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Diseases in chilli (*Capsicum* spp.): A comprehensive overview with integrated management strategies

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Abstract
Chilli (*Capsicum* spp.) is one of the world's most important spice and vegetable crops. It is widely grown for its economic and nutritional value. The production of chilli is adversely affected by the widespread distribution of diseases caused by fungi, bacteria, viruses and nematodes. Such diseases incur heavy losses of yield and quality and most of them require intensive management practices. This review covers the complete pathogenesis of the various common diseases affecting the cultivation of chilli, including damping-off, anthracnose, leaf spot, powdery mildew, wilt, mosaic, leaf curl and root-knot nematode infestations. Each disease is discussed in terms of fungi species, symptoms, disease cycle, favourable climatic conditions and integrated disease management strategies including cultural, biological, chemical and host resistance strategies. Integration of integrated disease management (IDM) was found to promote sustainable fruit production not only but also minimize environmental impact and eliminate chemical residues in the produce. The aim of this review is to provide a comprehensive reference work for farmers, extension workers, researchers and students on the development of effective disease control strategies for cultivating chilli.

Keywords: Chilli diseases, *Capsicum* spp., fungal infections, bacterial wilt, viral diseases, nematodes, integrated disease management, IDM, crop protection, sustainable agriculture

Introduction

Chilli (*Capsicum* spp.) is an important food crop in the world, which belongs to the family Solanaceae and is grown on or in many different climates [11, 12]. It has been classified as a culinary food, a medicinal food and a profitable crop in food processing, trade and marketing [23]. Common varieties are: The world's largest and most commercially grown chilli crop is from India (*Capsicum*s), China, Mexico, Indonesia and Thailand, all of which produce large quantities of chilli with significant area distribution, production and consumption, respectively. According to FAO (2023), world-wide production of chilli exceeds 4. 5 million metric tons every year with Indians accounting for more than 36% of chilli [65, 110]. Nearly 7, 000 years ago, chilli plants were believed to have appeared in central and south-American regions [38]. Evidence from archaeological sites suggests that they were one of the first crops domesticated there. It was introduced to other parts of the world following the voyage of Christopher Columbus (circa 1520-38) in the late 15th century [50, 51]. Portuguese traders brought chilli with them to India by the 16th century when they found it an integral part of daily life and local cuisine. Many varieties of the plant's adaptation to its various climates contributed to the genetic diversity of its genetic race and the spread of various landraces [24, 100].

Chilli (*Capsicum* spp.) is one of the world's most important spice and vegetable crops. It is widely grown for its economic and nutritional value. The production of chilli is adversely affected by the widespread distribution of diseases caused by fungi, bacteria, viruses and nematodes [52, 111]. Such diseases incur heavy losses of yield and quality and most of them require intensive management practices [67]. This review covers the complete pathogenesis of the various common diseases affecting the cultivation of chilli, including damping-off, anthracnose, leaf spot, powdery mildew, wilt, mosaic, leaf curl and root-knot nematode infestations [53]. Each disease is discussed in terms of fungi species, symptoms, disease cycle, favourable climatic conditions and integrated disease management strategies including cultural, biological, chemical and host resistance strategies [66]. Integration of integrated disease management (IDM) was found to promote sustainable fruit production not only but also minimize environmental impact and eliminate chemical residues in the produce [13]. The aim of this review is to provide a comprehensive reference work for farmers, extension workers, researchers and students on the development of effective disease control strategies for cultivating chilli. Chilli (*Capsicum* spp.) is an important food crop in the world, which belongs to the family Solanaceae and is grown on or in many different climates [1]. It has been classified as a culinary food, a medicinal food and a profitable crop in food processing, trade and marketing [68]. Common varieties are: The world's largest and most commercially grown chilli crop is from India (*Capsicums*), China, Mexico, Indonesia and Thailand, all of which produce large quantities of chilli with significant area distribution, production and consumption, respectively [25]. It was introduced to other parts of the world following the voyage of Christopher Columbus (circa 1520-38) in the late 15th century [69]. Portuguese traders brought chilli with them to India by the 16th century when they found it an integral part of daily life and local cuisine. Many varieties of the plant's adaptation to its various climates contributed to the genetic diversity of its genetic race and the spread of various landraces [14, 112, 113].

Fungal Diseases in chilli

Damping-off

Damping-off is a serious disease that attacks seedlings of chilli in their infancy, at nursery level or when transplanted. It is caused by a collection of soil-borne pathogens, including *Pythium* spp., *Phytophthora* spp. and *Rhizoctonia solani* [39]. These pathogens promote it in moist conditions. Diseased seedlings are attacked by lesion bodies from which water flows to the collar area [70]. The lesions are water-soaked, tissue maceration occurs during which the seedling crumbles on its spines. Infected seeds do not germinate and these can result in poor plant stands and large losses at nursery level [15]. The characteristic symptom patterns and mechanisms of damping-off are as follows: High soil moisture, poor drainage, low temperatures (15-25 °C), excess number of seedbeds and un-decomposed organic matter occur in very favourable climates. Pre-emergence (seed rot) and post-emergence damping-off (collar rot) occur in conditions suitable for the disease [71]. Integrated Management of Damping-Off Pre-emergence damping-off is treated with biocontrol agents like Trichoderma harzianum (6-10 g/kg seed) or with fungicides such as Carbendazim (0. 2%). During the first three to four weeks before the sowing stage soil must be solarised to lower pathogen load. Crop rotation and using disease-free certified seeds are critical for long-term control [72, 73, 114].

Table 1: Overview of Damping-off Disease in Chilli

Aspect	Details
Pathogens	*Pythium spp., Phytophthora spp., Rhizoctonia solani*
Symptoms	Water-soaked collar lesions, seedling collapse, poor germination
Favourable Conditions	High moisture, low temperature, poor drainage, overcrowding
Management	Raised beds, seed treatment, soil solarisation, crop rotation

Integrated Management Strategies of Damping-off in chilli

Effective management of damping-off involves a combination of cultural, biological and chemical practices:

Cultural Control

- Establish raised nursery beds (15 cm above ground level) to enhance drainage and reduce water logging.
- Ensure proper spacing between seedlings to avoid overcrowding and improve air circulation.
- Avoid excessive watering; maintain optimal moisture levels in the nursery bed [74, 101].
- Practice crop rotation and deep ploughing during summer to reduce pathogen load in the soil.

Biological Control

- Treat seeds with *Trichoderma harzianum* or *Trichoderma viride* at 5-10 g/kg seed to suppress pathogen activity [2].
- Apply *Pseudomonas fluorescens* at 10 g/kg seed or incorporate into the soil at 2.5 kg/ha along with 50 kg of farmyard manure (FYM).
- Drench nursery beds with a suspension of *Trichoderma* spp. at 10 g/liter of water to control soil-borne pathogens [86].

Chemical Control

- Treat seeds with fungicides such as Captan (3 g/kg seed) or Carbendazim (1-2 g/kg seed) before sowing [102].
- Drench nursery beds with Copper oxychloride at 2.5 g/liter or Mancozeb at 3 g/liter to manage pathogen populations in the soil.
- Implementing these integrated management strategies can significantly reduce the incidence of damping-off, ensuring healthy seedling establishment and robust chilli crop production [54].

Anthracnose and Fruit Rot

Anthracnose and fruit rot is a disease caused by *Colletotrichum capsici* which, among others, is one of the most widespread and significant economic diseases of chilli in relation to growth and yield. It occurs during the pre-and post-harvest stages of fruits [16, 115]. The pathogen survives in crop residues and infected seeds and can spread rapidly in favour of the plant unfavourable conditions. In particular, it may cause severe reductions in yield and quality of fruits [40]. Significant symptoms typically develop as small, circular, sunken lesions on the fruit surface. The lesions then become larger and dark concentric rings with a pinkish spore mass on the centre. Severely infected fruits become soft and shrivelled and finally rot. In later storage period, even good-looking fruit can develop signs of the disease [3]. The plant also develops an anthracnose effect due to the presence of:--Warm and humid weather (25-30 °C and >90% relative humidity) is said to favour development of and spread of anthracnose. Rain splashes, overhead irrigation and mechanical injuries occur during harvesting and handling [26].

Integrated Management for Anthracnose in chilli

Integrated Disease Management (IDM) practices are essential for effective control of anthracnose and fruit rot. The following strategies are recommended:

Cultural Practices

- Use certified, disease-free seeds [103].
- Follow crop rotation with non-host crops to reduce inoculums build-up.
- Avoid injury to fruits during harvest and post-harvest handling.
- Remove and destroy crop residues after harvest to eliminate primary inoculums [87].

Biological Control

- Apply neem cake at 100 kg/ha in the nursery or field to suppress soil-borne phases of the pathogen.
- Use *Trichoderma harzianum* as a soil or seed treatment to competitively inhibit *Colletotrichum* spp [116].

Chemical Control

- Spray Carbendazim (0.1%) or Mancozeb (0.2%) at intervals of 10-15 days starting from flowering stage.
- Use a combination of contact and systemic fungicides in alternate applications to prevent resistance development [75].

Table 2: Overview of Anthracnose and Fruit Rot in Chilli

Aspect	Details
Causal Agent	*Colletotrichum capsici*
Symptoms	Circular, sunken lesions with concentric rings; pinkish spore masses
Favorable Conditions	Warm and humid climate; overhead irrigation; mechanical injuries
Cultural Control	Disease-free seeds, crop rotation, removal of infected debris
Biological Control	Neem cake application, *Trichoderma harzianum* seed/soil treatment
Chemical Control	Carbendazim (0.1%) or Mancozeb (0.2%) sprays every 10-15 days

Powdery Mildew

Powdery mildew (bug, disease) is a common disease of chilli that is caused by the fungal pathogen *Leveillula taurica* [4]. It is commonly seen in dryland farming regions and its main effect is foliar disease. It can also cause indirect loss of yield in some cases by loss of photosynthetic efficiency and speeding up defoliation. It appears as small, irregular chlorotic spots on the upper surface of the leaves at first [17, 117]. When progressing, a white to grayish powdery fungal growth occurs at the underside of the leaves [41]. In most instances infected leaves turn yellow, curl and drop prematurely damaging the plant and exposing fruits to sunscald and secondary infections [55]. In contrast to many other fungal pathogens, *Leveillula taurica* thrives in dry conditions with high relative humidity (>60%), mostly in well-canopied fields with poor air circulation. It spreads by wind dispersed conidia and can become epidemic under favourable conditions [27].

Integrated Management of powdery mildew in chilli

Integrated disease management of powdery mildew in chilli involves reducing pathogen spread and maintaining plant health through cultural, chemical and host resistance strategies:

Cultural Practices

- Maintain proper plant spacing to ensure good air circulation and reduce humidity build-up.
- Avoid excessive nitrogen fertilization, which encourages dense foliage susceptible to infection [42].

Chemical Control

- Spray wettable sulfur (0.2%) at the first sign of infection, especially effective during early stages.
- For systemic control, apply fungicides such as Hexaconazole (0.1%) or Tebuconazole, at 10-15 day intervals.
- Rotate fungicides with different modes of action to avoid resistance build-up [88].

Host Resistance

- Use resistant or tolerant chilli varieties if available in the local region [118].

Table 3: Overview of Powdery Mildew in Chilli

Aspect	Details
Causal Agent	*Leveillula taurica*
Symptoms	White powdery growth on the underside of leaves, chlorosis, early leaf drop
Favourable Conditions	Dry weather with high relative humidity (>60%)
Cultural Control	Proper plant spacing, balanced fertilization
Chemical Control	Wettable sulphur (0.2%), Hexaconazole or Tebuconazole sprays
Host Resistance	Use of resistant/tolerant varieties (if available)

Leaf Spot

Leaf spot is a severe foliar disease of chilli, caused by Cercospora capsici and occurs in nursery and field grown plants [56]. As it affects the plant's photosynthetic capacity, plant destruction can occur and defoliation, reduced flowering and poor fruit development can occur, leading to plant loss and defoliation [119]. At initial appearance, leaf spot first develops as small circular or irregular brown necrotic spots (with greyish centres) on the surface of older leaves [5]. These lesions enlarge and may coalesce creating large areas of dead tissue. In severe infections the affected leaves turn yellow and drop prematurely reducing plant viability and yield potential [76]. The fungus thrives in warm and humid conditions (more than 70% humidity) and low temperatures (20-28 °C). Concentration of canopies and poor airflow are generally factors conducive to the development and spread of leaf spot and reduces yield potential [28, 120].

Integrated Management of leaf spot in chillie

Integrated management of leaf spot requires a combination of sanitation, chemical application and cultural interventions:

Cultural Practices

- Collect and destroy infected plant debris, which serves as a source of primary inoculums.
- Ensure proper plant spacing and pruning to enhance air circulation and reduce humidity within the canopy.
- Use resistant or tolerant cultivars when available [89].

Chemical Control

- Apply Mancozeb (0.25-0.3%) or Copper oxychloride (0.3%) at 10-15 day intervals during disease-prone periods.

- Begin fungicide application at the first sign of symptoms and repeat as necessary based on weather and crop stage [29].

Table 4: Overview of Leaf Spot Disease in Chilli

Aspect	Details
Causal Agent	*Cercospora capsici*
Symptoms	Brown necrotic spots with gray centres; premature defoliation
Favourable Conditions	High humidity (>70%), moderate temperatures (20-28 °C)
Cultural Control	Remove infected debris, pruning for air circulation, plant spacing
Chemical Control	Mancozeb (0.3%), Copper oxychloride (0.3%) sprays at regular intervals

Fusarium Wilt

Fusarium wilt, caused by *Fusarium oxysporum* f.sp. *capsici*, is a serious soil-borne disease that affects chilli plants, especially in warm climates with prolonged monocropping practices [57]. The pathogen enters the plant through the roots and colonizes the vascular system, causing blockage and disrupting water and nutrient transport [43]. The first visible symptom is yellowing of the lower leaves, followed by progressive wilting of the entire plant. A key diagnostic feature is the brown discoloration of the vascular tissues, which can be observed by cutting the stem longitudinally [77]. The disease typically starts in isolated patches and can rapidly spread throughout the field under favourable conditions. Fusarium wilt thrives in warm soils (25-30 °C) and is exacerbated by continuous chilli cultivation, poor soil health and water stress. It persists in soil for many years in the absence of a host, making eradication difficult once established [18].

Integrated Management of Fusarium wilt in chilli

Since there are no curative measures once the plant is infected, prevention through integrated strategies is crucial:

Cultural Practices

- Practice crop rotation with non-host crops like cereals for at least 2-3 seasons.
- Implement soil solarisation (covering moist soil with transparent polythene sheets for 4-6 weeks during summer) to reduce soil inoculums levels.
- Improve soil drainage and organic matter content to support beneficial microbes [90].

Biological Control

- Apply Pseudomonas fluorescens and Trichoderma viride to soil at 2.5-5 kg/ha mixed with compost or farmyard manure.
- Seed treatment with these bioagents also reduces initial infection [30, 121].

Host Resistance

- Use resistant or tolerant cultivars, which offer effective and sustainable disease suppression [91, 122].

Table 5: Overview of Fusarium Wilt in Chilli

Aspect	Details
Causal Agent	*Fusarium oxysporum* f.sp. *capsici*
Symptoms	Yellowing, wilting and vascular browning of stem tissues
Favourable Conditions	Warm soil (25-30 °C), monocropping, water stress
Cultural Control	Soil solarisation, crop rotation, good drainage
Biological Control	*Pseudomonas fluorescens*, *Trichoderma* spp. soil and seed treatments
Host Resistance	Use of resistant/tolerant cultivars

Bacterial Diseases

Bacterial Leaf Spot

Bacterial leaf spot, caused by *Xanthomonas campestris* pv. *vesicatoria*, is a widespread and economically important bacterial disease of chilli. It affects foliage and fruits, reducing photosynthetic area, causing premature defoliation and compromising marketability of the produce due to visible blemishes [31]. Symptoms begin as small, water-soaked lesions on the leaves, which later enlarge and become brown and necrotic, often with a yellow halo. These lesions may coalesce, causing large areas of dead tissue and leaf drop [44, 123]. On fruits, the bacterium causes slightly raised, rough, scab-like spots that reduce fruit quality. In severe cases, the disease may cause significant yield losses due to premature defoliation and fruit drop [78]. The disease thrives under warm (25-30 °C) and moist conditions, particularly with frequent rainfall, overhead irrigation or high relative humidity. The pathogen spreads through contaminated seeds, transplants, rain splash and handling of wet plants [92].

Integrated Management of bacterial leaf spot in chilli

Effective management of bacterial leaf spot focuses on prevention and sanitation, as bacterial diseases are generally difficult to control after establishment:

Cultural Practices

- Use certified disease-free seeds and healthy transplants to prevent introduction of the pathogen.
- Avoid overhead irrigation, which promotes splash dispersal of bacteria.
- Practice crop rotation with non-host crops like cereals to reduce inoculums in the soil [93].

Chemical Control

- Apply copper-based bactericides (e.g., copper oxychloride at 0.3%) starting from the nursery stage.
- Combine with streptomycin-based antibiotics only under expert supervision, to minimize resistance risks [19, 124].

Sanitation
- Remove and destroy infected plant debris.
- Disinfect tools and equipment used in the field [6, 125].

Table 6: Overview of Bacterial Leaf Spot in Chilli

Aspect	Details
Causal Agent	*Xanthomonas campestris* pv. *vesicatoria*
Symptoms	Water-soaked lesions on leaves/fruits, turning necrotic with yellow halos
Favourable Conditions	Warm (25-30 °C), humid environments; overhead irrigation
Cultural Control	Use certified seeds, avoid overhead irrigation, rotate with non-hosts
Chemical Control	Copper-based sprays (e.g., copper oxychloride 0.3%)
Sanitation	Remove infected debris, disinfect tools

Bacterial Wilt
Bacterial wilt, caused by *Ralstonia solanacearum*, is one of the most devastating and rapidly spreading bacterial diseases affecting chilli and other solanaceous crops [79]. It primarily attacks the vascular system, causing sudden wilting and plant death [58]. The disease is soil-borne and difficult to control once established in the field. Initial symptoms include sudden wilting of leaves without any yellowing. As the disease progresses, leaves may droop permanently and the whole plant may collapse [80]. A tell-tale sign is bacterial ooze—a milky exudates—from freshly cut stem sections when placed in water. Internally, infected plants show browning of the vascular tissues, especially near the collar region. The bacterium thrives in high temperatures (28-35 °C) and poorly drained soils. It can persist in soil, water and infected plant debris for years, making it especially problematic in continuously cropped fields [20, 126].

Integrated Management of bacterial wilt in chillie
Managing bacterial wilt involves sanitation, soil health improvement and the use of resistant materials:

Cultural Practices
- Avoid planting chilli in fields with a history of bacterial wilt, especially if tomato or brinjal was previously grown.
- Improve soil drainage through raised beds or ridges.
- Use grafted plants with resistant rootstocks to reduce susceptibility [94].

Chemical & Soil Treatments
- Apply bleaching powder (10-20 kg/ha) to the soil before planting to suppress the bacterial population.
- Incorporate lime and organic matter to improve soil health and suppress pathogen growth [104].

Sanitation
- Remove and burn infected plants as soon as symptoms appear to prevent spread.
- Disinfect pruning tools and irrigation equipment [32, 127].

Table 7: Overview of Bacterial Wilt in Chilli

Aspect	Details
Causal Agent	*Ralstonia solanacearum*
Symptoms	Sudden wilting, brown vascular tissue, bacterial ooze
Favourable Conditions	High temperatures (28-35 °C), poor soil drainage
Cultural Control	Avoid solanaceous crops in rotation, use grafted plants, improve drainage
Chemical Control	Soil drenching with bleaching powder (10-20 kg/ha)
Sanitation	Remove infected plants, disinfect tools and equipment

Viral Diseases
Chilli Mosaic Virus
Chilli mosaic, predominantly caused by the Cucumber mosaic virus (CMV), is a significant viral disease that affects the growth and productivity of chilli crops globally [45]. This disease results in a range of physiological distortions, making the crop commercially unviable if infection occurs early in the season [81, 129]. Symptoms typically include mosaic or mottling patterns on young leaves, which appear light green and yellow interspersed with dark green patches [105, 106]. Infected plants also exhibit leaf distortion, reduced internodal length and stunted growth. Fruits may develop malformations, reduced size and irregular colouring, rendering them unsuitable for market sale [95]. The virus is not seed-transmitted in most cases but is primarily spread by aphid vectors—notably *Myzus persicae* and *Aphis gossypii*—in a non-persistent manner, meaning even brief feeding can transmit the virus. Warm temperatures and high aphid populations significantly contribute to disease outbreaks [59, 130].

Integrated Management of mosaic in chilli
Effective management of Chilli Mosaic Virus focuses on vector control, cultural practices and preventive measures:

Cultural Practices
- Use virus-free seeds and seedlings sourced from certified nurseries [7].
- Install reflective mulches (e.g., silver-collared polyethylene film) around the base of plants to deter aphid landing.
- Remove and destroy infected plants promptly to reduce virus reservoirs [107, 131].

Chemical Control
- Apply systemic insecticides, such as Imidacloprid (0.3 ml/L) or Thiamethoxam, to control aphid vectors.
- Spray neem-based botanical insecticides as a part of IPM to reduce reliance on chemicals [33].

Host Resistance
- Cultivate CMV-resistant or tolerant chilli varieties where available [96].

Table 8: Overview of Chilli Mosaic Virus

Aspect	Details
Causal Agent	*Cucumber mosaic virus* (CMV)
Symptoms	Mosaic patterns, leaf distortion, stunting, malformed fruits
Vector	Aphids (*Myzus persicae, Aphis gossypii*)
Favourable Conditions	Warm weather, high aphid activity
Cultural Control	Virus-free seed, reflective mulch, removal of infected plants
Chemical Control	Imidacloprid or Thiamethoxam sprays to control aphids
Host Resistance	Use of resistant or tolerant varieties

Chilli leaf curl virus (ChiLCV)
Chilli leaf curl virus (ChiLCV), caused by the Begomovirus complex, is a major viral disease affecting chilli crops, particularly in tropical and subtropical regions [46]. The virus causes significant economic losses by reducing yield quality and quantity, as it severely impacts plant growth and fruit development [34]. The primary symptoms of ChiLCV are curling and crinkling of leaves, often accompanied by yellowing or chlorosis along the veins. Infected plants exhibit stunted growth and the fruits tend to be smaller and malformed. In severe cases, the plants may become unproductive and the yield can be significantly reduced [60]. The virus is mainly spread by whiteflies (*Bemisia tabaci*), which are the primary vectors. ChiLCV can severely damage the crop during the early stages of infection, especially if the virus is introduced early in the growing season. Warm temperatures and high whitefly populations contribute to the rapid spread of the virus in the field [20].

Integrated Management of leaf curl virus in chilli
Effective management of ChiLCV focuses on preventing virus spread, vector control and using resistant varieties:

Cultural Practices
- Use resistant or tolerant hybrids to reduce the risk of infection [108].
- Rogue infected plants early in the season to minimize the source of infection and prevent further spread.
- Sanitize equipment to avoid the mechanical spread of the virus during field activities [82].

Vector Control
- Deploy yellow sticky traps in the field to monitor and trap whiteflies.
- Apply neem-based insecticides (like neem oil or azadirachtin) to reduce whitefly populations in an eco-friendly manner [8].
- Use systemic insecticides (e.g., Imidacloprid) as part of an integrated pest management (IPM) strategy for controlling whiteflies.

Prevention
- Avoid late planting in areas where whitefly populations peak, to reduce the exposure period to high vector pressure [97].

Table 9: Overview of Chilli leaf curl virus (ChiLCV)

Aspect	Details
Causal Agent	*Begomovirus* complex (ChiLCV)
Symptoms	Leaf curling, crinkling, stunted growth, yellowing, reduced fruit size
Vector	Whiteflies (*Bemisia tabaci*)
Favourable Conditions	Warm temperatures, high whitefly populations
Cultural Control	Use resistant hybrids, rogue infected plants, sanitize tools
Vector Control	Yellow sticky traps, neem-based insecticides, Imidacloprid
Prevention	Avoid late planting, manage vector pressure early

Tobacco Mosaic Virus (TMV)
Tobacco mosaic virus (TMV) is a well-known viral disease that affects a wide range of crops, including chilli [98]. TMV causes significant yield loss by affecting the physiological functioning of plants, particularly during the early stages of infection [35]. It is highly contagious and spreads easily, primarily through contact transmission. Symptoms of TMV include mosaic mottling on leaves, with areas of light and dark green. Over time, the leaves may exhibit shrinkage and a brittle texture, leading to reduced photosynthesis and plant vigour. Infected plants may show signs of stunted growth, reduced fruit set and poor-quality produce [61]. TMV is primarily spread by mechanical transmission—through contaminated tools, workers' hands and the handling of infected plants. It is also carried by tobacco or other plant residues from previous crops, as well as through direct plant-to-plant contact [83]. TMV is a hardy virus and can persist in the environment for extended periods, often remaining viable on tools, hands and plant debris. Due to its ability to spread easily, it poses a serious threat to chilli production [47].

Integrated Management of tobacco mosaic virus in chillie
Managing TMV involves preventive measures and sanitation, as there is no cure for the disease once it is established:

Cultural Practices
- Sanitize tools, hands and equipment regularly to prevent the mechanical spread of the virus.
- Avoid smoking in the field or working with infected plants, as tobacco products can introduce the virus to healthy plants [62].

- Remove and destroy infected plant material promptly to reduce the risk of spreading the virus.

Use of Resistant Varieties
- Plant TMV-tolerant or resistant varieties to minimize the impact of the disease and reduce virus spread [9].

Prevention
- Implement strict field hygiene practices to reduce contamination from external sources.
- Rotate crops and avoid planting tobacco near chilli fields to prevent cross-infection [84].

Table 10: Overview of Tobacco Mosaic Virus (TMV)

Aspect	Details
Causal Agent	*Tobacco mosaic virus* (TMV)
Symptoms	Mosaic mottling, leaf shrinkage, brittle texture, stunted growth
Transmission	Contact, contaminated tools, tobacco products, plant-to-plant transmission
Cultural Control	Sanitize tools and hands, remove infected plants, avoid smoking in fields
Resistant Varieties	Use TMV-tolerant or resistant varieties
Prevention	Implement field hygiene practices, avoid planting tobacco near fields

Future Prospects and Research Needs
- As chilli cultivation faces increasing challenges from evolving pathogens, climate variability and changing agricultural practices, a proactive approach is required to safeguard yields and improve crop resilience. Future efforts must focus on integrating scientific advancements with on-ground practices to develop sustainable and long-term solutions for chilli disease management [63, 64, 99].
- One of the most promising avenues is the breeding of multi-disease resistant varieties. Current resistant lines often target single diseases, leaving crops vulnerable to complex pathogen pressures. Advances in molecular breeding, marker-assisted selection and CRISPR-based gene editing offer opportunities to develop cultivars that can withstand multiple pathogens simultaneously, including viruses, fungi and bacteria. This approach can drastically reduce the need for chemical interventions and improve farmer profitability [48, 49, 85, 109].
- The development of biopesticides and nano-formulations is another exciting frontier. Biopesticides derived from beneficial microbes (like *Trichoderma*, *Pseudomonas* and *Bacillus* spp.) and plant extracts are eco-friendly alternatives to chemical pesticides. Nano-formulations can enhance the stability, efficacy and controlled release of active ingredients, improving disease control while minimizing environmental impact and residue issues [10].
- Improving disease prediction tools is also critical. With the help of artificial intelligence (AI), remote sensing and big data analytics, it's becoming increasingly possible to predict disease outbreaks based on weather conditions, crop history and pathogen dynamics. Early warning systems, integrated with mobile apps or extension networks, can empower farmers to take timely action and reduce crop losses [36, 37].
- Finally, the success of Integrated Disease Management (IDM) depends heavily on farmer participation. Farmer training programs that focus on recognizing disease symptoms, adopting sanitation practices and understanding the safe use of fungicides and biocontrol agents are essential. Extension services and participatory research can bridge the gap between lab-based innovations and field-level application, ensuring that scientific breakthroughs translate into real-world impact [21, 22, 100].

Conclusion

Diseases in chilli present a persistent and significant threat to the crop's productivity, quality and marketability, often leading to considerable economic losses for farmers. Traditionally, disease control has relied heavily on chemical inputs, but growing concerns about resistance development, environmental impact and consumer safety have necessitated a more holistic approach. A shift toward Integrated Disease Management (IDM) is imperative for ensuring sustainable chilli production. IDM involves the strategic combination of cultural practices, biological control agents, chemical treatments and the use of resistant varieties, tailored to specific agro-climatic conditions and disease pressures. By integrating these components, farmers can minimize crop losses, reduce pesticide dependence and enhance the long-term health of their farming systems. Proactive disease management—founded on early detection, continuous monitoring and timely intervention—is essential. Furthermore, farmer education, community-level awareness and policy support for research and extension will play a crucial role in translating knowledge into action. The future of chilli cultivation lies in adaptive, research-driven approaches that are economically viable, ecologically safe and socially acceptable.

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