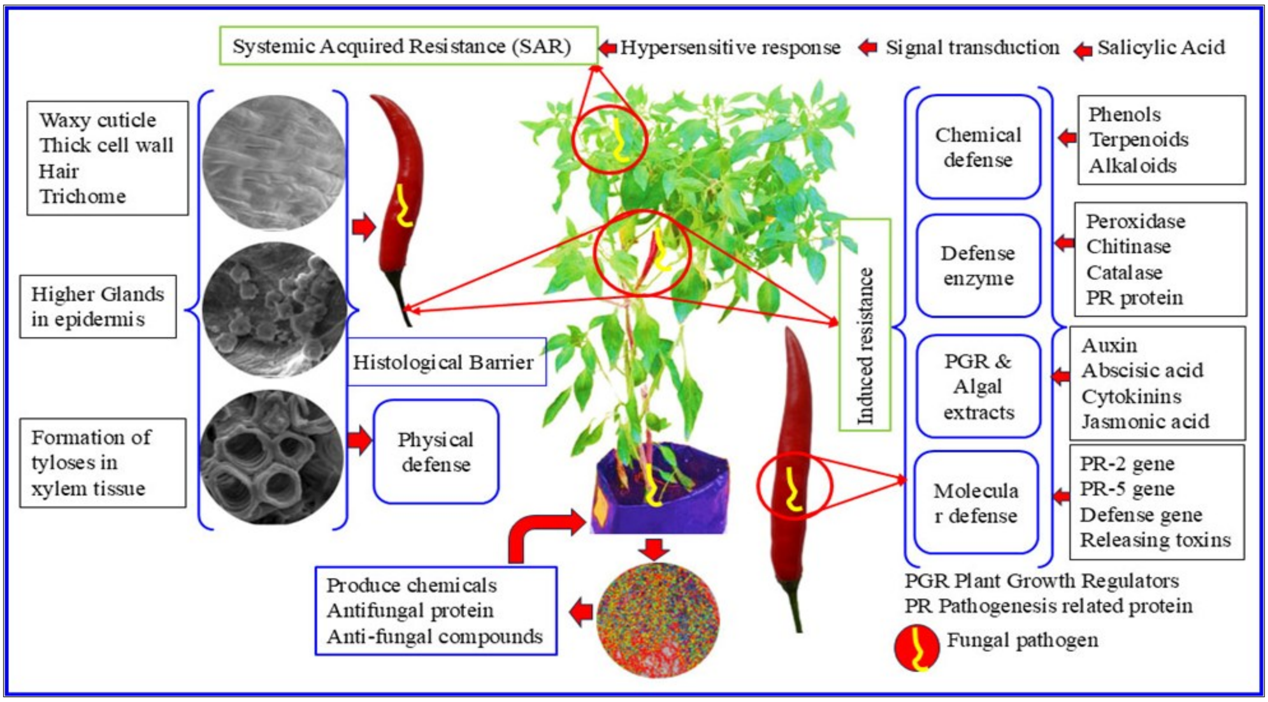

Fig. 4. Schematic representation of the various steps involved in the general mechanism of the defense response of the chilli plant against *Colletotrichum capsici.*

beneficial *Trichoderma* species present in chilli farms was investigated. The dual potential of these species as biocontrol agents against *P. capsici* and growth promoters for chilli roots was highlighted (71). Phylogenetic analysis further confirmed the antagonistic effects of *Trichoderma* species against *P. capsici*. *In vitro* assays revealed that *T. harzianum, T. viride* and *T.* reesei exhibited remarkable inhibition of *P. capsici* mycelial growth (about, 85.5 %). Moreover, under greenhouse conditions, soil application of *Trichoderma* species effectively mitigated root-rot severity by 11.24-6.50 %. This biocontrol effect not only proved effective in controlling pest but brought significant improvements in fresh weight of root and root lengths compared to control plants that were infected with *P. capsici* but not treated with *Trichoderma*.

In another study, the use of plant growth promoting rhizobacteria (PGPR) was investigated to combat *P. capsici* infects chill pepper plants (84). Two highly virulent *P. capsici* isolates causing damping-off in chilli peppers were identified. Out of the fifteen bacterial strains from the chilli rhizosphere, eight showed potential as antagonists to *P. capsici* in laboratory tests. These bacterial strains were identified as species of *Pseudomonas* and *Bacillus* through 16S rRNA sequence analysis. The bacteria exhibited various beneficial traits, including the production of hydrogen cyanide, catalase, indole -3-acetic acid and siderophores (small, high-affinity iron-chelating compounds). Greenhouse experiments demonstrated that these bacterial strains significantly reduced *P. capsici* infections up to 63 % and improved chilli pepper growth. These research studies present new findings on the efficacy of these rhizobacteria against *P. capsici*, suggesting their potential as eco-friendly alternatives to synthetic fungicides.

Powdery mildew

Symptoms and control of powdery mildew: Powdery mildew is a widespread and important disease. *Leveillule taurica* (holoparasite) (Lev.) Arn. is responsible for the powdery mildew. This pest obtains nutrition from the host plant but does not kill the plant. It causes severe leaf distortion, defoliation, shoot dieback and reduction in growth. Conidia (spores), produced in great numbers on the surface of the host plant by the powdery mildew fungi, impart a white powdery and filamentous appearance to affected tissue (Fig. 5B). This fungal infection reduces the plant productivity (85).

Powdery mildew is fungal disease affecting chilli crops in Pakistan. It leads to significant loss in crop yield, particularly in the major chilli-producing regions of Sindh province. Symptoms include the white powdery coating on leaves, stems and sometimes fruits; the yellowing and curling of leaves; premature leaf drop; and reduced overall plant growth and yield (Table 1). These symptoms are more prevalent in warm conditions, with optimal temperatures between 15.5 to 26.7 °C. The control measures mainly include use of fungicides (chemical control) such as tebuconazole 10 % + sulfur 65 % WG (400-500 g per acre ≈ 4000 m^2); sulphur 80 % WDG (750-1000 g per acre); hexaconazole 5 % SC (200–250 mL per acre) and azoxystrobin-based products. Cutting of the infected leaves, stalk, buds and other plant parts prevents the disease from spreading. Foliar water spray in the morning is a good technique to prevent the spread of the disease. Application of neem oil and sodium bicarbonate or baking soda, seed treatment with appropriate fungicides and optimum plant densities are natural remedies for powdery mildew. The other effective strategy to manage/control the disease is the integrated pest management approaches including the use of resistant varieties and proper cultural practices.

Fusarium and bacterial wilt

Symptoms of wilt: *Fusarium* and bacterial wilts are two distinct diseases that affect chilli plants. Each disease is caused by different pathogen and exhibit unique symptoms (Fig. 5C). For example, *Fusarium* wilt is caused by the fungus *F. oxysporum* and can survive in the soil for years without a host (in warm and inadequate soil temperature and moisture conditions). The infected plant will show yellowing of older leaves, downward curling of the apical shoots and wilting (Fig. 5C). Dark streaks may also be seen in the roots and the lower portion of the stem (Table 1). The control of *Fusarium* wilt includes use of, resistant chilli varieties, crop rotation techniques and the application of fungicides (86).

Bacterial wilt is caused by bacteria belonging to genera *Corynebacterium, Erwinia*, *Pseudomonas* and *Xanthomonas*. This disease is more prevalent in warm and moist conditions and can persist in plant debris and soil. The affected chilli plants exhibit drooping leaves and stems, stunted growth and withering. Stems often shrivel and show discolored water-conduction tissue (Table 1). The control of this disease involves growing resistant chilli varieties, planting in well-drained soil and practicing good sanitation. A proper understanding of the differences between the two diseases and the control methods can help manage and prevent them effectively in chilli crops.

Control of *Fusarium* and bacterial wilt: In a study where twenty-five varieties/advanced lines of chilli were checked for resistance against *Fusarium* wilt under natural field conditions for two consecutive years 2017-18 and 2018-19, results indicated that none of the varieties or advanced lines expressed the immune response against the disease (87). Only one variety (BPVLC 14-1) showed resistance with 18.76 % reduction in disease incidence. Uttal, Fengaio, Glaxy-2, Big daddy, GHHP 01, PH-275, Super sky AB, HPO33 and Super king are some varieties that showed Moderate Resistance (MR) with 21-40 % disease incidence. Four varieties/advanced lines viz. Hot-701, Hotshot, Omega and Silkey Red showed a Moderate Susceptibility response (MS) with 41-50 % reduction in disease incidence. Super-hot, Patiala F1, Angel F1 and Green King were found susceptible (S) with 51-70 % incidence of Fusarium wilt. Seven varieties / advanced lines exhibited High Susceptibility (HS) (Tejal, BSS-410, Big Red AB, SB 6864-HM, Glory F1, Revival and Amber F1). One resistant advanced line (BPVLC 14 - 1) and nine MR advanced lines/varieties (Uttal, Fengaio, Big daddy, Galaxy-2, GHHP 01, Super Sky AB, PH-275, HPO33 and Super King) were recommended for further breeding programmes in Pakistan (87).

Syzygium cumini (Jamun) leaf waste-derived biochar (BC) was used for managing bacterial wilt in chilli plants (88). The BC was applied at the rate of 3 % and 6 %, along with compost, to three chill cultivars namely F1 Zenia, Desi Chilli and F1 Green Queen. The results showed that BC amendments positively affected plant growth across all cultivars, even under disease stress. Notably, BC application significantly reduced disease incidence and severity in all cultivars. The F1 green queen cultivar exhibited strong resistance to bacterial wilt when treated with 6 % BC. The effectiveness of BC in disease management varied depending on its application rate, the specific chilli cultivar and the plants' biochemical composition (phenolics, catalases and flavonoids). These findings emphasize the complex interplay between BC, plant genetics and disease resistance, highlighting the importance of considering cultivar-specific responses when developing BC-based disease management strategies.

Aflatoxins

Aflatoxin contamination: Chillies contaminated with aflatoxin and pesticide residues are a major problem in the global market. Aflatoxins (AF) are toxic compounds produced by certain molds (*Aspergillus* species) that contaminate chillies, (especially in high temperature and moist conditions) (89,90). These toxins pose significant food safety and public health risks due to their carcinogenicity and prevalence in staple spices like chilli powder. *Aspergillus flavus* and *Aspergillus parasiticus* strains are the main toxigenic fungi that can produce AF. The contamination of AF and other diseases of chillies differ primarily in their causes, symptoms and management strategies. The symptoms of AF are not visible on the plant but can be detected in harvested chillies (Fig. 5D).

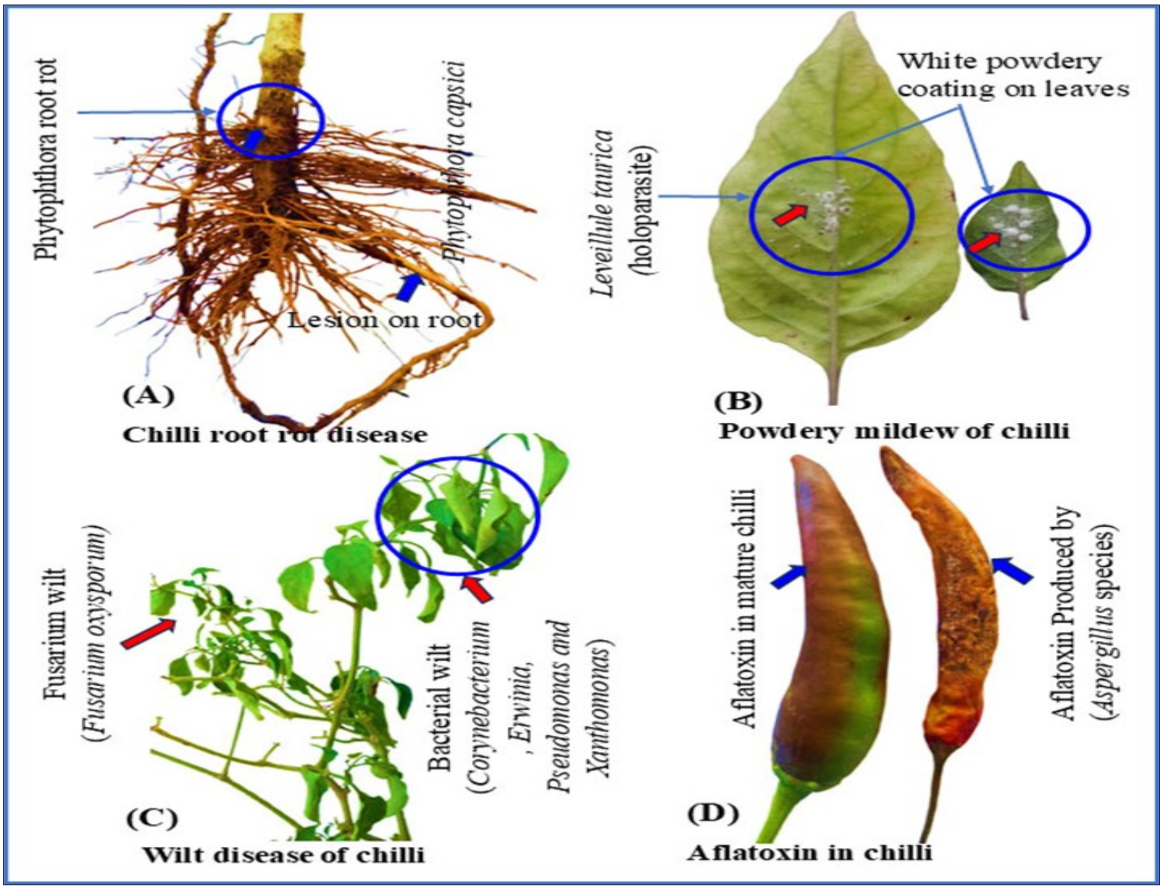

Fig. 5. Major diseases and mycotoxin contamination affecting chilli crops. (A) Phytophthora root rot; (B) Powdery mildew; (C) Wilt disease; (D) Aflatoxin contamination

Studies conducted across tropical and sub-tropical countries, or in specific regions within these climates, consistently report high rates of AF contamination in chillies and chilli powder (91–98). A study from China in which of 480 spice samples were analysed showed detectable levels of aflatoxin (approximately 11 %) and highest concentrations were noted in chilli products (93). Recent studies in Bhutan (20 districts) have identified chilli products as the most prevalent food commodity with the highest aflatoxin contamination. Aflatoxin concentration of 11.49 ppb and a mean AFB1 concentration of 17.62 ppb was reported. Specifically, chilli powder exhibited a mean total aflatoxin level of 19.65 ppb and a mean AFB1 level of 28.01 ppb, in 94 % of chilli powder samples and 77 % of dry chilli samples. These levels are much higher than regulatory limits set by the European Union (EU) (94).

The estimated daily intake of AFB1 from chilli products ranged from 0.98 to 5.34 ng kg^{-1} body weight per day indicating a significant public health risk after exposure. Furthermore, the estimated liver cancer risk associated with chilli consumption was found to be 0.01 cases per 100000 people per year, underscoring the need for stringent public health measures (72). In Myanmar, the estimated liver cancer risk related to the chilli consumption ranged from 0.042 to 0.047 cases /year/100000 people, indicating significant health risks (95). In India, 59 % of chilli samples were contaminated with AFB1, 18 % exceeded permissible levels (often >30 ppb) and the highest recorded level was 969 ppb in lower-grade samples (96). However, in Pakistan (Sindh, falls under a tropical climate zone), a recent study reported that the AFs in most of the chilli samples collected from different areas were less than 20 ppb.

The highest incidence of *Aspergillus flavus*, followed by *A. niger*, *A. parasiticus*, *A. fumigatus, A. candidus* and *A. terreus*, was found in all 81 chilli samples of two chilli varieties (Sanam and Longi) collected from Sindh, Pakistan. Findings indicated that about 60–80 % chilli samples showed aflatoxin contamination and contained AFs within the range 20 ppb which is acceptable for the human consumption. The lower level of AFs (2.3-7.1 µg kg^{-1}) was found in chillies dried on net surfaces as compared to the samples dried on cemented ground (6.7-14.5 µg kg^{-1}) (97,98).

The permissible levels of AF in chillies differ for each country and its regulatory authority (98). For example, the Codex Alimentarius (CODEX) generally sets a maximum limit of 15 ppb for total AF in spices, including chilli, while EU enforces a stricter limit of 10 ppb for total AF (B1, B2, G1 and G2) in food products and the United States Food and Drug Administration (FDA) allows up to 20 ppb (99). The World Health Organization (WHO) recommends a limit of 30 ppb for total AF in food products. These standards are established to protect consumer health and ensure food safety and exporters need to comply with them to avoid rejection of their products in international markets (100).

Control of AF: The management of AF at the local level is focused on pre- and post-harvest practices, such as proper drying, storage and the conducting of regular inspections and testing of chilli crops to detect and manage AF levels at an early stage. However, other strategies being deployed in AF control include the application of biocontrol agents, development of resistant crop varieties and the application of good agricultural practices. In biocontrol method, non-toxic strains of *Aspergillus* are used to outcompete and reduce the population of toxin-producing fungi. The adoption of emerging technologies such as combined methods technology or hurdle technology, one health concept, improved regulations, online monitoring of AFs and creative art intervention to prevent or restrict the growth of target aflatoxin causative fungi have also been recommended.

Algal extracts

Algal extracts are purified liquid substances derived from marine or freshwater algae which contain a rich source of biostimulants. These algal extracts can be obtained from both macro and micro algae and offer a variety of potential benefits due to the presence of bioactive compounds. Algal extracts stimulate plant growth and development and enhance resistance against various plant pathogens.

Algal extracts on plant growth and development

Many marine algal seaweed species are bioresources that have been used as agricultural products for industry, medicinal, food source and botanical purposes from several years (101,102). Though a combination of various chemicals that stimulate plant development, enhance resistance against diseases are used, seaweed and products produced from it are frequently employed as supplements in crop production systems. The brown seaweed species namely *Sargassum* has been used commercially in South China sea basin. A subclass of seaweed extract acts as natural bio stimulant and helps in aids faster growth of crops, more production and induction of more resilience (Fig. 6).

The biostimulant properties of seaweed extracts are attributed to the presence of various plant hormones, including auxins, cytokinins, gibberellins, abscisic acid, phenols, flavonoids and ethylene (101). The seaweeds namely brown algal species such as *Ecklonia maxima*, *Sargassum* spp. and *Ascophyllum nodosum*, red algal species namely, *Pterocladia pinnata*, *Jania rubens*, *Corralina mediterranea* and green algal species viz. *Ulva lactuca*, *Enteromorpha intestinalis* and *Cladophora dalmatica*) have good biostimulant activity and can be used as bio-elicitors (102,103). Additionally, phenols, flavonoids, plant growth regulators, specifically cytokinins, are primarily contributing to ageing delay in plants, induction of mitosis, growth of shoot and lateral buds and stimulation of chloroplast maturation (Fig. 6).

Further, seaweed biomass or algal extracts have been used as biofertilizers and growth stimulants in the agricultural and horticulture industry. Algal extracts have shown the potential to mediate biotic stress, antioxidant activity and growth. Algae have a strong binding affinity, high tolerance, are grown easily, produce large surface area, are eco-friendly and cost-effective (101). Macro and microalgae are believed to serve as an excellent alternative to mitigate biotic stress because of their bioremediatory properties.

Role of algal extracts in inducing resistance

Algal extracts are important for increasing disease resistance in chilli plants due to their ability to enhance plant immunity and resilience against pathogens (104). These extracts contain bioactive compounds such as polysaccharides, phenolics, antioxidants, vitamins and signalling molecules that trigger the plant's defense mechanisms (101,105). For example, cyanobacterial extracts have demonstrated significant effectiveness in reducing fungal infections like *Fusarium* wilt in chilli plants by inducing systemic resistance, increasing phenolic content and activating antioxidant enzymes such as polyphenol oxidase (PPO) and peroxidase (POD) (106) (Fig. 6). Additionally, algal extracts promote stress tolerance by reducing oxidative damage caused by Reactive Oxygen Species (ROS) and enhancing the accumulation of osmo-protectants and photosynthetic pigments in the infected plants (105).

Seaweed-based bio-stimulants further contribute to disease resistance by improving plant tolerance to both biotic and abiotic stresses, making them eco-friendly alternatives to chemical fungicides (101) (Fig. 6). These extracts also influence hormone level (e.g., salicylic acid and auxin), which are critical for activating defense responses (102). Chilli plants can achieve improved growth, reduced vulnerability to pathogens and enhancement in ecosystem sustainability when algal extracts are integrated into agricultural practices.

The seaweed extract can be applied topically and with foliar spray. The algal extract increased plant vigour, disease resistance, root development, leaf quality and germination (102). According to past reports, applying seaweed extract boosted tolerance to plant biotic and abiotic stresses. It is further reported that brown algae control plant diseases and mitigate environmental stress effectively (107). *Ascophyllum nodosum* extracts regulate plant growth, development and gene expression. Seaweed extracts exhibit a wide range of distinct biological properties such as antifungal, antitumoral, antiviral, insecticidal, cytotoxic, phytotoxic and anti-proliferative effects.

Application of algal extracts increases the resistance against stress, leaf sugar content, anthocyanin content and flower number of *Begonia* plants. *Sargassum* spp. has gathered a lot of attention because it contains secondary metabolites, phenols, flavonoids, plant hormones and nutrients than other species of another genus. It has been reported that foliar aqueous extract of *Sargassum polycystum* improved the morpho-physiology, photosynthesis, leaf and root anatomy and increased the expression level of the *Rubisco* gene of Cd stressed Pak Choi under potted condition (108). Hence, the exogenous application of *S. polycystum* extracts can play a significant role in crop improvement, inducing resistance and mitigating the negative effects of biotic stresses (Fig. 6).

Chilli nurseries play a crucial role inducing disease resistance by providing a controlled environment that minimizes exposure to pathogens and enhances plant defenses. Nurseries protect the plants by means of physical barriers such as netting and treatments like Trichoderma-based compost and PGPR to shield seedlings from diseases like anthracnose and plant rot. These treatments stimulate systemic resistance in chilli plants by activating defense mechanisms (109).

The production of phenolic compounds and antioxidative enzymes further reduces disease severity. Nurseries also improve yield by i) reducing disease incidence, ii) promoting sustainable farming practices using natural protective agents rather than harmful agrochemicals and iii) serve as an ideal environment for breeding resistant chilli varieties, enabling the development of plants with enhanced genetic resistance to fungal pathogens. Nurserymen and all stakeholders could potentially prevent severe outbreaks during later growth stages, ensuring healthier plants and higher productivity (109).

Case studies

Case study 1 - remodelling native chilli dry processes

Drying is an indispensable step in the chilli quality as it ensures product quality, safety and economic viability while meeting consumer expectations (110,111). Pakistan is a top exporter of dried chillies. Several distinctive varieties of chillies grown across the country include Dundicut, Sannam/Sindhi Mirch, The Longi F1, Thai Bird's Eye, Kashmiri Mirch, Red Cherry and Carolina Reaper. In collaboration with the Market Development Facility (MDF), Australia, the National Food Limited (NFL), Pakistan tackled the AF threat by remodelling the handling by reducing the drying time (Fig. 7) (112). NFL worked together with their suppliers to ensure that "Geotex" (new drying sheets) was being used by all the suppliers. The use of the Geotex drying sheets potentially reduced the AF concentration less than 10 ppb. The farmers were also incentivized to use these new drying sheets by paying more premium which accounts to approximately USD 53 per tonne (one USD is equivalent to 280.7 Pak Rupees was used to convert the currency). This initiative of incentivizing the farmers led to a boost in overall quality of red chillies and increasing their competitiveness in the global market.

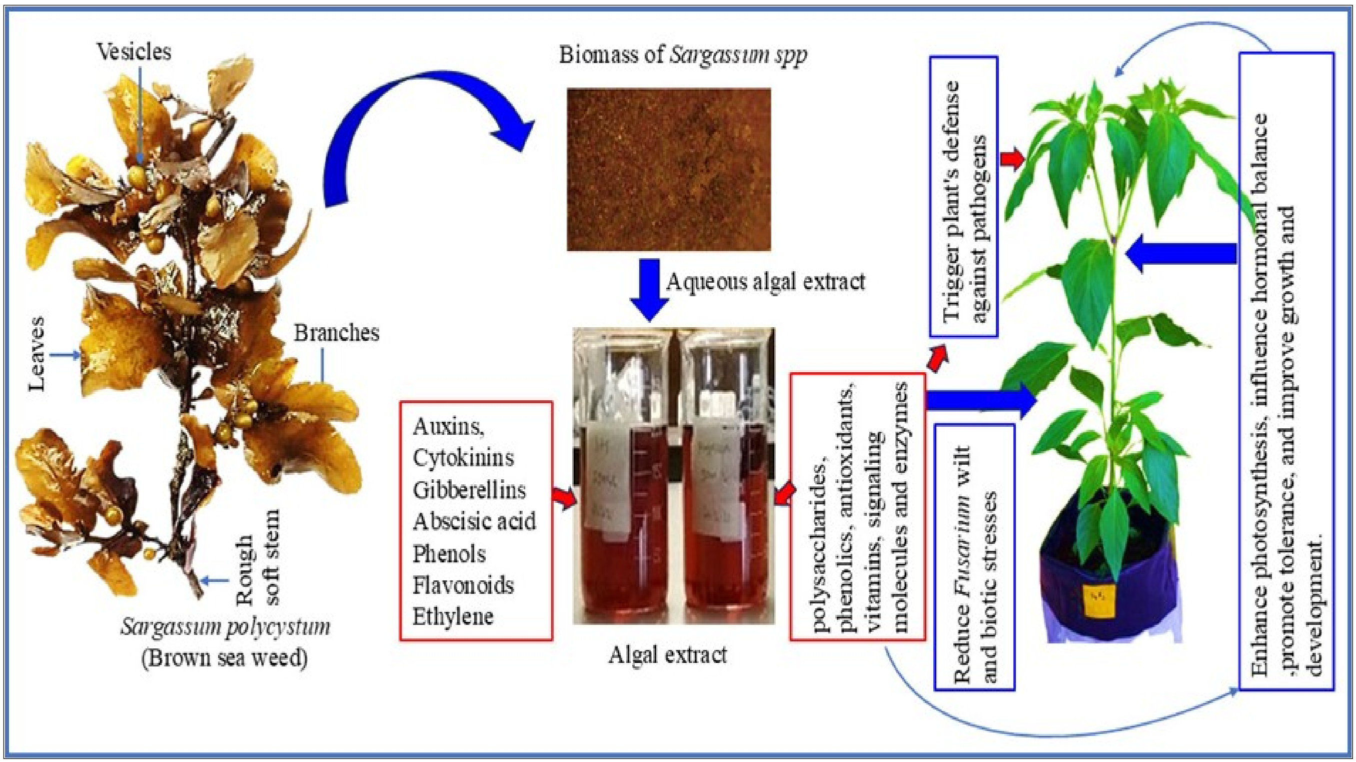

Fig. 6. Schematic diagram of algal extracts on disease resistance, stress tolerance, growth and development of chilli plants.

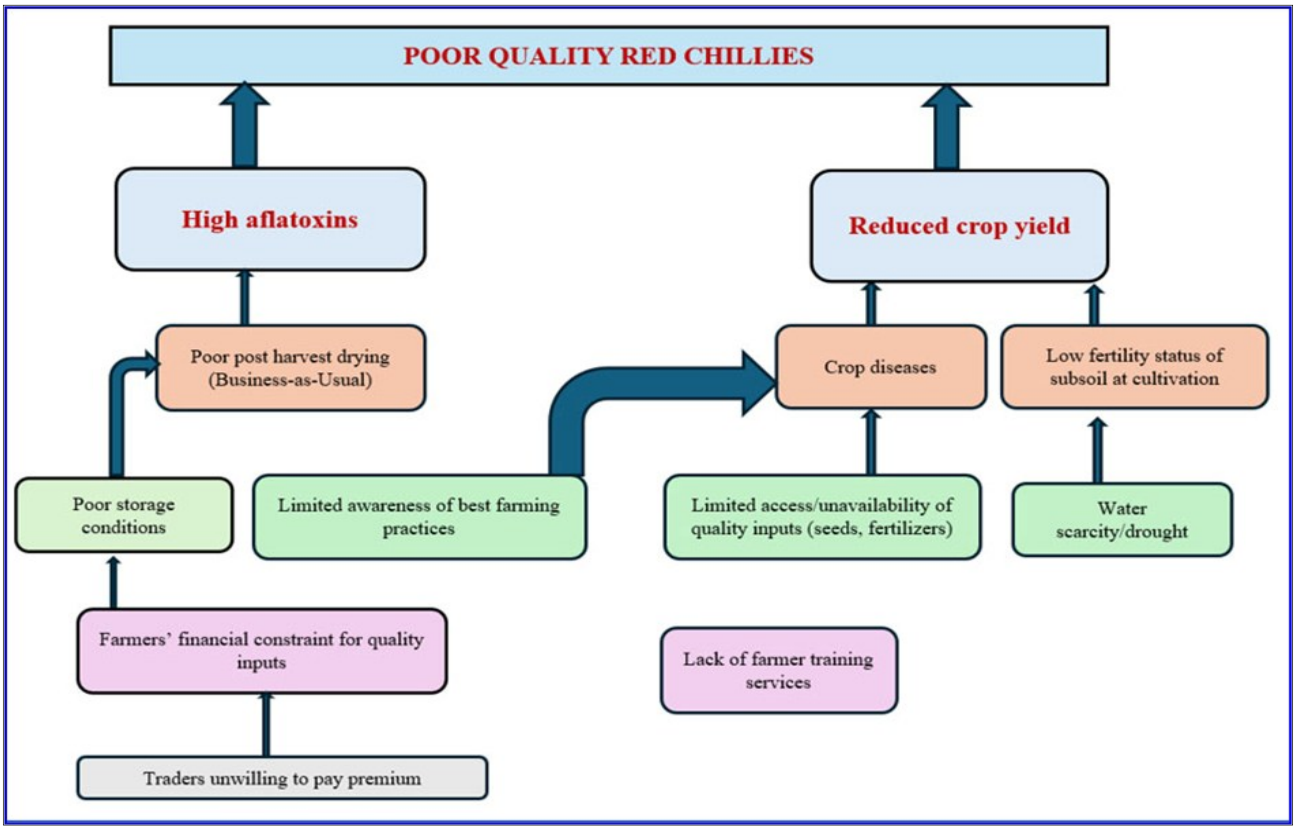

Fig. 7. Constraints matrix of aflatoxins production in red chillies (112).

Case study 2 - postharvest handling

Literature shows that correct and adequate post-harvest handling of chillies is essential to minimize spoilage and losses, maintain quality, economic viability, meet market compliance standards, enable value addition and support cold chain management (113). On the other hand, neglecting post-harvest handling leads to economic losses, reduced shelf life and poor produce quality. This could directly impact farmers' income due to spoilage and downgraded produce, while also affecting consumers' satisfaction through discoloration, mold growth or loss of pungency.

Sindh province of Pakistan contributes 80 % of the total chilli production at country scale. In this province, a significant initiative was undertaken at Kunri, district Umerkot to improve post-harvest handling of chillies through the introduction of solar tunnel dryers. This technology aims at reducing aflatoxin risks and enhancing drying efficiency. The solar tunnel dryers proved highly effective in reducing drying time by up to 56 % as compared to traditional open sun drying methods. The total aflatoxin content of treatments, T1- solar tunnel, T2- solar cum gas and T3 open sun or traditional method were 1.4, 3.0 and 2.7 ppb, respectively. The measured values were below the recommended values of the aflatoxin. Hence, both T2 and T2 drying methods served as a better alternative for open sun drying (business-as-usual) and ensure good product quality. The solar tunnel-dried chillies exhibited superior colour retention and reduced aflatoxin contamination, enhancing their export potential (110). These methods are not subject to weather conditions like rainy season.

Case study 3- farmers' indigenous knowledge and market linkages (Indonesia, Malaysia and Thailand)

Indigenous practices could potentially enhance chilli resilience. However, such practices require formal recognition, policy support for preserving indigenous seeds, gender inclusion and empowerment through training and resources and improving market access infrastructure.

In Indonesia Java contributes over 60 % at country scale. West Java leads with an annual yield of 198000 tonnes, while East Java, particularly Malang district, accounts for 50 % of the cultivated area. Popular types of chillies are Cabe Rawit (Bird's Eye Chilli), Cabe Merah Besar (Large Red Chilli) and Cabe Keriting (Curly Red Chilli) (114,115). Farmers intercrop rice with vegetables including chillies. This practice is followed for informal seed exchanges to maintain resilient local varieties. This indigenous practice further triggers thrips infestations and climate sensitivity. Women dominate post-harvest tasks, while men handle land preparation. High input costs and price volatility remain the biggest challenges in West Java though the yields (12 tonnes per ha) exceed the national average (7.1 tonnes per ha). This variation in productivity highlights the disparities in farming efficiency, resource allocation and unavailability quality inputs (116).

Malaysia's chilli sector blends traditional farming with modern fertigation technology yet struggles with pest pressures and heavy import reliance. Major chilli growing areas like Johor, Perak, Kelantan and Sarawak cultivate chilli in 14560 ha annually. The local production (23000 tonnes) in Malaysia falls short of 33000 tonne total demand. Popular varieties include MC 10, Kulai Series such as 469, 151 and 423, Chilli Tarat (ARC-C-C1/L7) and Hot Beauty. In Sarawak, Dayak communities practice agroforestry with chillies, using Mongkaakng (ritual burning) to enhance soil fertility. Mongkaakng refers to the indigenous fire practices that involve controlled burns to manage landscapes, promote biodiversity and fulfill ceremonial purposes (ARC: Chilli Cultivation - Laman Web Rasmi Jabatan Pertanian Sarawak).

However, inherent acidic soils, inadequate cold storage and land-use disputes threaten farmers' profit margin. Initiatives like the Malaysian Agricultural Research and Development Institute's (MARDI) hybrid Cili Semerah (spicier, faster-growing) and urban farms adopting fertigation (earning approximately USD 18000 per month) aim to reduce import dependency. For sustained growth, the industry must address infrastructure gaps and empower farmers through seed preservation and market access. In summary, Malaysia's chilli future hinges on balancing indigenous wisdom (e.g., Dayak agroforestry) with scalable technology (fertigation, hybrids) to curb imports and boost rural livelihoods (Malaysian Agricultural Research and Development Institute).

Thailand grows popular varieties like Bird's Eye Chili (Prik Kee Noo), Prik Chee Fah and Prik Kaleang., which cater to a variety of heat levels and culinary applications (115). Unlike Indonesia's intensive farming, farmers in Thailand face erratic markets and lack post-harvest infrastructure (115). Karen communities practice rotational farming to sustain soil health for chillies, alongside other crops. Modern tools like virtual reality trainings help bridge traditional knowledge with technology, though land rights disputes persist (117).

Case study 4 - irrigation scheduling (Gansu, North-West China)

Chilli plants are sensitive to water stress. Under-irrigation reduces fruit size and yield, while over-irrigation has been found to promote diseases. Irrigation scheduling is the key to quality production in chillies. All water-scarced regions, including arid and semi-arid areas deserve special focus as over irrigation in chilli cultivation could promote diseases outbreaks (e.g., root rot, fungal infections) and significantly impact the economic returns of the farmers.

China cultivates popular varieties of chilli, such as Er Jing Tiao, Chaotian and Yunnan chillies (115). Gansu Province is situated in the arid and semi-arid regions of Northwest China, characterized by a dry climate with limited rainfall (about 281 mm annually in main crop farming areas), making efficient irrigation practices crucial for agricultural activities. The province includes parts of the Gobi Desert and other deserts, further exacerbating arid conditions (118). A study was conducted for over 2-years in Wuwei City to explore the impact of Soil Matric Potential (SMP) based irrigation strategies on mulched-drip irrigated chilli peppers. The study indicated that the best yield and good fruit quality could be achieved by reducing the use of irrigation water and maintaining crop evapotranspiration and SMP within the range of -30 to -40 kPa. It was found that SMP at -50 or -10 kPa led to yield losses due to water stress and an excess of water at the respective SMP readings. This case study further stressed the need for the use of scheduled irrigation practices alongside maintaining the SMP between -30 to -40 kPa for high quality chilli fruit production under water-scarced regimes (119).

Case study 5 - exploring disease resistance through germplasm collection using Fluidigm SNP genotyping

This case study provided valuable insight into capsicum disease resistance and the role genetically modified and selectively bred species play in combating commonly reported diseases. A total of 5658 accessions of various capsicum species and geographical regions were analyzed through a fluidigm genotyping system (a high-throughput platform designed for analyzing genetic variations across large numbers of samples and employs integrated fluidic circuits enabling thousands of simultaneous reactions). The fluidigm platform can be applied to the realm of Single-Nucleotide Polymorphism (SNP) and the development of SNP markers to differentiate cultivars in plant species (120). The accessions were screened against powdery mildew, bacterial spot, anthracnose and root rot and other four diseases. Most notably accession from *C. chacoense* and *C. baccatum* showed resistance to various major chilli diseases. The former capsicum highlighted the potential of wild capsicum in breeding programs, being even more resistant to disease than the former chilli species. The study identified resistant chilli accession from diverse locations such as Argentina, the United Kingdom and Bolivia indicating widespread disease-resistant traits across various environments (120).

A recent study explored the use of gamma irradiation to develop anthracnose-resistant chilli pepper varieties (121). Researchers irradiated *C. annum* L. seeds with gamma rays at doses ranging from 0 to 500 Gy, determining an LD50 value of 264.83 Gy. Seeds irradiated at 300 Gy were then cultivated for mutation selection. The irradiated plants showed improved survival and fruit production when exposed to anthracnose infection compared to the control. Through successive generations (M2-M5), 28 healthy chilli pepper plants exhibiting anthracnose-resistant traits were selected. Two lines in the M4 generation demonstrated the highest resistance to both *Colletotrichum gloeosporioides* and *C. capsici*. The resistant lines also displayed desirable characteristics such as shrub-shaped plants and upright fruits. Field trials conducted in 2021 showed promising results, with the resistant lines producing good yields and demonstrating disease resistance on different locations. This research highlighted the potential of gamma irradiation as an effective tool for developing anthracnose-resistant chilli pepper varieties with improved agronomic traits (121).

Recommendations

Research and development

- Promote cluster-based development - a strategy that focuses on creating clusters of interconnected agricultural activities within a specific geographic area. This approach aims to enhance the efficiency and productivity of the agricultural sector by fostering collaboration among farmers, processors and other stakeholders
- Conduct a broad diagnostic study of contamination and the use of different natural extracts.
- Use aflatoxin contamination of chillies (supply chain and other related) as a model to establish systems to address contamination and international trade barriers
- Identify and analyze issues related to the extent of aflatoxin contamination and scrutinize management practices in the production and supply chain
- Expand research and surveillance on Disability-Adjusted Life Years (DALYs) attributable to the consumption of contaminated chillies across the tropical countries especially in regions experiencing increasing chilli consumption and production to strengthen early warning systems and inform targeted public health interventions
- Identify critical control points in the chillies supply chain and assess the feasibility of improvements to existing procedures and processes. A comprehensive evaluation of chilli nurseries is recommended
- Develop a detailed follow-up project proposal to improve existing processes and procedures, provide guidance and offer training and necessary tools

Policy domain

- Support appropriate policies at the government level to overcome trade barriers and establish quality-based procurement systems
- Develop national quality standards and establish procedures and manuals on safe production, handling and storage of chillies
- Provide recommendations for improved procedures to maximize and protect the chill harvest during picking, post-harvest handling, drying, storage, marketing and processing

Communication and outreach

- Organize a stakeholder workshop with international experts to address key issues and provide a platform for experts and key stakeholders to share commitment and ownership of the project
- Raise awareness among growers, processors and exporters to maintain produce quality standards and promote best practices
- Provide training in mycological techniques, chemical analysis of aflatoxins and rapid on-site screening methods
- Facilitate the exchange of staff and students between institutes and universities with additional funding
- Ensure the provision of safe and high-quality chillies to consumers at global and regional scales (tropical countries)

Conclusion

This comprehensive review has explored the complex landscape of disease resistance in *C. annuum* focusing on the integration of indigenous and non-indigenous practices to enhance crop resilience. The review has highlighted the significant economic importance of chilli pepper as a cash crop and the critical challenges it faces from various biotic and abiotic stressors. Key findings underscore the importance of combining traditional knowledge with modern agricultural techniques to effectively combat diseases such as powdery mildew and *Fusarium* wilt. The implementation of good agricultural practices, including proper cultural methods, the use of disease-resistant varieties and the judicious application of biological and chemical controls, has shown promising results in reducing crop losses and improving produce quality. The review has also emphasized the critical role of aflatoxin management in chilli production. This highlights the need for a multifaceted approach to disease management that addresses both visible plant pathogens and harmful contaminants. Advancements in genomic research and breeding programs offer exciting prospects for developing more resilient chilli pepper varieties. These scientific developments, when combined with traditional farming wisdom, present a powerful tool for enhancing disease resistance in *C. annuum.* To capitalize on these opportunities, there is a pressing need for increased technical and financial support, as well as the establishment of modern processing and supply centres that meet international standards. This review advocates an integrated approach to enhancing disease resistance. This integrated strategy not only promises to improve crop yields and farmer livelihoods but also expands opportunities for economic growth.

Acknowledgements

This review study was supported by Universiti Sultan Zainal Abidin (UniSZA), DPU-2 grant number RD073, project reference code (UNISZA/2023/DPU 2.0/20). The authors also extend their appreciation to Taif University, Saudi Arabia, for publication support through project number (TU-DSPP-2024-144).

Authors' contributions

SK drafted the manuscript. MMK developed the conceptual framework, edited the manuscript and prepared the figures. WA reviewed and improved the manuscript. AM edited the manuscript. MMA and MHS improved the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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