PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–14
https://doi.org/10.14719/pst.5064

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REVIEW ARTICLE

Advancements and challenges in onion phytopathogens management: A comprehensive review

Yazhini P[1], Angappan K[1*], Karthikeyan M[1], Anandham R[2], Anitha B[3] & Nivedha M[1]

[1] Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

[2] Department of Microbiology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

[3] Department of Nematology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

*Email: angappan.k@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 14 September 2024
Accepted: 13 October 2024
Available online
Version 1.0 : 22 November 2024

Check for updates

Additional information

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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Yazhini P, Angappan K, Karthikeyan M, Anandham R, Anitha B, Nivedha M. Advancements and challenges in onion phytopathogens management: A comprehensive review. Plant Science Today.2024;11(sp4):01-14. https://doi.org/10.14719/pst.5064

Abstract

Onion (*Allium cepa* L.) stands as a vital commercial vegetable globally, ingrained in the culinary practices of homemakers worldwide. Beyond its culinary significance, the organosulfur compounds found in onions provide a solution for managing plant diseases. Onions face escalating disease challenges despite various antimicrobial properties due to climate fluctuations and pathogen evolution. Biotic factors, including fungi, bacteria, viruses and insects, contribute to pre-harvest and postharvest losses, accounting for nearly 50% yield reduction in fields and 10-30% loss in storage conditions. The importance of integrated disease management practices, such as early detection using e-nose, conventional methods, biological control and novel biotechnological tools, including CRISPR/Cas, were explained. Therefore, implementing effective control measures at the field level is crucial to mitigating these losses. This review emphasizes the need for continued research to provide more practical and long-lasting solutions for controlling onion phytopathogens.

Keywords

onion; phytopathogens; yield loss; disease cycle; management strategies

Introduction

Onion, botanically known as *Allium cepa* L. (*Amarylidaceae*), is a ubiquitous spice and vegetable from southern Asia (1). Its global presence underscores its significant economic value in culinary and therapeutic domains (2). China is the foremost producer of onions worldwide, followed by India, while the Netherlands, Spain and India lead in onion exports. In India, the annual onion production of 30205.3 MT yields 17.4 MT per ha across 1740.5 ha under cultivation (Indiastat, 2023) (https://www.indiastat.com). Maharashtra emerged as the leading onion producer in India, followed by Gujarat and Karnataka (3). Onion bulbs' distinct flavour, aroma and pungency are due to the volatile compound "oil allyl-propyl disulphide". Rich in bioactive substances, onions harbour potential anti-inflammatory, anti-cancer, antioxidant and anti-obesity properties (4). Further, propyl-propane thiosulfinate (PTS) and propyl-propane thiosulfonate (PTSO) noticed by Falcón- Piñeiro et al. (5) in onion can be applied as a revolutionary solution for plant diseases like *Clavibacter michiganensis* sp. *michiganensis* in tomato, *Fusarium graminearum* in maize and *Penicillium digitatum* in sweet orange.

Despite their culinary and medicinal allure, onions face numerous threats from biotic and abiotic factors. Microbial deterioration accounts for

15%-20% of postharvest losses, while poor handling, sprouting, rotting, careless storage and a lack of infrastructure can cause up to 40% of losses (6). Fungal, bacterial and viral infections, including white rot, neck rot, soft rot, purple blotch, *Fusarium* basal rot, downy mildew, pink root, damping-off, smudge, black mould, bacterial brown rot and onion yellow dwarf, significantly impact onion production and quality (7). Beyond diseases, insects such as thrips, maggots and nematodes like stem and bulb nematodes, root-knot nematodes and stubby root nematodes and environmental stresses like drought, salinity and cold pose risks to onions both in the field and during storage, (8) diminishing onion quality and yield. Latent infections acquired in the field exacerbate postharvest losses during warehouse storage periods. Addressing these challenges is pivotal for sustaining onion production and meeting global demand. For these biotic challenges, recent management strategies, viz., sensor-based Internet of Things (IoT) systems, mobile applications like PlanteSaine developed using artificial intelligence (AI), electronic noses (e-nose) for early detections, CRISPR/Cas, and other biotechnological tools (9-11) were addressed. Data analytics in crop decision support systems (DSS) is transforming modern agriculture by utilizing AI, machine learning, and deep learning technologies. These tools enable precise decision-making by analyzing real-time data from sensors, satellite imagery and weather stations and help farmers to detect crop diseases early, improve pest management, select resistant crop varieties, optimize fertilization, schedule irrigation and make informed choices for better yields (12). So, in this paper, we reviewed some recent disease management techniques and evaluated their importance in the integrated disease management of onions (Table 1).

Table 1. Major diseases of onion with their management strategies.

Disease	Causal organism	Management strategy	References
Basal rot	*Fusarium oxysporum* f. sp. *cepae*	Detection of infected bulbs using Electronic nose (e-nose)	(11)
		Biological control of basal rot by yeast *Saccharomyces cerevisiae* effective in controlling FBR under greenhouse conditions	(29)
		Chemical control by the mixture of Fludioxonil 2.5% + Seamen 2.5%	(28)
Stemphylium blight	*Stemphylium vesicarium* (Wall.) Simmons	The combination of Azoxystrobin 25% + Flutriafol 25% SC at 25 g a.i. /ha can manage Stemphylium blight under field conditions	(44)
		Spraying botanicals like 10% clove extract or 10% *Alovera* extract	(46)
		Foliar application of salicylic acid	(48)
		Diagnosing purple blotch using convolutional neural network (CNN) technique	(50)
Purple blotch	*Alternaria porri* (Ellis) Cif.	Foliar spraying of botanicals formulated with *Moringa oleifera* showed the highest efficacy, followed by *Azadirachta indica* and *Allium sativum*	(56)
		Increased seed quality and reduced Infection by nano-priming of onion seeds with ZnO	(61)
		Incorporation of resistant genes like ApR1 into onion against *Alternaria*.	(62)
Anthracnose/ Twister/seven curl disease	*Collectotrichum gloeosporiodes*	Application of Biological control with combination of *Trichoderma viride* 10g/l + *Pseudomonas* at 10 g/l	(67)
		Seed treatment with plant oils like clove and citronella reduce inoculum	(72)
Downy mildew	*Peronospora destructor*	Use of resistant cultivars such as *Superprecoce – Agroecológica* and *Bola Precoce - Agroecológica* integrated with Ridomil® Gold MZ	(105)
		Low plant population (0.71 million plants/hectare) treated with spraying of mancozeb + metalaxyl at the interval of 15 days	(106)
		Application of Nutrient sources like Nitrogen and Potassium tranches in fertigated no-tillage systems has little effect on the severity of downy mildew with low-density planting.	(107)
Blast/Neck rot	*Botrytis allii*	Red-scaled cultivars instead of white cultivars are preferable	(84)
		Polyclonal antibody (pAb) developed using antigen from neck rot in onion caused by *B. alli* can be used for early and rapid detection of neck rot	(85)
Black mold	*Aspergillus niger*	Spraying of essential oils like palmosa oil (0.60ml/l) and plant hormones like salicylic acid (20mM) reduce postharvest Infection	(86) (87)
		Ethanol extract of *Jatropha curcas* leaf and seed at the rate of 40 mg/ml effectively controls black mould of onion	(93)
		Eugenol fumigation can be used to reduce black mould incidence during the storage period	(90)
1. Iris Yellow Spot Virus (IYSV) (Tospovirus) 2. Onion Yellow Dwarf Virus (Potyvirus)		CRISPR/Cas-based approaches offer the advantage of targeting both DNA and RNA with high specificity and sensitivity, making them an emerging technique for use in managing plant viral diseases	(104)
		Vector control is important. Application of fipronil 5% SC @ 1.0 mL l-1 for thrips)	(108)
		Using machine learning (ML)-based image analysis, the vector population for onion viral diseases could be identified with 96.3% accuracy by linking weather and soil data. Additionally, three of the twelve pesticide calendar sprays can be prevented.	(9)

Fusarium basal rot (FBR)

Fusarium oxysporum f.sp. *cepae* (FOC) is a soil-borne fungus responsible for Fusarium basal rot (FBR) in onions, leading to yield losses of over 50% in crops and 30-40% in stored produce and has been reported from Asia, Europe, America and Africa (4), (13)-(15). The fungus infiltrates the basal plate during different growth stages, often facilitated by pests like maggots, leading to bulb rot (16) and severe infections result in complete decay of the basal plate with visible white mycelial growth (17,18). FBR incidence is higher during storage and spreads through contaminated soil (19,20).

In India, the dominant species were *F. oxysporum, F. solani* and *F. proliferatum* (21,22). Globally, reported species encompass *F. commune, F. acuminatum, F. anthophilium, F. redolens, F. verticillioides, F. equiseti, F. culmorum, F. triticinum, F. falciforme, F. brachygibbosum* and *F. acutatum* (23)-(24) were involved in basal rot incidence. As *Fusarium*, a soil-borne fungus persists in the soil as chlamydospores, saprophytes, or infected plant debris. Contaminated soil is pivotal in short-distance FBR spread (Fig. 1) (18). In Karnataka, India, FBR incidence is minimal in dry seasons with loamy soils and maximal during rainy seasons with black soils (24). Effective FOC infestation and disease development necessitate moisture and high temperatures, with an optimum range of 25-32°C (25). Disease incidence varies by season and soil type, with higher susceptibility in transplanted onions and organic farms (26).

Management strategies

Being soil-borne, FOC poses challenges in control due to long-lasting survival structures like chlamydospores. Cultural techniques include crop rotation, clean transplanting, certified planting materials and resistant cultivars. A rotation system involving non-host crops for at least four years can inhibit loss due to FBR (27) and transplanted onions are more susceptible than direct-seeded ones. Fungicides like Imidazoles 50% WP (Prochloraz-manganese) and Triazoles 20% SC (Tebuconazole) are commonly used to control FBR (19), followed by 0.15% Prochloraz and a mixture of Fludioxonil + Sedaxen (28) was studied to control FOC and *F. acutatum* effectively. Overall results show that Prochloraz is an effective chemical in controlling FBR. However, chemical usage is gradually phasing out due to associated adverse effects. Biocontrol agents and organic amendments offer eco -friendly alternatives.

The yeast *Saccharomyces cerevisiae* effectively controlled FBR under greenhouse conditions (29). *Bacillus* strains protect onion roots from pathogen invasion, promote plant growth and solubilize soil phosphorus (30). Phosphate-solubilizing bacteria (PSB) suppress FBR mycelial growth through various diffusible antifungal substances (31). When applied as seedling dips, Trichoderma viride and Pseudomonas fluorescens significantly reduce disease under field conditions (2). Combining *Trichoderma* spp. with arbuscular mycorrhizal fungi further diminishes basal rot incidence (32). Employing gas chromatography ion-mobility

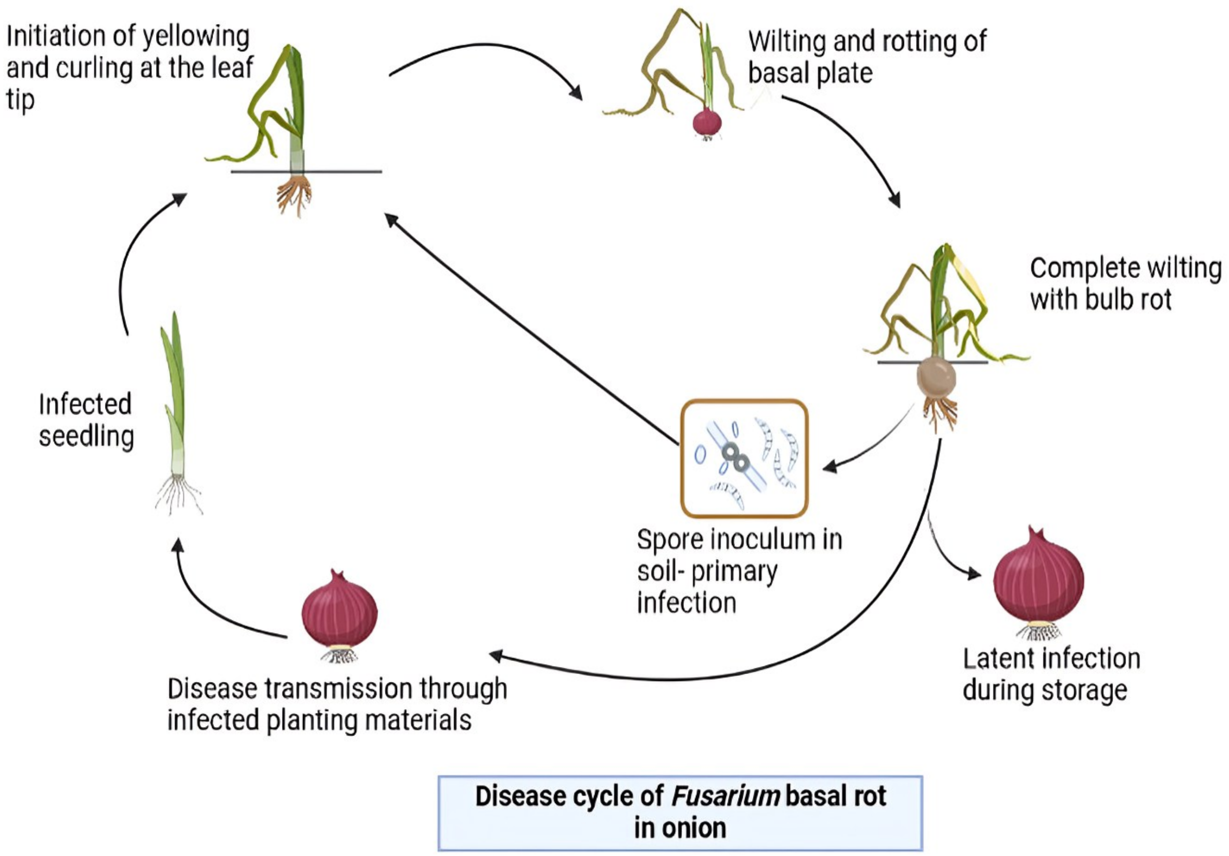

Fig. 1. Disease cycle of onion basal rot caused by *Fusarium oxysporum* f.sp. *cepae*. Fusarium basal rot in onions starts with diseased seedlings, causing curling and yellowing at leaf tips. The pathogen enters plants through the basal plate, causing primary Infection and wilting. Contaminated planting materials and soil further spread the disease.

spectrometry (GC-IMS) in detecting diseases is becoming a new technology that compares volatile organic compounds produced by the produce when infected and healthy. Wesoly et al. (33) identified sulfides and di-sulfides produced by the infected bulbs that could be associated with basal rot in onions. So, further studies should be conducted to detect the diseased bulb accurately. Labanska et al. (11) made the first successful implementation of the electronic nose (e-nose) in identifying FBR-affected bulbs during the postharvest period, which showed 96.9% accuracy in detecting the infected bulbs of onions and proved the e-nose as an effective and fast method to detect the diseases. Mandal et al. (34) attempted to increase the resistance for FBR in onion cultivars by continuously inoculating the spores and recorded a partial resistance to FBR in selected short-day cultivars, which could be used in the coming days to develop commercial FBR resistance varieties.

Stemphylium leaf blight (SLB)

Stemphylium leaf blight is caused by *Stemphylium vesicarium* (Wallr.). E.G. Simmons (35)-(36) is a severe threat to onion farming globally, with rising infections in Northern and Eastern India. SLB affects many plants, including onions, cotton, spinach and others (37)-(38). The anamorph, *Sphaeria herbarum*, was first reported by C. H. Persoon in 1801, with the teleomorph stage identified as *Pleospora allii*, reported from Varanasi, India. The disease was notably recorded in 1975, spreading across multiple Indian states (39). SLB can lead to up to 90% yield loss in onions. The pathogen forms lesions on leaves, eventually killing the plant and is spread via seeds and spores, with weeds serving as reservoirs (36), (39, 40) (41). The primary inoculum of spores overwinter in weeds such as yellow nutsedge, red root pigweed, field horsetail and *Datura stramonium* (40), with conidia acting as secondary spreading agents (Fig. 2). Nainwal et al. (42) emphasized SLB's destructive potential, particularly when combined with Alternaria purple blotch, a significant challenge in onion production.

Management strategies

Adjusting the sowing date for the crop is the initial step for avoiding the disease. The incidence of SLB is comparatively reduced during the rainy season compared to the winter and summer seasons (43). Various cultural practices such as minimizing crop density, avoiding excessive application of nitrogen fertilizers, selecting resistant varieties and providing good drainage facilities are commonly followed. The combination of azoxystrobin 25% + flutriafol 25% SC at 25 g a.i./ha and fluopyram 20% + tebuconazole 20% SC @150 g a.i./ ha can manage stemphylium blight under field conditions (44). Traditionally, foliar fungicide sprays have been employed to manage SLB. However, Stricker et al. (41) stated that the development of insensitivity to the fungicides occurred, which was mainly attributed to their short asexual lifestyle and multiple disease cycles per season of the crop. So, turning to biological methods of controlling disease was preferable. The application of *Trichoderma harzianum* reduced SLB by 26% (45) and Mishra et al. (46) studied eight plant extracts and biocontrol agents against SLB in onions under *in vitro* conditions and revealed that 10% clove extracts of *Allium sativum* inhibited growth at the highest level (57.31%), followed by *Aloe vera* extract at 10% (47.15%) and

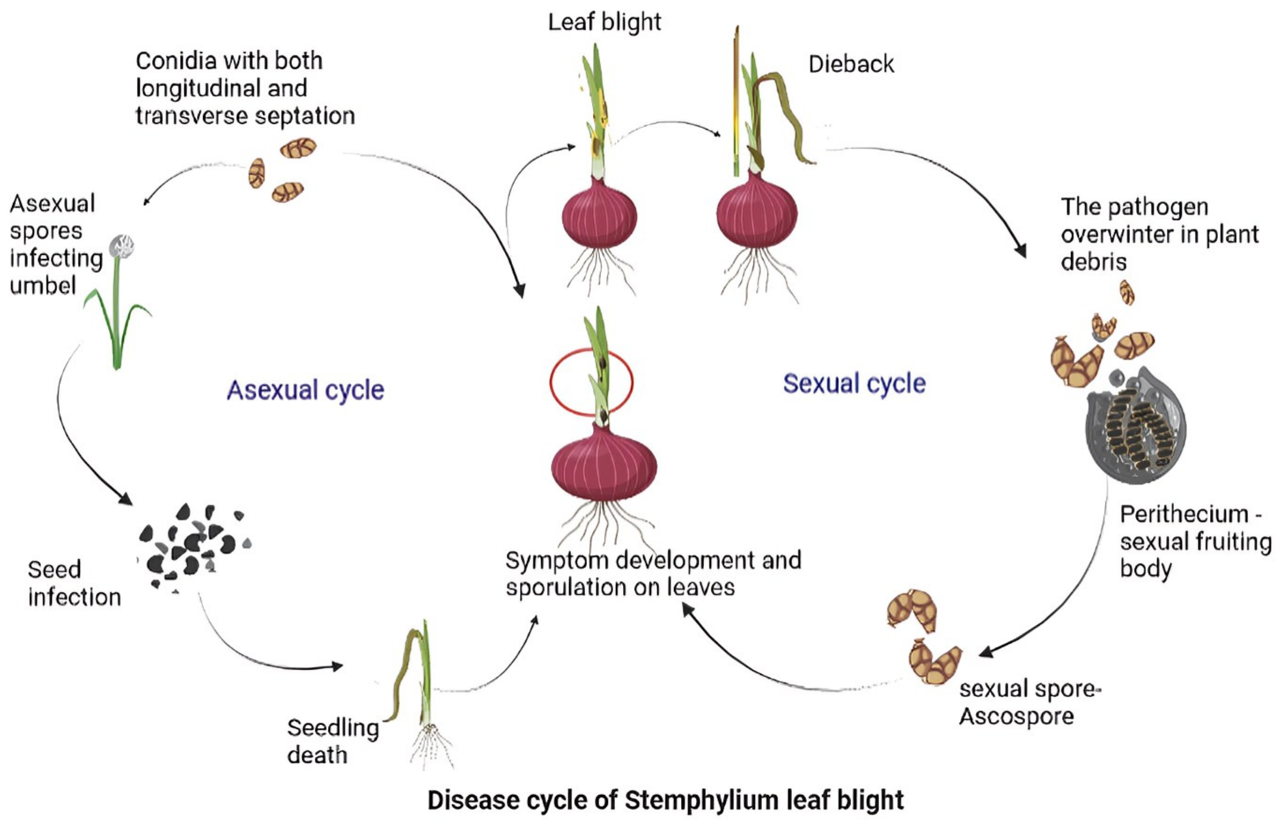

Fig. 2. Disease cycle of Stemphylium leaf blight in onion. Stempyhilium leaf blight has both asexual and sexual cycles, starting with seed infection by conidia, leading to leaf blight symptoms, dieback of onion plants and sporulation on leaves. The pathogen overwinters in plant debris, allowing further Infection.

T. viride outperformed other bioagents in terms of growth inhibition. Roylawar et al. (47) stated that the endophytic fungi from the root, *Piriformospora indica,* effectively reduced the SLB incidence by inducing resistance and promoting the bulb's growth. Abo-Elyousr et al. (48) reported a 40% reduction in disease incidence with the application of salicylic acid to the foliage, which induced the systemic acquired resistance and triggered the plant's defence system.

Onion Purple Blotch

Alternaria porri causes purple leaf blotch (PLB), a significant disease of onions, leading to crop losses of 30-100% annually in seed and bulb production. Symptoms include water-soaked lesions that develop into dark rings where the fungus sporulates, producing necrosis and wilt (49), (50). This disease, often occurring with Stemphylium leaf blight (SLB), forms a complex known as purple blotch complex (PBC) (51), (52). The fungus overwinters on infected crop debris, with wind and rain aiding in spore dispersal under favourable conditions (Fig. 3). Infection typically occurs through the stomata and epidermis and high humidity and temperatures favour disease development, particularly during March-April (53), (54).

Management strategies

Early disease detection is crucial for implementing effective management strategies. Zaki et al. (50) proposed using a convolutional neural network (CNN) technique to identify onion purple blotch in photos, achieving a classification accuracy of 85.47%. This study presents a new method for quickly and accurately diagnosing plant/crop diseases, laying the groundwork for deep learning in agricultural data. Various cultural strategies, such as reducing crop density, avoiding excessive nitrogen fertilizer application, selecting resistant cultivars, and ensuring adequate drainage in the field, are commonly employed for PLB management. Three sprays of 0.25% Ridomil MZ effectively inhibited disease severity to 4.4%, compared to 90.2% severity in the control (55). Ul Haq et al. (56) investigated three plant extracts against purple blotch in the field, with *Moringa oleifera* showing the highest efficacy, followed by *Azadirachta indica* and *Allium sativum*. *Aureobasidium pullulans, Sporobolomyces roseus, Cryptococcus luteolus* and *Penicillium* spp. isolates reduced *A. porri* infection by 79% (57). Three entomopathogenic fungi, *Metarhizium anisopliae*, *Beauveria bassiana* and *Verticillium lecanii*, inhibited *A. porri* development (58). Seed priming with aqueous extracts of nine plants effectively managed purple blotch (59). Micronutrients such as zinc, boron, magnesium, and botanicals proved effective, with a combination of micronutrients and botanicals recommended for bio-rational control (60). Nano-priming of onion seeds with zinc oxide (ZnO) and graphene oxide (GO) increased seed quality and protected against Infection (61). Quantitative trait loci (QTL) are regions of DNA associated with a trait or phenotype that varies within a population. QTL mapping identified the ApR1 gene conferring resistance to purple blotch, offering better resistance against *Alternaria* (62).

Anthracnose

Anthracnose, commonly known as the twister disease of onion, is caused by *Colletotrichum gloeosporioides* (63). In Brazil, it is addressed as cigar/hot dog disease (63). This disease poses a significant risk to onion cultivation during the wet season (64, 65). Recently, a new species, *C. siamense* from

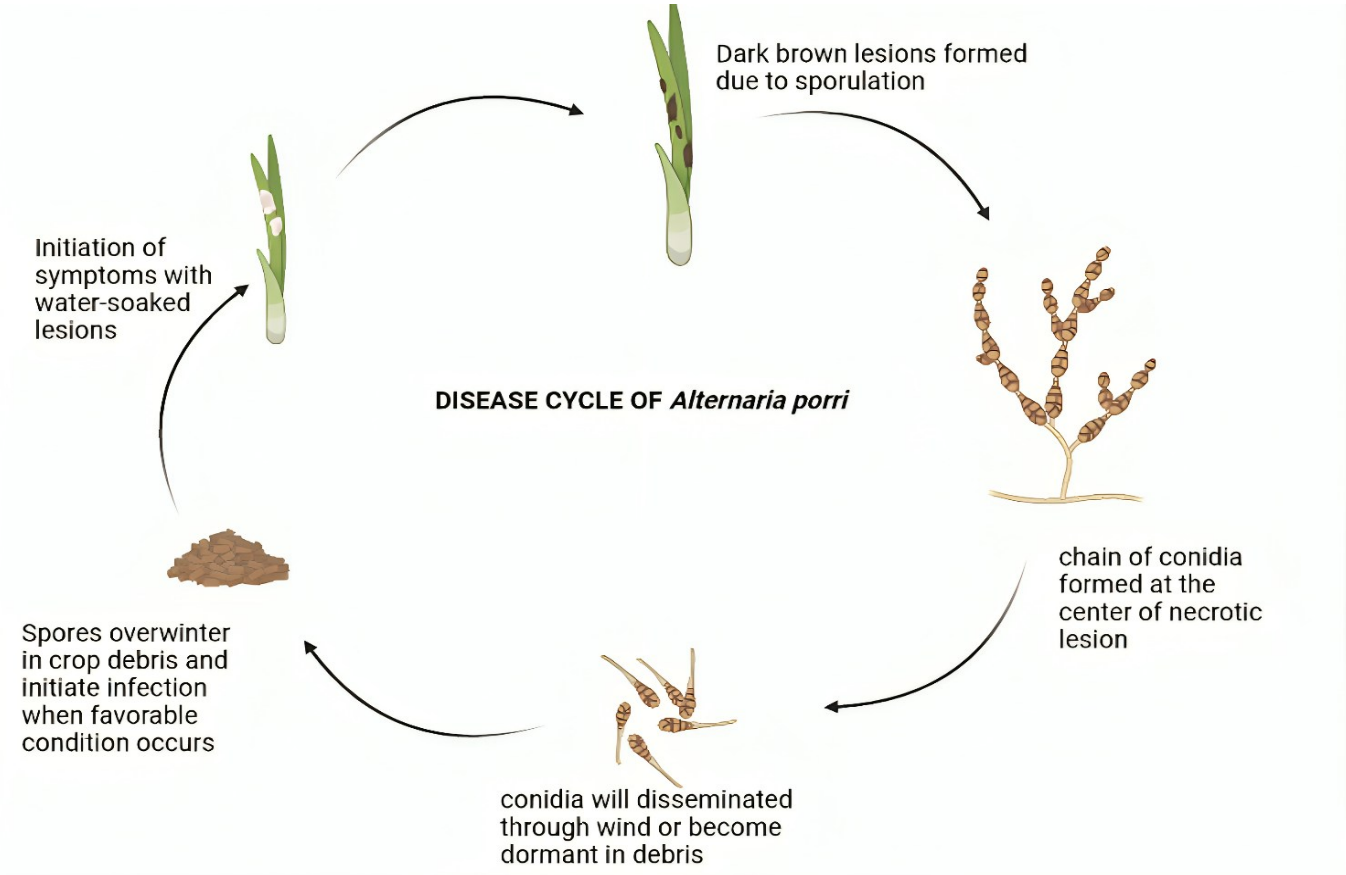

Fig. 3. The disease cycle of Alternaria porri is causing purple blotch. *Alternaria porri* disease starts with water-soaked lesions on onion leaves. It progresses to dark brown lesions due to sporulation, overwintering in crop debris and forming conidia at the centre of necrotic lesions.

Taiwan, was reported by Yuan et al. (66). Severe outbreaks occurred in Karnataka and Maharashtra during the Kharif seasons of 2019 and 2020, increasing onion demand (67). Symptoms include water-soaked lesions on leaf sheaths, which progress to necrotic zones. In severe cases, bulb rot and plant destruction occur. *C. gloeosporioides* cause the twister-anthracnose complex disease and *Fusarium* spp. is prevalent in tropical and subtropical regions (68), (69). The disease cycle typically does not start in the nursery but occurs in the field approximately 30 days after planting. Over time, the fruiting structure forms over the leaf (68). Rainfall favours the disease development, and the dissemination occurs readily in hot, humid environments, with transmission occurring through infected seeds, contaminated soil, wind-borne conidia and rain splashes. Leaf wetness promotes the pathogen germination, adhesion and penetration into host tissues (Fig. 4) (64).

Management strategies

Management strategies for anthracnose include using disease-free seeds and bulbs, crop rotation with non-host crops, cultivating resistant varieties, proper field sanitation, and ensuring adequate curing and drying of produce. Late transplanting and providing a space of 15×15 cm reduces the infestation (70). Pre-inoculation with nonpathogenic or avirulent pathogen strains can stimulate the plant defence system. Among various treatments, foliar application of carbendazim 12% + mancozeb 63% 75 WP at 2.5 g/l and propiconazole 25 EC at 1 ml/l showed promising results, followed by *Trichoderma* + *Pseudomonas* combination at 10 g/l concentration (67). Treating onion bulbs combined with the foliar spraying of *T. viride* effectively controls anthracnose (71). Seed treatment with some botanicals like clove oil and citronella oil effectively controlled anthracnose disease by reducing the inoculum load of the pathogen (72). Forecasting models, such as geographically weighted regression (GWR), can predict disease incidence based on environmental parameters, recommending measures such as reducing excess moisture, wider spacing, crop rotations, soil solarization and efficient drip irrigation systems to mitigate disease occurrence (73).

Downy Mildew

The downy mildew pathogen *Peronospora destructor* (Berk.) was first described by Berkley in 1841 as an obligate biotroph that poses significant challenges in treatment and can cause yield loss of up to 75% (74). The pathogen initiates Infection in onions, with violet growth over leaf and flower stalks (69). Later, brownish-purple velvet-like sporulation on mature leaves develops, leading to tissue collapse (75). The pathogen exhibits dichotomous branches with severely tapered ends. Conidia germinate into germ tubes, leading to the development of appressoria on leaf surfaces. Sporangia are light brown and ellipsoidal (76). This disease is prevalent in steep tracks and plains, particularly in high-humidity areas. The pathogen follows two infection cycles (Fig. 5). Primary Infection is induced by oospores in soil, which can be asymptomatic and secondary Infection is due to conidia from diseased leaves (77). Sporulation of the pathogen occurs in daily cycles of light and darkness, with temperature and humidity playing crucial roles in the process (78). The latency period after Infection varies

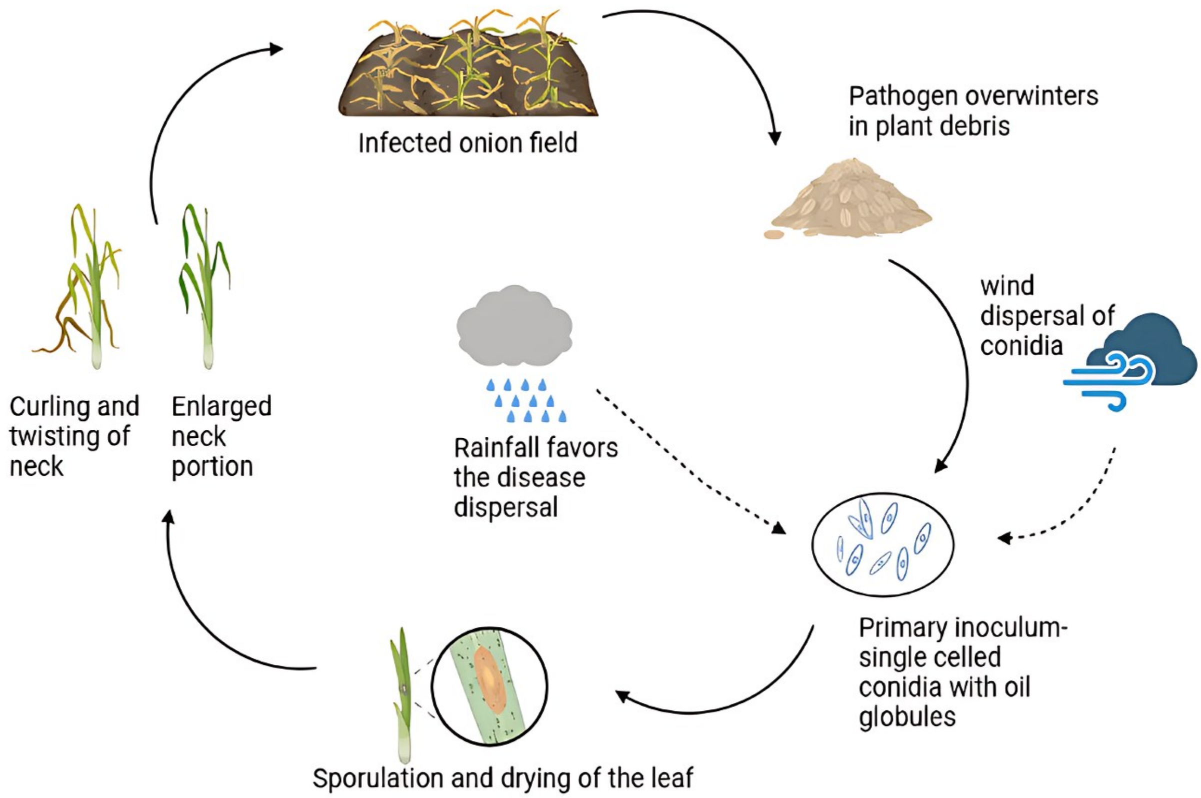

Fig. 4. Disease cycle of Anthracnose-twister disease of onion. The disease cycle of *Colletotrichum gloeosporioides* affects onions, starting with the pathogen overwintering in plant debris, dispersing conidia through wind and rain, establishing on the host, causing symptoms like sporulation, drying leaves and neck curling. The pathogen continues to overwinter and initiate future infections.

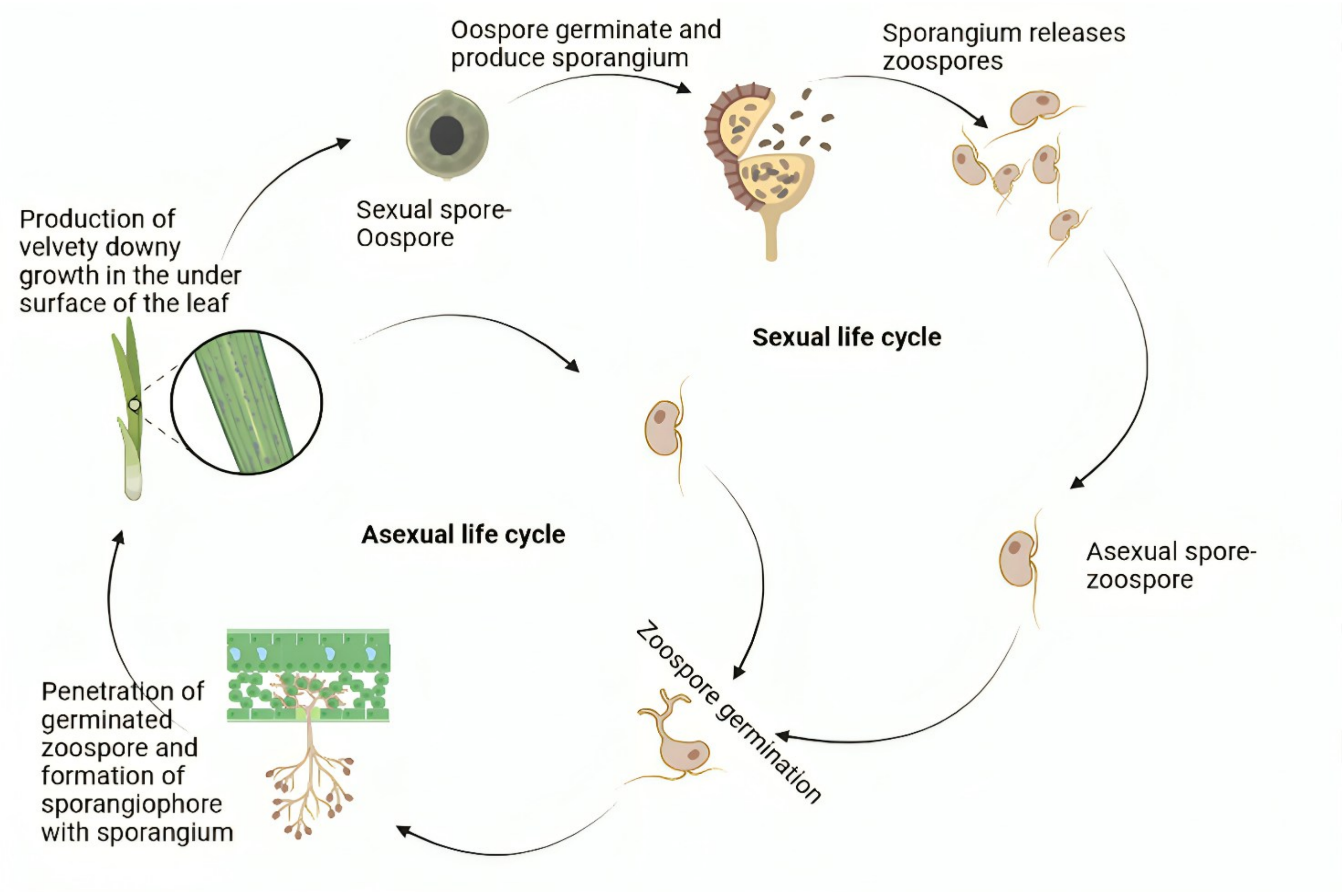

Fig. 5. Disease cycle of *Peronospora destructor* causing onion downy mildew. The sexual and asexual life cycles of a pathogen illustrate the formation of sporangia and sporangiophores in the sexual life cycle and the formation of velvety downy growth in the asexual life cycle. Both life cycles are essential for the pathogen's reproduction and the spread of the disease in the host.

depending on temperature and can range from 13 to 17 days.

Management strategies

Mishra et al. (69) reported that factors such as late crop planting, excessive fertilizer application, and frequent watering exacerbate its incidence. Exposing onion seeds to sunlight for at least 12 days has significantly reduced inoculum levels (69). Fujiwara et al. (77) developed alternative PCR primers for *P. destructor* using RNA sequencing data, enabling real-time PCR detection of the pathogen in plants and soil, even in symptomless infections. Fungicides such as metalaxyl 8% + mancozeb 64% have effectively controlled disease (79). Additionally, sprays containing a combination of metalaxyl-M (100 g/ha) + mancozeb (1600 g/ha) have shown promising results in disease management (74). In a study by Abd-Elbaky et al. (80), treatments with *Pseudomonas fluorescens*, limonene (L) and acetylsalicylic acid (ASA) reduced onion downy mildew severity, with foliar spraying of recommended fungicides being the most effective. A study by Kim et al. (81) also presented an on-site image-based field monitoring system for automatically detecting onion crop diseases like downy mildew, employing deep learning techniques for symptom recognition.

Blast/Neck Rot

Neck rot caused by *Botrytis allii*, a significant postharvest disease in onions, affects all *Allium* spp., including garlic, leek, and shallots, but onions are particularly susceptible to this pathogen (82). Neck rot causes more than 50% of yield losses in onions (75). Symptoms of neck rot manifest in the neck area of the onion, as the name suggests, followed by softening and rotting of the neck, which are prominently observed in infected onions. Under unfavourable conditions, the pathogen produces resting structures in mycelium or sclerotia (Fig. 6), which may be visible between the infected scales of onion bulbs. Sometimes, gray-colored mycelium is visible on the neck region (75). Other species, including *Botrytis allii*, *B. byssoidea*, *B. cepa* and *B. squamosal,* infect onions. *B. byssoidea* exhibits less sclerotial production with more mycelial growth, leading to mycelial neck rot, whereas the disease caused by *B. squamosal* is known as small sclerotial neck rot (82). Onion seeds carrying fungal inoculum in their internal tissues become a significant source of disease spread (55), (83).

Management strategies

For the management of neck rot disease, proper curing (1-2 weeks) followed by topping is recommended to prevent the spread of botrytis neck rot, as the disease can spread through green tissue and into the bulbs as infections do not spread in dry tissues (84). Leaving a 2-3-inch neck on the bulb is recommended to reduce the risk of rotting. Using resistant varieties also helps minimize the disease, with red-scaled onion cultivars generally more resistant than white-scaled ones. Sahoo et al. (85) developed a polyclonal antibody (pAb) for the early detection of antigens from neck rot in onions caused by *B. alli.* This can be used to detect neck rot at the early stage rapidly. Kou et al. (86) used palmarosa essential oil at a rate of 0.60 ml/l, which showed maximum neck rot

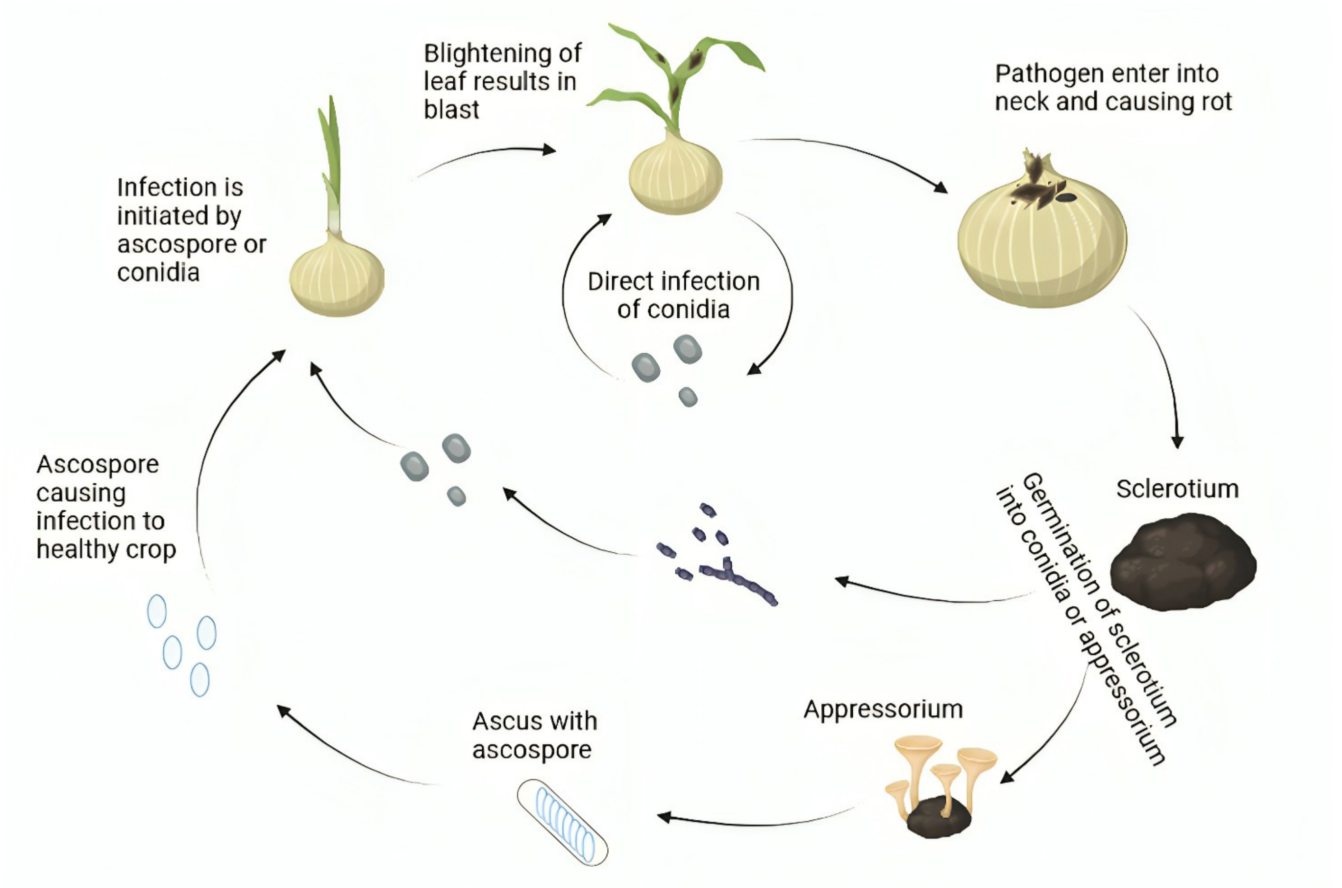

Fig. 6. *Botrytis alli* causes the disease cycle of neck rot. The cycle illustrates the pathogen's Infection in onions, starting with sexual or asexual spores which were germinated from the resting spore. The pathogen infects healthy crops, causing leaf blight, leaf blast, or rot, which releases infective spores and continues the disease cycle.

reduction of post-harvested onion. Plant hormones exhibiting antifungal solid activity, particularly 20 mM salicylic acid (SA), have demonstrated inhibitory effects on the pathogen mycelium (87). Salama et al. (88) studied the effectiveness of the NP compound MgO at a rate of 0.3 mM in controlling the neck rot of onions, and this can be used as an alternative source of chemical fungicide. The BOTcast (BOTrytisforeCASTer) model, designed for managing botrytis leaf blight caused by *B. squamosa* Walker in onions, computes disease severity values (DSVs) based on leaf wetness length and average temperature during wet periods. Fungicide treatments are recommended when cumulative DSVs reach or exceed a predetermined threshold value (41).

Black Mould

Black mould caused by *Aspergillus niger* was first identified as the cause of onion storage rot in New Zealand in 1959 as a widespread soil saprophyte and represents one of the most devastating diseases in storage and in the field (63), (89). Bulbs affected by black mould exhibit shallow lesions on dried outer scales, streaks of mycelial growth and the development of black-coloured conidia beneath the outer scales. Eventually, the bulb surface darkens, shrivels and loses quality. Rot typically appears at the damaged neck of bulbs or necrotic leaf tissues. The fungus can also grow on wounded or diseased roots and bruised or torn outer scales along the sides of bulbs (63). *A. niger* was identified based on both macro and microscopic observations. Microscopically, the hyphae are finely wrinkled and 3-6 µm broad, with sharply angled or tree-like branching. Conidia occur in chains or disconnected and the spores are globular or ellipsoidal. *A. niger* is known for producing mycotoxins such as ochratoxin A, aflatoxin, 3-nitro propionic acid and fumonisin, which can induce acute or chronic toxicity in both animals and humans, affecting cytokine and antibody production and impairing immunological responses (90). *A. niger* was the most frequently encountered pathogen in market loss, especially during the wet season (91). Although the disease occasionally manifests in the field, this issue can cause significant losses in warehousing, particularly under tropical circumstances (92). Prajapati and Patil (63) reported that spores germinate within 3 to 6 hours at high relative humidity, while germination is impeded at less than 75% relative humidity. *A. niger* grows optimally at temperatures between 28 and 34 °C and the sporulation can occur 24 hours after Infection.

Management strategies

Selecting healthy propagules for planting is the most effective way to reduce the emergence of black mould rot disease. Crop rotation with other non-host crops should be practiced every 3 to 4 years. Deep soil ploughing during the hot summer helps destroy pathogens present in the soil by direct exposure to high solar radiation. We can also go for soil solarization by covering the soil surface with 100-gauge linear low-density polyethene LLDPE transparent plastic film for 15 days during the hot summer after providing light irrigation by raising the temperature within the plastic by up to 10°C. Irrigation should be halted 10-14 days before harvest to allow proper drying (63). 0.1% carbendazim effectively minimizes disease incidence while applying as a foliar spray for standing crops and dipping bulbs after harvest reduces the loss in storage (93)-(94). A combination of tebuconazole + trifioxystrobin (2 g/kg) for seed treatment can be used. Eugenol fumigation can be used to reduce black mould incidence during the storage period (90). Applying *T. asperellum* effectively controls black rot disease (63). Ethanol extract of *Jatropha curcas* leaf and seed at 40 mg/ml effectively controls the black mould of onion (95); furthermore, clove and African nutmeg extracts also reduce black mould (96).

Iris Yellow Spot Virus (IYSV) and Onion Yellow Dwarf Virus (OYDV)

Iris Yellow Spot Virus (IYSV) is a tospoviral disease transmitted predominantly by thrips of the species *Thrips tabaci* (97) in a persistent and propagative manner, with *Frankliniella fusca* showing less efficiency (98). Both nymph and adult thrips can transmit IYSV, but only nymphs can acquire the virus from infected hosts. IYSV tends to overwinter in volunteer onions and weeds found among or near crops. Virions of IYSV are pleomorphic particles measuring 80-120 nanometres in size. They consist of RNA, protein, glycoprotein and lipids. Symptoms of IYSV in onions include lenticular-shaped lesions with or without green islands, referred to as diamond eyes and large necrotic lesions that can cause scape-lodging (98)-(99).

Onion Yellow Dwarf Virus (OYDV) is a potyvirus transmitted by aphids, with its host range restricted exclusively to onion cultivars. The characteristic symptom of OYDV in onions is exhibiting yellow or chlorotic stripes on the leaves, with some leaves appearing crinkled and twisted, which can also be observed on the flower stalk. Plants affected by OYDV typically produce only a few essential flower buds, leading to no seed setting and a complete loss of seed output (100, 101).

Management strategies

Implementing threshold-based pesticide applications for thrips (102) and reducing nitrogen levels during planting can limit non-target impacts and delay the emergence of pesticide resistance, ensuring the long-term sustainability of onion production. Avalon, a moderately thrips-resistant cultivar, exhibited reduced seasonal mean densities of onion thrips larvae and lower severity and incidence of the Iris Yellow Spot Virus (IYSV).

Using virus-free propagules is crucial for sustainable agricultural production and eliminating plant viruses. Combining thermotherapy (36°C for 0, 2 and 4 weeks) of onion plants with meristem culture had shown improvement in the reduction of Onion Yellow Dwarf Virus (OYDV) infection (103). Shoot tip cryopreservation is a dual-purpose technique, allowing for either viral eradication or virus preservation in cryo-derived plants. Meanwhile, thermotherapy reduced the rate of OYDV regeneration in cryotreated shoot tips.

CRISPR/Cas proteins, known as molecular scissors, can bind to specific DNA and RNA sequences, making them helpful in diagnosing viral particles. CRISPR/Cas-based approaches offer the advantage of targeting DNA and RNA with high specificity and sensitivity, making them an emerging technique for managing plant viral diseases (104).

Other Minor Diseases

Onion smudge, caused by *C. circinans, is* particularly prevalent in white onion cultivars in the field and during storage or transportation. It primarily targets the bulbs and forms dark green to black patches of varying sizes and shapes on the outer scales. In advanced cases, it manifests classic smudge signs of black spots grouped in concentric rings (109, 110). Chen et al. (111) reported the first-ever case of *C. circinans* causing anthracnose of *Allium fistulosum* var. *giganteum* in China. Spraying Hexaconazole (0.1%) and Difenconazole (0.1%) effectively controlled the disease in both field and storage conditions (112). A pioneering study on live, in-situ freshness detection of stored onions and potatoes using volatile organic compound sensing with an electronic nose was conducted by Ghosh et al. (113). The e-POT device's performance was highly stable in field and warehouse conditions.

Damping-off, caused by different pathogens, including *Pythium* sp., *Rhizoctonia solani* and *Fusarium* sp., affects onions before and after emergence. *Pythium* spp. and *Rhizoctonia solani* present comparable symptoms in immature seedlings, causing plant collapse, often known as 'damping-off'. Excessive seeding and high soil moisture levels contribute to this illness. *Pythium* spp. and *Rhizoctonia solani*, being soilborne pathogens, do not generate airborne spores but can quickly spread from one seedling to another through contaminated agricultural soil (114-115). Ikeda and Yasuoka (116) made the first report that *Botrytis byssoidea* causes damping-off in onions. Gunaratna et al. (117) formulated *T. asperellum* alone and in conjunction with *T. virens* and applied it to the soil followed by seed priming, effectively decreasing damping-off disease and increasing seedling development during the nursery stage.

Another soilborne pathogen, *Sclerotium cepivorum*, mainly affects onions and garlic, causing white rot with symptoms of soft rot gradually developing in the bulb and a thick white mycelial growth at the base of the bulb, later producing numerous sclerotia (75, 118). Elshahawy et al. (119) used sclerotial germination stimulants like powder, garlic powder, onion oil, garlic oil and Allium waste. They repeatedly applied them, which decreased disease incidence in onions at harvest compared to untreated controls. Mishra et al. (69) stated that combining biocontrol agents like Trichoderma and AMF (arbuscular mycorrhizal fungi) would control the disease incidence.

Onion sour skin, caused by *Burkholderia cepacia*, is transmitted by irrigation water capable of infecting onion plants in the field, resulting in light-brown lesions on the leaves and watery rot in the necks. *Burkholderia gladioli* pv. *alliicola* is the causative agent of slippery skin, where the central scales of an infected bulb "slip" out the top of the bulb when pressure is applied to its base (120). Overhead irrigation, over-irrigation and excessive nitrogen fertilizer exacerbate the field symptoms of bacterial diseases (121). Proper ventilation in storage and sorting out infected, rotten bulbs at least once every 15 days can reduce bacterial incidence (110).

Conclusion and Future Prospects

In recent decades, human civilization has witnessed remarkable progress alongside significant changes in global climatic conditions, leading to the proliferation of phytopathogens. As we navigate the era of artificial intelligence, relying solely on conventional management practices may prove inadequate in effectively combating evolved pathogens. While these traditional methods have been instrumental in disease management, they often fall short in prevention and control, especially in shifting climatic patterns. Despite ongoing efforts by researchers to develop forecasting models, e-nose technology, AI-based techniques, novel chemical formulations, and gene editing tools such as microRNA and CRISPR/Cas-based management, implementing these advancements in field conditions remains challenging.

Bridging the gap between scientific innovation and practical application is essential. This requires concerted efforts to streamline the integration of cutting-edge technologies into existing agricultural practices. Collaborative initiatives involving researchers, policymakers, agricultural practitioners and industry stakeholders are pivotal in facilitating the adoption of innovative solutions. Policies support integrating new technologies in farming by providing financial incentives, funding R&D, and enhancing market access. Additionally, improving awareness and providing training opportunities for farmers on the benefits and proper utilization of these advancements can significantly contribute to their effective implementation. Only through collective action and innovation can we effectively combat the threats posed by evolving phytopathogens and ensure a resilient future for agriculture. Looking ahead, the future of plant disease management lies in the seamless integration of advanced technologies with traditional agricultural practices. As the challenges posed by evolving phytopathogens intensify, particularly under changing climatic conditions, it is crucial to accelerate the development and field implementation of AI-based tools, genetic engineering techniques and predictive models.

Acknowledgements

We want to acknowledge the Department of Plant Pathology, Tamil Nadu Agricultural University for allowing us to write this review article.

Authors' contributions

PY wrote the original manuscript and made a visual representation of the disease cycle. KA reviewed and edited the manuscript. MK carried out technical editing. RA and BA reviewed the manuscript. MN edited 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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