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Eco-Friendly Management Strategies for Fusarium Wilt in Okra: Challenges and Future Aspects

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Okra (*Abelmoschus esculentus*) is a vital crop widely cultivated in tropical and subtropical regions. Okra has much economic importance in okra growing areas but okra production faces significant challenges due to various diseases among which Fusarium wilt caused by *Fusarium oxysporum f. sp. vasinfectum* is particularly destructive. This disease can cause substantial yield losses especially under environmental conditions that favor its spread. Traditionally, management strategies for Fusarium wilt have relied heavily on synthetic chemicals. However, these approaches often contribute to increased pathogen resistance and cause risks to the environment. This review highlights the potential of plant-based extracts with antimicrobial properties as sustainable and eco-friendly alternatives for managing Fusarium wilt in okra. These natural solutions not only offer effective disease control but also minimize the ecological impact associated with chemical pesticides. Adopting such environmentally responsible strategies is crucial for enhancing okra production while preserving ecosystems.
Keywords: Okra, *Fusarium oxysporum*, biocontrol agents, antifungal properties, essential oils, plant extracts .

INTRODUCTION

Okra (*Abelmoschus esculentus*) is an important vegetable crop, widely known as Lady's Finger in English and by several other names across different languages, such as bhindi (Urdu, Hindi, Punjabi), quimgombo (Spanish), gombo (French), and bamia (Wang et al., 2023). The crop belongs to the *Malvaceae* family and although its geographic origin remains uncertain but studies suggest it may have originated in Ethiopia, West Africa or South Asia (Wang et al., 2023). Thriving in warm climates, okra can be grown in various soils but well-drained and nutrient-rich soils which yield the best results (Ahmed et al., 2023). Okra production is substantial with a reported cultivation area of 2.8 million hectares and a production of 11.23 million tons in 2022. India leads global production followed by Nigeria, Sudan, Mali and Pakistan. Okra is valued for its nutritional content and has become increasingly important in fulfilling market demands for vegetables (Khan et al., 2022; Woldetsadik et al., 2022). However, Fusarium wilt caused by *Fusarium oxysporum f. sp. vasinfectum* is a major threat to okra crops which cause significant yield reductions and economic losses. Traditionally, chemical fungicides including methyl bromide were used to manage Fusarium wilt. Methyl bromide was banned under the Montreal Protocol in 1986 due to its ozone-depleting properties (Gullino et al., 2015). This coupled with environmental concerns and the development of fungicide-resistant fungal strains has led to the search for alternative control methods (Kowalska, 2021; Lamichhane et al., 2024).

***Climate change and the need for alternative solutions*:** Changing climatic conditions are exacerbating the incidence and severity of plant disease outbreaks including Fusarium wilt by altering pathogen dynamics, host-pathogen interactions and the emergence of new pathogenic strains

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(Lahlali et al., 2022; Lahlali et al., 2024; Singh et al., 2023). Such climate-induced changes pose significant risks to agricultural productivity and global food security contributing to biodiversity loss in vulnerable regions (Roussin-Léveillée et al., 2024; Waheed et al., 2023). Consequently, there is an urgent need for adopting environmentally friendly and sustainable control measures.

***Plant extracts as an alternative to chemical pesticides*:** Plant extracts including oils, resins, crude extracts and their fractions have been identified as promising alternatives to chemical pesticides. These extracts exhibit antimicrobial properties and are generally less toxic and makes them safer for both human health and the environment (Khursheed et al., 2022; Singh et al., 2023). For example, neem oil has been shown to be effective against various pathogens affecting crops like tomatoes. In fact, 92% of the plant extracts studied and 67% of the species tested in in vitro assays were in the form of extracts demonstrating their antimicrobial activity and long-term potential in plant disease management (Vaou et al., 2021). Essential oils are volatile compounds produced by aromatic plants and play a crucial role in defending plants against bacteria, viruses and fungi. The antimicrobial activity of these oils is attributed to their phenolic compounds and aldehydes which degrade enzymes and alter cell membrane permeability (Khaled et al., 2024; Zhang et al., 2021). Neem (*Azadirachta indica*), clove (*Eugenia caryophyllene*) and cinnamon (*Cinnamomum zeylanicum*) oils have shown efficacy against various pathogens, including *Pythium ultimum* and *Rhizoctonia solani* (Bianchi et al., 1997; Maqbool et al., 2010).

***Fusarium wilt and its economic impact on okra*:** Fusarium wilt remains a critical challenge for okra cultivation and responsible for wilting and root rot, which cause significant yield losses in major growing areas. Despite its impact, growers often do not account for the economic losses caused by this pathogen (Agbaglo et al., 2020; Ali et al., 2023; Paul et al., 2024). The continued reliance on chemical pesticides has not only led to environmental degradation but has also contributed to pesticide resistance in pathogens (Kowalska, 2021; Lamichhane et al., 2024).

***Integrated management and eco-friendly solutions*:** Given the environmental and economic challenges posed by Fusarium wilt and chemical pesticides, there is an urgent need to explore integrated management strategies. These strategies should combine biological control, cultural practices (e.g., crop rotation, soil management) and plant-based solutions to provide sustainable alternatives to chemical pesticides. This paper aims to address the economic losses caused by Fusarium wilt in okra by exploring eco-friendly management strategies, focusing on the use of plant extracts and other biological control methods.

***Okra diseases*:** Okra is susceptible to various diseases caused by viral, bacterial and fungal pathogens. Here are some of the common okra diseases.

***Yellow Vein Mosaic Virus (YVMV)*:** (Bajwa et al., 2024) indicated that the Yellow Vein Virus is the most critical and detrimental viral pathogen impacting okra crops during all growth stages (Figure 1). The afflicted plants produce malformed, tiny, tough-textured fruits that range in hue from pale yellow to white (Mubeen et al., 2017; Singh et al., 2023). (Rao & Reddy, 2020) stated that if the plants get infected within 20 days after germination, the yellow vein Mosaic Virus causes a 50-100% loss in quality and yield. Use various resistant cultivars. Sow-certified disease-free seeds. Roughing of plant diseases. Follow crop rotation. Keep fields free of weeds. Use appropriate pesticides to control vectors (Mubeen et al., 2021; Shafique et al., 2024).

Figure 1. Typical yellowing and vein chlorosis caused by Yellow Vein Mosaic Virus (YVMV) on okra leaves.

***Cercospora leaf spot*:** Cercospora Leaf Spot is a significant disease affecting okra, caused by three species of the *Cercospora* genus: *Cercospora hibiscus, C. malayensis and A. abelmoschi are three Cercospora species in India that* cause okra leaf marks (Singh et al., 2014). *C. abelmoschi* causes sooty black, angular dots and *C. malayensis* causes brown, irregular spots. The affected leaves roll, wilt and fall. The leaf spots are frequent during wet seasons and severely defoliate the leaves. (Banvasi et al., 2020) reported that Cercospora Leaf spot can cause losses of up to 40% in severe cases. In mild cases, losses can range from 5% to 10%. Rotate crop to non-host to reduce the build-up of inoculum in the soil and avoid water stress to plants by irrigating when required as reported by (Singh et al., 2014). *C. abelmoschi* is characterized by sooty black, angular spots, while *C. malayensis* produces brown, irregular patches on the leaves.

Infected leaves typically exhibit symptoms such as rolling, wilting and eventual drop. The incidence of leaf spots is exceptionally high during wet seasons, leading to severe defoliation (Fig. 2).

Figure 2. Brown to dark brown circular leaf spots caused by fungal infection on okra leaves.

Powdery mildew**:** According to the reports of (Kumar et al., 2010), two pathogens that cause powdery mildew disease are *Sphaerotheca fuliginea* and *Erysiphe cichoracearum* (Figure 3). The latter has just been recorded from Bangalore, while the former is more common in locations where okra is grown. (Kumar et al., 2010) reported that Powdery mildew can cause losses of up to 30% in severe cases. In mild cases, losses can range from 5% to 10%. Some practices are carried out to manage powdery mildew of Okra, including using overhead irrigation to remove fungus from leaves and decrease viability and crop rotation. Proper fungicide sprays may be required to control the disease.

Bacterial blight**:** (Kumar, 2019) stated that bacterial blight is caused *by Xanthomonas campestris* pv. *malvacearum* affects the okra plant's leaves, stems and pods (Figure 4). The symptoms include water-soaked lesions that turn brown and necrotic. They also reported that Bacterial wilt can cause up to 100% crop loss in severe cases. In mild cases, losses can range from 20% to 50%.

Figure 3. White powdery fungal growth covering the leaves, characteristic of powdery mildew infestation on okra plants.

Figure 4. Necrotic and discolored lesions on okra leaves, symptomatic of blight infection.

Southern blight**:** (Saleem et al., 2020) stated that Southern Blight shows the symptoms of abrupt leaf wilting, yellowing foliage, browning branches and stems above and below the earth and a possible fan-like mycelial mat covering the stem (Figure 5). The fungus can survive in the soil longer in tropical and subtropical areas. Disease emergence is favored by acidic soil, high humidity and high temperatures and disease is found mainly in tropical and subtropical regions. However, this disease is managed and reduces infections by removing contaminated plants, rotating crops with less vulnerable plants, pushing crop trash deeply into the soil and minimizing crowding plants to encourage air circulation.

Figure 5. Extensive tissue damage and wilting caused by Southern blight in okra plants.

Enation leaf curl: (Asare-Bediako et al., 2014) proposed that whiteflies are the primary vector for spreading leaf curl disease of Okra (Figure 6). The main symptoms of this disease are curling in the front part of the leaf and some roughness (thickening, deformation) in the upper part of the leaf. Moreover, this disease can delay the growth of plants; the fruits of the plant become small, deformed and unsuitable for sale. (Saleem et al., 2020) determined that in this disease, the lower surface of leaves has tiny pinhead-sized enations, which later on, this enation take on a rough, warty form. Reduction in leaf size. Twisting transpires along the petioles' stem, side branches and leaves. The leaves seem leathery and thick. The newly developing leaves of severely diseased plants exhibit bold enations and curling. Moreover, it yields a small number of distorted fruits. White fly transmits them. Remove and burn the contaminated plants to stop the disease from spreading further. The population of whiteflies was managed and monitored by using sticky yellow traps. Moreover, suitable insecticides were also used to manifest the whitefly infestation.

Insect pest on okra plant: (Sabyasachi et al., 2013) proposed that the appearance of insects is an essential factor affecting okra production (Figure 7). Many pests attack crops, the largest of which is the twig and fruit borers *Earias villa* (Fabricius) and *Earias insulana* as these take the right hand and cause damage directly to young fruit. Fruit borers cause 88% to 100% damage to fruit. (Rahman et al., 2012) investigated that compared to healthy fruits, there are 16.47% fewer seeds per fruit, 200% more stained seeds and 18.70% more damaged seeds. The emergence of fruit borer usually occurs in wet conditions after rain (Bilqees et al., 2020). Old females lay single eggs on young fruits' leaves and flower buds. Before fruit is formed, tiny brown caterpillars' nest in the upper branches and feed on the branches. It then turns into a fruit and feeds on the fruit.

Figure 6. Leaf deformation, curling and enations typical of viral infections on okra leaves.

Figure 7. Effects of Mealybug insect attacking okra.

Fusarium wilt: (Ounis et al., 2024) reported that *Fusarium oxysporum* f. sp. *Vasinfectum* is a deadly disease called Fusarium wilt in areas where okra is produced extensively (Figure 8). The fungus colonizes the vascular system, invades the roots and prevents water from moving through the plant. Intercultural operations disseminate the disease severity. Moreover, Fusarium wilt can cause up to 100% crop loss in severe cases. In mild cases, losses can range from 20% to 50%. However, this disease was managed by using certified, disease-free seed and fumigating the soil may lessen the incidence of the disease. Furthermore, a plant with a higher resistance against Fusarium disease can also be an excellent method to manage this disease.

Figure 8. Symptoms of Fusarium wilt of okra plants.

***Host range and symptoms of fusarium wilt*:** (Armstrong & Armstrong, 1968) assessed that the host range of Fusarium vascular wilt was more extensive than previously anticipated. The concept of primary and secondary hosts was developed for Fusarium wilt of Cotton. Moreover, cotton is the principal host of Fusarium, but several secondary hosts can thrive but produce only sporadic symptoms or none. (Grover & Singh, 1970) described that a plant species might be a secondary host for one disease race but not for another. Race 1 has been known to infect *Abelmoschus esculentus* naturally while races 3 and 4 could not replicate on this host. The growth of the pathogen in the field; results from artificial inoculation may suggest a much more extensive host range. However, these results should be viewed with caution. Fusarium wilt signs might show up at any stage of crop development. Plants may die at the seedling stage when inoculum density is excessive or when infection starts at the seed. The lower leaves are where symptoms initially appear in older plants. Chlorosis of the leaf's spreads between the prominent veins and starts at the margin. As the illness progresses, more leaves turn chlorotic and become flaccid, giving the plant a wilted appearance in the middle of the day. Leaves with symptoms may drop off the plant. Stunted plants may also have an infection. All leaves get infected as the infection worsens and as the wilt becomes permanent and the plant succumbs to moisture stress, necrosis replaces chlorosis. Plants with foliar or wilting symptoms will only have minor stem vascular darkening restricted to the lower stem in root-rotting races when there is also significant root rot. From brown to black lines in the center of the root to more extensive internal root rot, together with apparent outward root rot signs, root rot can be noticed as early as the one actual leaf growth stage. Often, there is no outward root rot, so cutting the roots lengthwise is necessary for diagnosis. Pima cultivars that are susceptible often exhibit more severe symptoms than Upland types that are sensitive. Internal root rot may still exist when there are no obvious foliar or external root symptoms in some sensitive types.

***Distribution of okra wilt*:** (Paul et al., 2024) stated that the pathogen *Fusarium oxysporum* is caused by the fungal disease okra wilt, which is soil-borne. This disease affects the Okra plant root system, causing wilting, yellowing and stunted growth, ultimately leading to plant death. Okra wilt has a widespread geographic distribution, as reported in several African countries, Asia, Europe and the Americas. (Mokhtari et al., 2023) reported that in Africa, okra wilt has been reported in countries such as Nigeria, Sudan and Egypt. The disease has been reported in India, Pakistan, Bangladesh and China in Asia. (Sampaio et al., 2020) determined Bahadurthat Fusarium wilt has been reported in Europe, Greece, Italy and Spain. Moreover, okra wilt has been reported in several countries, including the United States, Mexico and Brazil (Hernandez-Zepeda et al., 2010).

***Life cycle of Fusarium Oxysporum*:** (Bahadur, 2021) reported that *Fusarium oxysporum* reproduces asexually and produces microconidia, chlamydospores and macroconidia. (Ebbole, 2010) reported that microconidia are the most abundantly produced spores. Microconidia are uninucleate and germinate poorly, with germination efficiency ranging from 1 to 20%.

***Molecular characterization of okra wilt*:** Okra wilt is a disease that affects the growth and productivity of okra plants. Several pathogens, including fungi, bacteria and viruses, cause the disease. The molecular characterization of these pathogens is essential for understanding their pathogenicity and developing effective control strategies. (Jabeen et al., 2024) reported that Fungal pathogens that cause okra wilt include *Fusarium oxysporum*, *Rhizoctonia solani* and *Macrophomina phaseolina*. The soil that can survive for an extended period is soil-borne. Molecular characterization of these pathogens has been done using PCR, DNA sequencing and phylogenetic analysis techniques. For example, PCR-based detection of F. oxysporum using species-specific primers has been reported. (Molla et al., 2013) reported that DNA sequencing and phylogenetic analysis of *R. solani* isolates have been used to define the population structure of the pathogen and genetic diversity. (Tripathi et al., 2024) reported that bacterial pathogens cause okra wilt, including *Pseudomonas syringae* pv. *syringae*, *Xanthomonas campestris* pv. *vesicatoria* and *Erwinia carotovora*. These bacteria can infect the plant via natural openings, wounds, or insect vectors. Molecular characterization of these pathogens has been done using techniques such as PCR, DNA sequencing and multilocus sequence typing (MLST). For example, PCR-based detection of *P. syringae* using species-specific primers has been reported. (Rahman et al., 2024) reported that MLST analysis of *X. campestris* pv. *vesicatoria* isolates have been used to study the genetic diversity and phylogeny of the pathogen. (Kumar, 2011) reported that Viral pathogens that cause okra wilt include Okra leaf curl virus (OLCV), Tobacco mosaic virus (TMV) and Cucumber mosaic virus (CMV). These viruses are transmitted by insect vectors such as whiteflies and aphids. Molecular characterization of these viruses has been done using techniques such as PCR, reverse transcription PCR (RT-PCR) and genome sequencing. For example, RT-PCR-based detection of OLCV using specific primers has been reported. Similarly, genome sequencing of CMV and TMV isolates has been used to study their genetic diversity and evolution.

***Okra wilt detection*:** (Mokhtari et al., 2023) stated that Okra wilt is a severe disease that disturbs the productivity and growth of okra plants. Different soil-borne pathogens, including *Fusarium oxysporum* f.sp and *vasinfectum* cause this disease. *Fusarium solani* f. sp. *cucurbitae* and *Rhizoctonia*. Different molecular techniques, such as polymerase chain reaction (PCR, are used to detect the presence of the pathogens causing okra wilt). Specific primers and probes used for the detection also provide information that can be helpful for researchers and growers trying to identify and manage the disease.

***Strategies to control Fusarium Wilt*:** According to the reports of (Gordon & Martyn, 1997) human activity is the primary factor contributing to the growth of new Fusarium oxysporum infestations. (Narayanasamy, 2013) states that human cultural practices can also lessen the harm and occurrence of *Fusarium oxysporum*. However, tainted or sick seeds can spread pathogens (Chalam et al., 2020). A successful quarantine or certified pathogen-free seedlings are crucial strategies for controlling *Fusarium* wilt. Moreover, planting *Fusarium oxysporum-free* seeds on non-infested soils is crucial for maximizing their usefulness. Staying away from infected soils can drastically lower disease incidence when land is not a constraint (Gupta & Kumar, 2020). However, cultural techniques such as crop rotation and soil solarization must be established to reduce the occurrence of inoculum in these situations. The inoculum in the soil can be decreased by solarization, which is achieved by covering the soil with mulch to raise the temperature of the soil. (Jiménez Díaz & Jiménez-Gasco, 2011) reported that since this is expensive, it needs to be taken into account together with crop harvest economy and disease forecast. (Wright et al., 2015) reported that Crop rotation may lessen the inoculum in the soil for soil-borne pathogens such as *Fusarium oxysporum*. However, it will be less effective because *F. oxysporum* chlamydospores can persist in the soil for long. (Gordon, 2017) added that the inoculum can multiply in the roots of carriers that do not show symptoms. Furthermore, resistance breeding to develop diseases resistance cultivars is a sustainable strategy to manage the plant's pathogens (Bhatti et al., 2024; Mubeen et al., 2024). (Panth et al., 2020) proposed that using resistant cultivars is generally acknowledged as the safest, most practical and most efficient crop protection technique to manage soil-borne illnesses, aside from all the previously mentioned control measures. (Priyanka et al., 2011) reported that the economic loss of okra production may rise significantly due to the lack of proper harvest management practices. This article briefly presented different pre-storage treatments such as (Ali et al., 2024; Ali et al., 2022) pre-cooling, biological and chemical treatment to defuse the infection, modification in atmospheric packaging, irradiation and coating to enhance the shelf-life of okra (Nel et al., 2006). Therefore, the biological control of plant pathogens using fungal biocontrol agents (Ali et al., 2021), beneficial edaphophytes (Ali et al., 2023; Tabbasum et al., 2022), bacterial biocontrol agents (Azeem et al., 2020) plant extracts (Ali et al., 2020) yeast species (Ali et al., 2024), green synthesized nanoparticles (Ali et al., 2024) and RNA interferences based management strategies (Ali et al., 2024) have gained popularity in recent years due to their effectiveness and eco-friendly sustainability. (Shah et al., 2015), that aqueous neem, citrus and garlic extracts were used alongside *Fusarium oxysporum* to inhibit the growth of Fusarium wilt of Okra. However, the growth of *Fusarium oxysporum* was inhibited at Higher doses of garlic and neem extract, which were more efficient than the other extracts. The pot experiment showed that a greater dosage of neem leaf extract, succeeded by citrus leaf extract, significantly enhanced plant growth compared to the control group. Optimal seed germination and little plant mortality were observed with elevated concentrations of neem leaf extract, succeeded by garlic extract, in combating *F. oxysporum*. (Gullino et al., 2015) studied Fusarium wilt diseases. Variety resistance must be combined with cultural, biological and chemical strategies, forming a comprehensive management strategy. Many chances to stop Fusarium wilt illnesses have been lost due to ignorance of the sources of inoculum and how it spreads. Many strategies have been investigated to achieve suppression once the disease has become established in a production system. However, most have fallen short of the industry's strict requirements for a zero-disease threshold. The following review aims to identify areas where further study and technology development are needed and highlight management studies that have contributed to our understanding of minimizing Fusarium illnesses. (Desai et al., 2017) found that systemic fungicides known as carbendazim and propiconazole were highly successful at radially suppressing the development of *Fusarium oxysporum* in laboratory screening, yielding growth inhibition rates of 72.96

and 94.81 percent, respectively. The two non-systemic fungicides that were most successful at inhibiting or preventing the growth of *F. oxysporum* were copper hydroxide and thiram, with respective growth inhibition rates of 93.33 and 82.96 percent. Combined products of fungicides like pyraclostrobin +metiram, carbendazim + mancozeb and captan + hexaconazol were most effective and gave 100 % inhibition of test fungi. Table of different diseases of okra, their causal organism, symptoms, transmission sources, yield losses and management are given in Table 1.

Plant extracts and their antifungal properties: Numerous plant extracts have demonstrated antifungal activity against *Fusarium oxysporum* which is a soil-borne pathogen known to cause wilt diseases in various crops. Below is a detailed summary of key findings from several studies:

Garlic and neem extracts**:** Inhibition of Fungal Growth: Both garlic and neem extracts have shown considerable efficacy in inhibiting the growth of *Fusarium oxysporum* colonies. Increased concentrations of these extracts were particularly effective with garlic and neem leaf extracts outpacing other plant extracts in terms of antifungal activity (Shah et al., 2015). Pot experiments indicated that higher dosages of neem

Table 1. Different diseases of okra their causal organism, symptoms, transmission sources, yield losses and management.

Disease	Causative organism	Symptoms	Transmission sources	Yield losses	Management
Yellow vein mosaic disease	Yellow vein mosaic virus (family *Geminiviridae* Genus *Begomovirus*)	Yellowing of vein, vein clearing, reduction in size of leaves and okra fruit Stunted plants	Vector whitefly	In world 80% - 90% In Pakistan, 84%	Spray Azadirachtin 0.03 WSP @ 5 g/10l or or methyl demeton 25 EC @ 1.6 ml/l or thiamethoxam 25 WG @ 2 g/lit Chlorpyriphos 2.5 ml + neem oil 2 ml lit of water Resistant variety
Cercospora leaf spot	*Cercospora abelmoschi Cercospora malayensis*	First appear on the lower, older leaves, then new lesions appear on the younger, upper leaves, Necrotic spots on leaves and stem	Wind, rain, irrigation, or mechanical tools	In world 76.49% In Pakistan 61 %	Use protective fungicides such as Copper oxychloride @ 0.3%, mancozeb @ 0.25%, zineb @ 0.2% a month after sowing and repeat this procedure at fortnightly intervals.
Fusarium wilt	*Fusarium oxysporum f. sp. vasinfectum*	Stunting, yellowing and wilting leading the death of the plant	Soil or infected seed	In world, 10-45% In Pakistan, up to 100%	Copperoxychloride50 % wp @ 2gm/ltr Thiophanate Methyl 70% WP@250-600g/acre Carbendazim 12 % + Mancozeb 63 % WP@300-400g/acre
Powdery mildew	*Podosphaera xanthii*	White fungal growth on leaves leaves curl upwards, *cleistothecia* on lower side of leaves, purple to reddish blotches	wind	In world, 17-86.6% In Pakistan, 20-40%	Difenoconazole 25 % EC@120 ml - 150 ml / Acre Azoxystrobin 23 % sc@200ml/acre Hexaconazole 5 % SC@200-250ml/acre Thiophanate Methyl 70% WP@200-600g/acre
Bacterial blight	*Pseudomonas cichorii*	Small, round, Subtle, whitish spots on stem, leaves, spots collapse giving necrotic edges of leaves	Water splash seed	Significant yield losses	• Use certified disease-free seeds. • Avoid overhead irrigation. • Avoid working in the field when wet. • Remove crop debris after harvest. • Spray with copper-based fungicides
Southern blight	*Sclerotium rolfsii*	Browning of branches and stem above and low ground, yellow foliage, white fungal mat appears on ground	Sclerotia contains soil, plant debris, irrigation water, tools, etc.	In the world, approx. 76%	• Remove weeds and plant debris. Remove and destroy infected okra plant matter immediately • To remove sclerotia, remove the upper soil up to 10cm deep
Okra leaf enation curl disease	Leaf enation curl virus	Pinhead enation on the upper side of the leaf, warty and rough texture of leaves, curling/cupping of leaves upward	Vector, *Bemisia tabasi*	In world,80-90% In Pakistan 20-30%	• Use of resistance varieties • Weed-free field. Roughing of infected plants and burned • Whitefly management by spraying insecticides at 10-15 days intervals, starting 20 days after sowing

leaf extract followed by citrus leaf extract significantly promoted plant growth compared to the control group. The application of neem leaf extract resulted in enhanced seed germination and reduced plant mortality (Abd-Elsalam & Khokhlov, 2015).

Antifungal activity of Azadirachta indica and citrus limon: neem extract**:** Neem extract exhibited a high percentage of inhibition against *Fusarium oxysporum* with 43.11% fungal growth inhibition higher than that of lemon leaf extract (39.62%) (Khudair, 2022). Neem's strong antifungal properties were noted as a promising natural alternative to synthetic fungicides.

Citrus limon: Citrus leaf extracts also demonstrated effective antifungal activity although slightly less potent than neem but providing a green substitute for synthetic fungicides (Selim et al., 2020).

Other plant extracts with antifungal activity**:** Clove and Mint Oils: Extracts from *Syzygium aromaticum* (clove) and *Mentha arvensis* (mint) have shown significant antifungal effects against *Fusarium oxysporum*. Clove oilwas found to be the most effective followed by mint oil. Essential oils from these plants considerably suppressed fungal growth and spore population (Kanwal et al., 2024; Selim et al., 2020).

Aloe vera**:** Aloe vera extract also demonstrated effective suppression of *Fusarium oxysporum* growth and sporulation under both laboratory and greenhouse conditions and further confirmed the potential of plant extracts as biocontrol agents for soil-borne pathogens (Selim et al., 2020).

Methodology for testing plant extracts**:** Various studies employed methods such as the Blotter Test and seed treatment techniques to evaluate the impact of plant extracts on seedling health and pathogen inhibition. For example, after soaking seeds in plant extracts, their health was evaluated by counting fungal spores and monitoring disease progression in seedlings under greenhouse conditions (Ahmed et al., 2023; Silva et al., 2023).

Essential oils as antifungal agents**:** Several studies have explored the potential of essential oils as natural alternatives to chemical fungicides for controlling *Fusarium oxysporum*.

General findings on essential oils**:** Essential oils such as clove, neem, cinnamon and thyme have shown significant antifungal activity against *Fusarium oxysporum* with dose-dependent efficacy. Studies have tested different concentrations of essential oils (0.5%, 1%, and 2%) in treating soil infected with *Fusarium oxysporum*. Observations on pathogen population densities were made on days 3, 5, and 7 providing insights into the oil's long-term effectiveness (Bell et al., 2019; Sharma et al., 2017).

Clove oil (Syzygium aromaticum)**:** Clove oil was found to be the most effective essential oil in controlling *Fusarium oxysporum*. Inhibitory effects on spore germination and mycelial growth were observed in a dose-dependent manner. Clove oil demonstrated total suppression of spore germination at 125 ppm with an IC50 of 18.2 ppm (Sharma et al., 2017).

Thyme, basil, and marjoram oils**:** Essential oils from *Thymus vulgaris* (thyme), *Ocimum basilicum* (basil), and *Majorana hortensis* (marjoram) were evaluated for their antifungal properties. Thyme oil was particularly effective in inhibiting fungal growth and preventing sporulation and spore germination at 2000 µg/ml dosage (Ali et al., 2022). Thyme, basil and marjoram oils significantly reduced Fusarium growth in in-vitro conditions and made them promising candidates for use in agricultural disease management.

Other essential oils**:** Peppermint (*Mentha piperita*) and Spearmint (*Mentha spicata*) oils showed antifungal activity against *Fusarium oxysporum* particularly when formulated into emulsions or nano-emulsions. These formulations enhanced the oil's ability to inhibit Fusarium growth and provided more effective and stable treatments (Nel et al., 2006). Cinnamon (*Cinnamomum zeylanicum*) and Lemongrass (*Cymbopogon citratus*) oils also exhibited inhibitory effects on Fusarium growth even though their potency was generally lower compared to clove and thyme oils (Ahmed et al., 2023; Sharma et al., 2017).

Nano-emulsions and emulsions for enhanced effectiveness**:** Nano-emulsions and emulsions were developed by combining essential oils with surfactants like Tween 80. This formulation improved the stability and antifungal efficacy of the oils. Transmission electron microscopy (TEM) and particle size analysis showed that these nano-emulsions had a spherical shape and moderate dispersion, enhancing their ability to control *Fusarium oxysporum* (Nel et al., 2006).

Conclusion**:** The Fusarium wilt, caused by *Fusarium oxysporum f. sp. vasinfectum*, is a severe threat to okra production, with substantial yield losses in various regions worldwide. The disease significantly reduces the quality and quantity of crops, making effective management crucial. Current control methods mainly depend upon chemical fungicides such as copper oxychloride, thiophanate methyl and carbendazim. However, these chemical approaches present risks such as environmental pollution and the development of fungicide resistance. In recent years, plant-based alternatives have gained attention as sustainable options for managing Fusarium wilt. Plant extracts and essential oils, known for their antifungal properties, have shown potential in reducing the severity of the disease. These natural remedies and biocontrol agents offer a more eco-friendly and sustainable approach. Furthermore, molecular tools for early pathogen detection can enhance the precision of management strategies that can prevent large-scale outbreaks. An integrated approach combining chemical, biological and natural plant-based methods is essential for long-term control. Efforts should focus on breeding Fusarium-resistant okra varieties to minimize disease impact. Plant extracts and essential oils, which have proven antifungal properties, should be further researched and integrated into management practices to reduce dependency on chemicals. Biocontrol agents also present a sustainable alternative and their combination with natural treatments could enhance efficacy against Fusarium species. Early detection through molecular diagnostic tools is necessary for preventing severe outbreaks and research should continue to refine these methods for field application. Additionally, understanding the role of soil health and microbiome interactions in suppressing Fusarium will be valuable for developing more natural control strategies. Ongoing farmer education and establishing disease monitoring systems will ensure that early intervention and integrated disease management practices are applied effectively. Resistant varieties, biocontrol, plant-based treatments and minimal chemical use are essential to control Fusarium wilt in okra.

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***SDGs addressed*:** Zero hunger, good health and well-being, responsible consumption and production, climate action.

***Policy referred*:** Environmental Regulation Compliance; Promotion of Sustainable Alternatives; Adaptation to Climate Policy Challenges; Encourages Integrated Pest Management (IPM).

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