Official publication of Pakistan Phytopathological Society
Pakistan Journal of Phytopathology
ISSN: 1019-763X (Print), 2305-0284 (Online)
https://pjp.pakps.com

REVIEW ARTICLE

Protecting The Future of Citrus: A Mini Review On Citrus Canker Threats, Control Strategies, And Future Outlooks

[a]Amjad Ali, [a]Parnaz Mortazavi, [b]Mustansar Mubeen, [a]Muhammed Tatar*, [c]Qaiser Shakeel*, [a]Meliha F. Sarıkaya

[a] Faculty of Agricultural Sciences and Technologies, Sivas University of Science and Technology, Sivas-58140, Türkiye.
[b] Department of Plant Pathology, College of Agriculture, University of Sargodha, Sargodha-40100, Pakistan.
[c] Cholistan Institute of Desert Studies, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur-63100, Pakistan.
Corresponding Authors: Muhammed Tatar, Email: mtatar280@gmail.com

Article History:
Submitted: September 03, 2024; Revised: November17, 2024; Accepted for Publication: December 26, 2024.

A B S T R A C T

Citrus canker, caused by *Xanthomonas citri* subsp. *citri* (previously known as *Xanthomonas axonopodis* pv. *citri*) is a devastating disease impacting citrus production globally. This review outlines the pathogen's origin, epidemiology, and spread, highlighting its severe economic impact, particularly in regions like Pakistan. The interaction between environmental factors and citrus leaf miners exacerbates disease severity, causing significant yield losses. Traditionally, citrus canker management has relied on synthetic chemicals such as copper-based bactericides, but their overuse has led to environmental concerns and pathogen resistance. Sustainable alternatives, including essential oils, are being explored for disease control. Recent studies demonstrate the potential of clove, cinnamon, and neem oils, with clove oil showing the highest antibacterial efficacy against *X. citri*. Integrated disease management strategies, incorporating quarantine measures, resistant cultivars, and plant extracts, are discussed as promising approaches to mitigate the spread and severity of citrus canker, with particular attention to eco-friendly options like induced systemic resistance and essential oils. However, gaps remain in understanding these alternatives' full efficacy and application methods, underscoring the need for further investigation. The review concludes with recommendations for future research into eco-friendly solutions, such as induced systemic resistance and essential oils, to reduce dependence on harmful chemicals and enhance citrus crop resilience.

Keywords: citrus canker, *Xanthomonas citri* Subp. *citri*, eco-friendly solutions, essential oils, systemic resistance.

INTRODUCTION

Citrus, a fruit crop from the Rutaceae family, is one of the most essential fruit tree crops globally, particularly in Pakistan. Citrus fruits are believed to have originated in the Indian subcontinent due to the high level of genetic variability found in the region (Aslam *et al.,* 2024). Citrus is gaining popularity daily due to its versatility and nutritional benefits; it supplies essential vitamins B and C, potassium, copper, magnesium, and phosphorus, and beneficial plant compounds like citric acid and flavonoids. These contribute to smooth skin, improved muscle elasticity, and strengthened immunity (Sebghatollahi *et al.,* 2022; Haq *et al.,* 2024; Jamil *et al.,* 2024). Moreover, citrus has natural anti-inflammatory and antioxidant qualities (Bhatti *et al.,* 2024; Khan *et al.,* 2020; Riasat *et al.,* 2020). It guards against lung, stomach, esophageal, breast, and pancreatic cancers; lowers the risk of heart attacks and strokes by lowering systolic blood pressure; raises "good" HDL and lowers "bad" LDL levels in the blood; and improves brain activity and prevents the degeneration of brain cells (Testai and Calderone, 2017). Approximately 91% of people worldwide do not get enough vitamin C; citrus fruits are also a great source of vitamins and minerals. Citrus is the primary fruit grown throughout a vast area, yielding 161.8 million tons of fruit from over 10.2 million acres. The only amount that exceeded this requirement was the total amount of bananas and plantains, or about 170.3 million tons (FAO, 2023). According to FAO (2023), Mexico, Spain, the United States of America, Turkey, Egypt, Nigeria, and Iran are the top ten countries in the world that produced citrus fruits in 2021 where the total harvested area of 9.93 million hectares, oranges are the most significant citrus crop, accounting for 46.7% of the world's citrus fruit production. The second most significant crop is tangerines, grown on 3.11 million hectares of harvested land and yielding 41.95 million tons, or 25.9% of all citrus fruit produced. On the other hand, 1.34 million hectares of harvested land produced 20.83 million tons of lime and lemons, or 12.87% of all citrus fruit production. In addition to *C. myrtifolia, C. bergamia, C. medica,* and *C. paradisi*, other well-known fruits are melons and grapefruits (*Citrus maxima* and *C. paradisi*). 9.56 million tons of melons and citrus medica are produced, while other citrus crops produce 13.90 million tons. China, Brazil, and India are the three countries that produce the most citrus. China's increased production is primarily attributed to its expanded cultivation of citrus fruits, especially tangerines. Brazil is the biggest producer and exporter of orange juice worldwide. However, the world's largest producer of limes and lemons is India. According to the Trade Development Authority of Pakistan, 2023 the total citrus produced was 2.13 million tons, double the previous year. Sweet oranges accounted for 70% of all citrus produced in Pakistan; the remaining 26% comprised mandarins, limes, and lemons. With 460,000 tonnes sold during the 2020–21 export season, Pakistan broke the previous record for Kinnow exports, which was 353,000 tons the year before (Cheema *et al.,* 2020). Punjab produces over 98% of the citrus crop produced worldwide. Sargodha, Toba Tek Singh, and Mandi Baha-ud-din are the main citrus fruit-producing regions of Pakistan; these places are renowned for their fruit that is suitable for export (Ali *et al.,* 2022; Ali *et al.,* 2023; Cheema and Jamali, 2020; Iftikhar *et al.,* 2024). Citrus production has many biotic and abiotic threats, but citrus canker is a major one (Mubeen *et al.,* 2024). It causes enormous losses for the citrus industry.

However, despite this thriving industry, citrus production faces numerous biotic and abiotic threats, with citrus canker emerging as one of the most severe challenges. *Xanthomonas citri* subsp. *citri*, citrus canker leads to significant crop and economic losses, threatening domestic production and export markets. The disease's impact extends beyond yield reduction; it affects fruit quality and marketability, leading to severe economic repercussions for citrus-growing regions. Given these challenges, understanding and managing citrus canker is crucial to maintaining the productivity and sustainability of citrus industries worldwide. This review aims to address the critical issues of citrus canker and evaluate effective management strategies to mitigate its impact.

Citrus Canker: *Xanthomonas citri subsp. citri (formerly X. axonopodis pv. citri)* was once considered a less major citrus canker incidental organism (Mazhar *et al.,* 2021). However, it has become a deadly concern for citrus yield in recent years. Furthermore, Citrus canker significantly reduces the amount and quality of fruit produced, leading to major losses in output. Recent estimates indicate that citrus canker can reduce yields by up to 30% in heavily affected orchards, with certain regions reporting millions of dollars in annual losses due to decreased marketable fruit and heightened management expenses (Mubeen *et al.,* 2015a, Mubeen *et al.,* 2015b). Information about this disease, the pathogen, and treatment methods remains scarce, making management challenging*. X. citri subsp. citri*, once considered less relevant, now poses a serious risk to citrus productivity in the modern period.

Origin and history: Li *et al.* (2007) reported that the oldest citrus herbaria, including *Citrus medico* from India (1827–1831) and *Citrus aurantifolia* from Indonesia (1842–1844), are housed at Herbaria. They concluded that citrus canker likely originated in Java and India. Tropical regions of Asia, such as Indonesia, southern China, and India, are the primary sources of this disease, spreading through budwood. The first citrus canker outbreak in the U.S. was reported in 1915 and is believed to have started from infected nursery stock from Asia (Ali *et al.,* 2023c). The disease also emerged in South Africa (Shahbaz *et al.,* 2022) and South America (Leduc *et al.,* 2011). Quarantine measures and tree destruction helped eliminate the disease in the Gulf States (Ali *et al.,* 2023c), but epidemics persist in regions like Brazil and Florida despite ongoing eradication efforts.

In Punjab, India, citrus canker was first identified in *Citrus aurantifolia* (acid lime) and remains a major issue in regions like Khera, Periyakulum, and Nellore (Das, 2003; Luthra and Sattar, 1942). Recent outbreaks were recorded in the Kinnow Mandarin nurseries, and Brazil, canker incidence was highest in the northwest (Barbosa *et al.,* 2001). The disease threatens citrus production globally, with studies highlighting its spread due to favorable environmental conditions (Kebede and Bamud, 2023). Citrus canker and other serious diseases pose a significant challenge to citrus production worldwide (Ali *et al.,* 2023c; Das, 2003).

Symptomology produced on host Plant: *Xcc* is the cause of citrus canker that infects the citrus plant seedling stage in harvested fruits (Figure 1). Mexican lime, Grapefruit, and other early oranges are extremely prone to *Xcc* (Naqvi *et al.,* 2022). The increased lesions on the surfaces of both leaves, but especially on the lower one. Subsequently, the pimples turn red, crater-like lesions surrounded by a yellow halo and featuring high rims and sunken centers. Because fruit can experience numerous infection cycles and the rind has an extended duration of exposure, fruit lesions vary in size. Stem infections and fruit twigs are comparable. The raised, corky-looking lesions may enhance the long-term survival of the bacteria. Saprophytic fungi, such as Colletotrichum spp., can color older lesions (Guarnaccia *et al.,* 2017). Graham *et al.* (2004) state that the age of the lesions, the part of the plant that is affected, and the type of citrus that is infected can all alter the symptoms of citrus canker. Usually, the abaxial surface of leaves develops little blister-like lesions first. Leaf lesions developed from gray to tan brown, usually surrounded by a yellow halo and having an oily edge. The center of the lesion got taller and corky, and the lesion showed on the leaf's two sides. The leaf tissues of the original lesion had fallen out and died. The lesions on young twigs and stems were usually asymmetrical in form, even though they superficially resembled those on leaves. The golden halo was missing, but the lesions had a raised corky appearance. According to Naqvi *et al.* (2022), one sign of citrus canker is brown spots on leaves, which frequently have an oiled or moist appearance. The lesions, which are the dots, are usually surrounded by a yellow halo and appear on both the leaf's upper and lower surfaces. Similar symptoms can appear on fruit. On stems, brown lumps or lesions may also be signs. The leaf patches turn tan and crusty with age, with a yellow ring encircling them. Eventually, the tan tissue may slip out of the leaf and leave a hole. Leaf spots have been compared to the yellow ring around a burn from a cigarette. The disease may cause early leaf and fruit loss in citrus plants in addition to twig and branch dieback. With time, trees deteriorate and stop producing fruit. The bacteria that cause the illness spreads from sick trees to healthy ones through wind-driven rain or contaminated clothes, tools, and equipment. It can travel quite far via machinery, strong storms like hurricanes, and the transit of tainted citrus goods. Insects do not transmit this disease. As per the findings of Jabeen *et al.* (2016), the early appearance of *Xanthomonas axonopodis* is characterized by tiny, circular spots ranging from 2 to 10 mm in size, which are saturated in water and usually develop on the abaxial surface of leaves. On fruits, stems, leaves, and thorns caused the round sores to rise and resemble blisters. After that, it became white or yellow spongy pustules. Subsequently, the pimples became denser and darker, transforming into a coarse-textured, light-colored to brown-colored, canker structure. Sometimes, young stems may girdle, and pustules on stems merge to break through the epidermis up the stem. Older lesions on leaves usually have higher borders, and sometimes, they have a sunken center encircled by a yellow, chlorotic ring that might eventually vanish. The study conducted by Dhiman *et al.* (2021) concluded that the relative humidity had no bearing effect on the Asiatic Citrus Canker and is not suppressed by it. Citrus canker lesions initially appeared as tiny, rounded, slightly elevated spots of pale green color. Then they burst and form a white-grayish color with a corky-looking brownish in the center. The edges of the lesions were frequently encircled by a halo of yellow (Behlau, 2021). Lesions frequently had a chlorotic halo encircling them and remained high at their margins. Lesions caused by citrus canker started as little eruptions that resemble blisters or slightly elevated pustules. These initially appear on the leaf's underside seven days after infection. The juvenile lesions were generally translucent because the tissue was submerged in water. Lesions were initially rounded or uneven. Lesions were initially pale in color, then they turned brown or tan. The sores became spongy or corky when the epidermis burst with the growth. Finally, the lesions developed the shape of elevated edges and depressed centers, like craters. Big, old lesions broke up or lost their central axis.

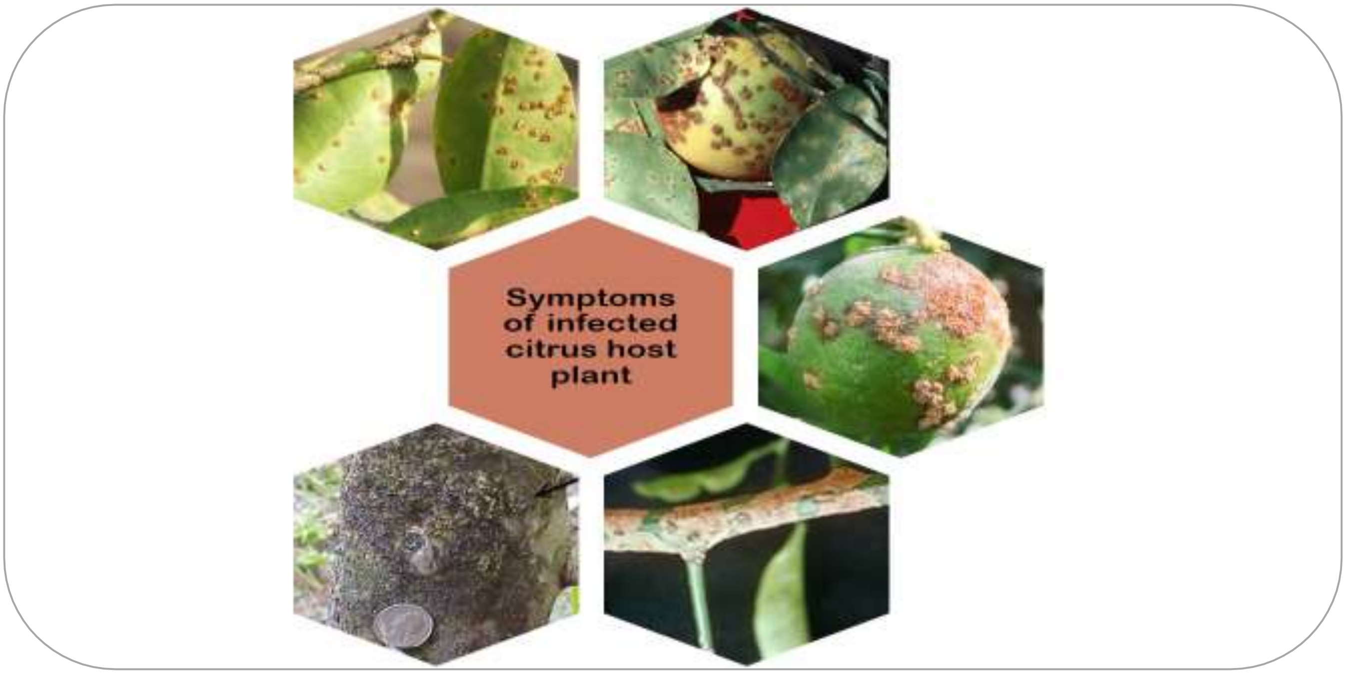

Figure 1. Symptoms produced by the *Xanthomonas* pathogen on citrus host plants

Taxonomy of Pathogen: The genus Xanthomonas includes 28 species and 150 pathovars (Caicedo *et al.,* 2021). The bacterium responsible for citrus canker was initially named *Pseudomonas citri* in the early 1900s, reflecting the limited understanding of bacterial phylogeny. In the late 1930s, it was reclassified as *Xanthomonas citri* (Ali *et al.,* 2023c), an important shift aligned with other Xanthomonas species known for causing plant diseases, highlighting the potential severity of citrus canker. As scientific advances in bacterial genomics progressed, further refinements were made. In 1978, the bacterium was reclassified as *Xanthomonas campestris* pv. *citri* is a designation that emphasizes its specialization for citrus (Chuang *et al.,* 2024). Gabriel *et al.* (1989), proposed returning the name to *X. citri*, distinguishing it as a unique species within the Xanthomonas genus. This renaming underscored the need to distinguish the pathogen among its related species due to its severe impact on citrus.

In the 1990s, *X. axonopodis* pv. *citri* was identified through DNA-DNA hybridization (Vauterin and Vauterin, 1995), bringing molecular precision to its classification. More recent genomic research confirmed *X. citri* pv. *citri* as the causative agent of canker type A, the most virulent form (Constantin *et al.,* 2017; Okoh *et al.,* 2024). The genus Xanthomonas as a whole now includes 240 taxa and affects approximately 350 plant species across 68 host families, including both dicots and monocots (Naqvi *et al.,* 2023). Canker A, caused by *X. citri* subsp*. citri* (*Xcc*) impacts all citrus species, with no reported genetic resistance. In contrast, *X. fuscans subsp. aurantifolii* type B (XauB) causes canker B to grow more slowly (Moreira *et al.,* 2010). The genome of *Xcc* strain 306 was sequenced in 2002, shedding light on the pathogen's mechanisms (Ference *et al.,* 2018). This Gram-negative, rod-shaped bacterium forms yellow colonies due to its exopolysaccharide, xanthan, a hallmark feature of Xanthomonas species (Caicedo *et al.,* 2017).

Strains and Pathogens: Numerous techniques are employed to distinguish and identify canker pathogens and strains due to their frequently similar symptoms: plasmid fingerprints, serology, DNA-DNA homology, PCR and RFLP analyses, plasmid fingerprints, and bacteriophage sensitivity (Naqvi *et al.,* 2022). Without DNA-based testing, Xac strains can be identified from other pathovars by infecting resistant cultivars and using them as host plants (Dia *et al.,* 2022). A pathogenicity test is crucial to the diagnosis and treatment of citrus canker infections, as noted by Naqvi *et al.* (2022). The European and Mediterranean Plant Protection Organization (EPPO/CABI, 1997) identified five main strains of citrus canker: "A," "B," "C," "D," and "E." These strains differ in host range, geographic origin, and level of aggression.

The key characteristics of these strains are summarized in the table below:

Strain	Characteristics	Host Range	Geographic	Diagnostic Methods	References

			Origin		
A	Gram-negative rods, single polar flagellum, produce yellow Xantho-mondain pigment.	Wide host range across citrus	Asia, Americas, Africa	ELISA, monoclonal antibodies, bacteriophage sensitivity test, pathogenicity tests	Goto, 2012; Naqvi *et al.,* 2022.
B	Slower growth than A, distinctive pathogenicity profile	Narrower host range	Southeast Asia, Brazil	Bacteriophage sensitivity test, no reaction to A strain monoclonal antibodies, distinct reaction patterns in pathogenicity tests	Naqvi *et al.,* 2022; Sun *et al.,* 2004
C	Similar to B in pathotype, biochemical features vary slightly	Limited host range	South America, Southeast Asia	Reacts differently from A in monoclonal antibody testing	Sun *et al.,* 2004; Naqvi *et al.,* 2022
D	Less aggressive, shows unique biochemical activity	Select cultivars	Middle Eastern regions	Pathogenicity testing under specific artificial growth conditions	EPPO/CABI, 1997
E	Biochemically diverse; production of proteolytic enzymes and yellow pigment influenced by growth media	Specific citrus species	Restricted to a few areas	Identified based on biochemical reactions, e.g., tyrosinase, catalase activity, breakdown of starch, aesculin, and gelatin	Rangaswami & Soumini, 1957; Goto, 2012.

Additional Pathogen Features: *Xac* strains produce polysaccharide slime when glucose is added to the culture medium, aiding colony growth. Optimal growth temperatures are between 28-30°C, with maximum tolerance up to 39°C. Diagnostic characteristics include positive reactions for tyrosinase, catalase, hydrogen sulfide, and casein hydrolysis but negative reactions in the methyl red test, indole synthesis, and nitrate reduction (Goto, 2012).

Disease Development Process/Disease Cycle: According to Naqvi *et al.* (2022), when the fruit is still forming or when new shoots are beginning to emerge. Bacteria infect leaves and shoots that are actively growing, resulting in the appearance of tiny, invisible spots (Figure 2). Not much is known regarding the type and scope of the bacterium's survival on citrus. Research has shown that the disease can live in soil, infected plant tissue debris, and in combination with non-citrus hosts for variable periods. Although edaphic and climatic factors might affect the pathogen, it usually only survives a short time in soil and diseased plant tissue waste. The bacteria can persist anywhere from less than 7 days to 62 days on the weeds' phylloplane and in their rhizosphere, depending on the host, the surrounding conditions, and the precise location. However, nothing is known about the epidemiological importance of *X. axonopodis* pv. *citri* about weeds and plant detritus that do not belong to the citrus family or in the soil. The only bacteria that are known to have a substantial impact on epidemiology are those that proliferate in citrus and related lesion types. In addition to poor saprophyte status on straw mulch, among plant debris, and epiphyte status on both host and non-host plants, long-term survival in damaged plant tissues, such as discolored tree trunk and limb bark, is also feasible. The citrus canker bacterium can linger in citrus lesions for up to ten months, whether on the fruit or in the soil. Overwintering lesions are the primary source of inoculum for the next season, particularly those that form on angular shoots. Naqvi *et al.* (2022) investigated how *Xcc* endures in tropical environments by overwintered leaf lesions and simulated splash propagation of inoculums. Bacteria can enter a plant through its stomata or wounds. Turgid leaves' stomata allow wind-blown inoculums to enter mesophyll cells directly. Additionally, while feeding, *X. axonopodis* pv. *citri* could penetrate leaf tissues directly due to damage caused by a small amount of exposed leaf mesophyll on citrus leaves. Additionally, minor larvae of citrus leaves become contaminated with bacteria, which spread through feeding galleries (Tennant *et al.,* 2009; Xiao *et al.,* 2021). In 1968, a survey was carried out in the different districts of Punjab, India, focusing on 35 types of citruses. They concluded that *P. citrella*-related injuries significantly raised the frequency and severity of cankers. Additionally, they proposed that using insecticides against *P. citrella* would enhance the effectiveness of disease control measures (fungicides and antibiotics). The pest of citrus, *Phyllocnistis citrella* Stainton, is known to have expanded its range extremely quickly over the past ten years (Naqvi *et al.,* 2022). The more citrus leaf minor injuries there are, the higher the disease incidence. The results of the study on the link between citrus canker (*X. axonopodis* pv. *citri*) and citrus leaf miner (*P. citrella*) on acid lime (*Citrus aurantiifolia*) indicated a substantial correlation between the two. Additionally, it was discovered that leaves attacked by leaf miners had more canker areas (Ullah *et al.,* 2019). Splashing rains mainly cause the pathogen's short-distance dissemination within and between trees. Rainwater splattering and running over the lesion's surface spread the bacteria. It travels to nearby trees or within individual trees in this way. The age of the lesion has a major impact on the concentration of bacteria, which can range from 100 to 1000 million cells/drop. Rainstorms facilitate citrus canker outbreaks because the bacteria can travel up to 100 meters through tiny raindrops and aerosols; nonetheless, a successful infection seldom happens a few rows or more downwind (Goto, 2012). Because the pathogen spreads by splashing, overhead irrigation exacerbates the disease's temporal and spatial growth. This is especially problematic for nurseries that produce young trees free of cankers intended to be planted in newly discovered groves (Jyothi and Shilpa, 2020). However, the regional spread of the bacteria, which typically happens due to human transport of ill or exposed citrus tree material and propagation materials from nurseries, such as budded trees, rootstock seedlings, and bud wood, is what causes the long-distance spread of the pathogen (Caglayan *et al.,* 2019). No verified record of seed delivery exists. The pathogen may also spread over great distances through contaminated clothing, equipment used in fruit handling and harvesting activities, and individuals infected with the disease.

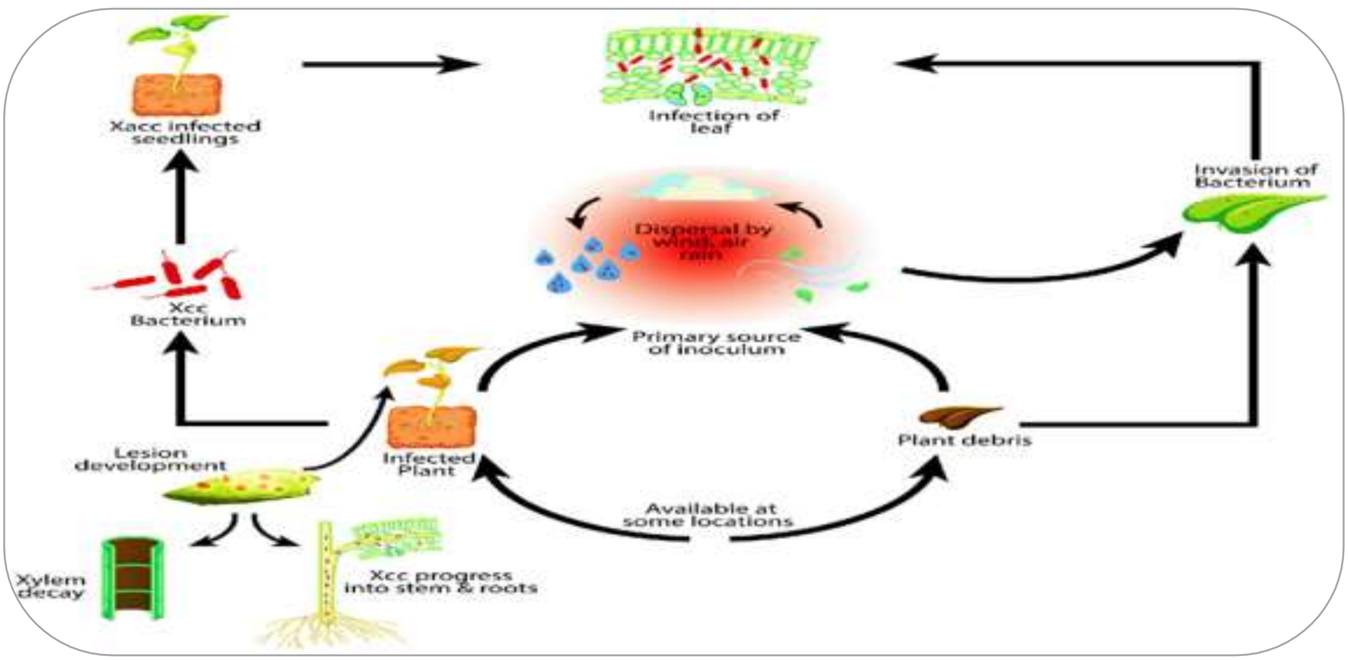

Figure 2. *Xanthomonas citri* subsp. *Citri* is spread by wind-blown rain and can infect all above-ground parts of the plant (Ali *et al.,* 2023c).

Disease Epidemiology: According to Hameed *et al.* (2023), the temperature (30–38 °C) and high relative humidity (RH) are important epidemiological factors. He also found that temperature (max. and min.), wind speed, RH, and rainfall (RF) were the main factors in citrus cankers. Additionally, it was observed that strong winds' raindrops create ideal conditions for the propagation of CC (Yan and Wang, 2012). These factors affect the host's sensitivity, survival, vigor, succulence, penetration rate of spores, rate of multiplication, direction of pathogen dispersion, and germination (Pathak *et al.,* 2018). With certain exceptions, the pathogen becomes more active in the summer heat and mild winter months regarding infection and transmission. Raindrop splashes allowed *Xcc* to move to healthier host plants and cause lesions on the leaves, stems, and fruits' surfaces. In the presence of free moisture, the rate at which bacteria propagated to infect the new host plant increased. When an active reservoir of inoculum is present, monsoon rainstorms with strong winds can enhance the risk of CC outbreaks (Graham *et al.,* 2004). On mature plants, citrus canker epidemics are characterized by their erratic nature. This suggests that the disease remains persistently in the fields, which later causes undetectable infection in plants. It is also not considered eradicated even if it has not been present in the field for the last 10 years. Large citrus canker outbreaks usually happen when the fruit is just starting to ripen or when new branches are starting to appear. This is especially true if there is significant rain during this crucial period. In warm temperatures, frequent rainfall, especially during storms, contributes to the emergence of disease. Although citrus canker is mostly a cosmetic issue, it can also cause defoliation, shoot die-back, and fruit drop under very conducive environments. The Asian leaf miner complicates leaf susceptibility. The colonies that leaf miner larvae create are more susceptible to damage and take longer to repair. As a result, leaves have extremely vulnerable sores for extended periods, which allow the bacteria to infect the leaf. Compared to citrus canker without leaf miners, the quantity and size of lesions are significantly increased, leading to a grove's inoculum pressure being multiplied many times (Ali *et al.,* 2023c). Climate conditions, particularly temperature and rainfall, are essential for the quick development and growth of *X. axonopodis* pv. *citri* (Graham *et al.,* 2004; Nauman *et al.,* 2023). Disease development is aided by frequent rains in warm weather, particularly during storms. The disease is most suited to temperatures between 20 and 30 degrees Celsius and evenly spaced rainfall (Das, 2003; Khan and Abid, 2007).

Interaction Between Leaf Miners: *Phyllocnistis citrella* Stainton, an Asian leaf miner, can infest fruit, leaves, and stems. This causes a large increase in small lesions that eventually merge to form massive, asymmetrical lesions that nearly mimic the shapes of the feeding gallery. Leaf miners wind leaves when they begin to feed. The feeding galleries are directly beneath the epidermis. Numerous gallium infections brought on by citrus canker bacteria can result in significant production of inoculum and canker infection. By the middle of the 1990s, it had spread to many citrus-growing countries globally from its limited distribution in Southeast and Southwest Asia at the beginning of 1994 (Ali *et al.,* 2023c). It was initially documented in Florida, Brazil, and Argentina in 1993 and 1996, respectively (Graham *et al.,* 2022). Furthermore, he found that the feeding patterns of the citrus leaf miner induce three different kinds of bacterial infections in the host. First, a direct bacterial infection results when a leaf is struck by a wind that disperses germs and a leaf miner tears away the mesophyll. Second, due to feeding activities, infected mesophyll cells are transported by virus-ridden leaf miner larvae and spread to the feeding galleries. Thirdly, minor wounds heal more slowly than those caused by mechanical means., making prolonged exposure to bacterial infections probable. Still, it has been thought that the host can withstand a small drop in leaf area (up to 10%) before leaf miner damage affects yield (Nawaz *et al.,* 2021); however, there have been studies indicating that a large yield loss can occur from a 16–23% reduction in leaf area (Ali *et al.,* 2023c) Given these complexities, integrated disease management (IDM) strategies become essential in mitigating the effects of these pests on citrus canker.

Integrated Disease Management Programs: Various disease management strategies have been applied to control this pathogen (Ali *et al.,* 2024c) (Table 1). Young seedling cases of CC disease have been successfully decreased by the integrated disease management (IDM) program (Hughes *et al.,* 2022). Since citrus cultivars are more vulnerable to treatment when leaf miners attack or climate change occurs, removing damaged trees is the only effective strategy to control the disease (Gmitter *et al.,* 2012). Nonetheless, certain integrated practices can decrease the severity of the illness by stopping the inoculum's spread. To address the problem locally, the farming community has generally accepted and observed these methods. However, their efforts to control the disease have not yielded much progress. Studies on resistant genotypes in citrus and allied genera have been conducted over an extended period worldwide (Ali *et al.,* 2024). Citrus fruits with specific resistance have only resulted from a small number of molecular breeding studies by introducing genes that fight bacteria, and the creation of resistant cultivars has not progressed significantly due to the lack of resistant varieties. However, total resistance has not been attained; instead, a decrease in the incidence of disease has been attained (Shahbaz *et al.,* 2022).

Table1. Integrated Management Strategies and Control Measures for Citrus Canker

Aspect	Details	Cultivars/Methods	Efficacy	Potential Drawbacks	References
Integrated Disease Management (IDM)	Resistant cultivars, tree removal, and integrated practices to reduce inoculum spread.	Valencia, Tahiti lime, Folhamurcha	Moderately effective, reduces disease spread	Requires removal of trees, slow adoption	Hughes *et al.* (2022); Gmitter *et al.* (2012)
Resistant Germplasms	Use of resistant species such as kumquats, mandarins, and calamondins. Complete resistance not yet achieved.	*Fortunella* spp., *C. reticulata, C. mitis*	Reduces incidence, partial resistance	Total resistance not attained, limited breeding success	Shahbaz *et al.* (2022)
Quarantine Measures	Barriers and restrictions to limit pathogen spread, including restricted planting and transportation. Equipment cleaning is mandatory.	Quarantine zones, eradication zones	Prevents the spread of the disease	Difficult to implement, impacts local agriculture	Villalta *et al.* (2018); Lee, (2020).
Field Screening	Screening different citrus varieties for resistance under local conditions. Avoiding vulnerable cultivars during early growth stages.	Navel, Hamlin, Tahiti limes, mid-late oranges	Effective for screening susceptibility	Time-consuming, requires ongoing monitoring	Shahbaz *et al.* (2022)
Control Strategies	Removed diseased trees and used copper-based bactericides. Collaboration is needed for long-term strategies.	Copper-based bactericides, tree removal	Widely used, established method	Pathogen resistance to copper, environmental concerns	Yu *et al.* (2023)
Cultural Control	Quarantine, removing infected trees, planting less susceptible cultivars, and using nanoparticles combined with bactericides.	Nanoparticles (TiO_2, Cu, Zn), quarantine	Reduces incidence in localized outbreaks	Expensive, complete eradication challenging to achieve	Graham *et al.* (2016)
Induced Systemic Resistance (ISR)	Boosting plant defense mechanisms with chemicals. ISR is applied early in the season to enhance plant immunity.	Benzothiadiazoles, Harpin proteins	Effective in early stages of infection	Requires early application, limited commercial use	Riseh and Vazvani (2024)
Plant Extracts and Essential Oils	Antibacterial activity of essential oils against X. citri. Use of natural extracts to suppress pathogen growth.	Clove, cardamom, ginger, cinnamon oils	Highly effective (e.g., clove oil)	Limited commercial adoption, variable results	Matrose *et al.* (2021), Nagy *et al.* (2023)

Quarantines: Federal quarantine barriers are one regulatory measure that addresses pathogens potentially present in nearly every nation. However, pinpointing the precise locations of these barriers is challenging due to biological and political considerations (Villalta *et al.,* 2018). These walls are typically erected two kilometers or more distant from any infestation that has been verified (Villalta *et al.,* 2018). The limited movement of host plant materials in quarantine zones impacts the citrus agriculture sector (Lee, 2020). Until the disease is declared completely eradicated, citrus plants cannot be planted in business or residential districts that have undergone eradication operations (Lee, 2020). Fruit deliveries to friends and family are prohibited, and any gardening and lawn care instruments transported between homes must be sanitized (Lee, 2020).

Field Screening: Field screening has been conducted worldwide to determine how different Citrus varieties could react to CC under certain local environmental circumstances (Shahbaz *et al.,* 2022). Screening procedures permit CC resistance in Tahiti limes, tangerines, and oranges from the mid-and late-seasons (Shahbaz *et al.,* 2022). These cultivars might be vulnerable in the early stages and require treatment with a leaf miner control product to shield them from infection-causing damage to growing flushes (Shahbaz *et al.,* 2022).

Control Strategies: For a long time, cutting down diseased trees to stop the infection from spreading was the most popular approach for disease control (Yu *et al.,* 2023; Azeem *et al.,* 2024). On the other hand, some citrus growers cultivate their oranges in disease-resistant types cultivated in nurseries free of CC. Furthermore, for over 20 years, CC has been managed using copper-based bactericides (Yu *et al.,* 2023). Regretfully, strains of *Xanthomonas* spp. resistant to copper have emerged due to the frequent use of these bactericides (Yu *et al.,* 2023). Additionally, bactericides based on copper can potentially induce phytotoxicity and other adverse effects on the environment, like leaving residues of copper on plants and cultivated soils. These effects eventually increase production costs (Yu *et al.,* 2023). Effectively mitigating the impacts of this disease requires international collaboration and study. Researchers must collaborate to share resources and best practices, identify the sources of infections, and develop effective disease control plans.

Cultural Control: The best course of action is eradicating a disease if it is uncommon in a particular location (Graham *et al.,* 2016). In order to enable survey teams to find and remove sick citrus trees, regulations have been put in place. Additionally, survey teams will seek to locate susceptible trees within 125 feet of a diseased tree and destroy them (Behlau *et al.,* 2014). As the incidence of CC in Brazilian plantations has changed, experts now advise planting less vulnerable cultivars and using proper orchard management techniques to stop and treat the disease. In Brazil, all plants within a 30-meter radius of an afflicted plantation will be removed if the infection rate is 0.5% or lower. On the other hand, the entire block will be eliminated if the infection rate is more than 0.5% (Behlau *et al.,* 2014). Nowadays, though, nanoparticles are capable of doing more than just bactericides. This is especially true when other materials, such as titanium oxide, copper, zinc, or iron, are loaded into the nanoparticles. These are the nanoparticles that, when combined with bactericides, can have a significant effect (Graham *et al.,* 2016).

Induced Systemic Resistance: Induced systemic resistance (ISR) is a primary form of innate resistance in host plants. It can be triggered by various factors, including applying pesticides or biocontrol agents to protect against phytopathogens (Ali *et al.,* 2023b; Ali *et al.,* 2022b). Riseh and Vazvani (2024) state that this technique bolsters the defenses mechanism of Plants against infection, both chemically and physically. Plants have an active resistance mechanism called induced systemic resistance (ISR), which can trigger both biotic and abiotic stresses. Chemicals like benzothiadiazoles, salicylic acid, and harpin protein can successfully boost a plant's resistance to disease (Naz *et al.,* 2024). In addition to treating the disease, ISR can stop pathogen resistance from developing (Naz *et al.,* 2024). ISR activity can be applied early in the development season to enhance copper's protective properties, which prevent bacteria from growing on developing leaves (Riseh and Vazvani, 2024).

Plant Extracts: To reduce the adverse environmental effects of synthetic pesticides, alternative strategies for managing plant-pathogenic microorganisms need to be developed (Ali *et al.,* 2020; Ayilara *et al.,* 2023). Green plants are an efficient chemotherapy substitute for synthetic pesticides and can be a valuable source of natural pesticides (Ayilara *et al.,* 2023). Several studies have shown that different plant byproducts, like extracts and diffusates, can fight against various dangerous bacteria and fungi (Ali *et al.,* 2023c). Because of their exorbitant price and the challenging financial circumstances small farmers in Pakistan confront, antibiotics are regrettably typically out of reach for the average farmer (Matrose *et al.,* 2021). In light of this, diffusive and plant extracts appear promising treatments for bacterial plant diseases (Matrose *et al.,* 2021). Farming communities have used a range of plant extracts, such as *Eucalyptus camelduensis, Azadirachta indica, Dalbrgia sissoo, Allium sativum* L., *Calotropis gigantea, Allium cepa* L., *Melia azedarach*, and *Gardenia florida*, to lessen the spread of *Xcc* (Naqvi *et al.,* 2023). "Essential oil" is a broad phrase used to characterize any aromatic, volatile substance made by plants (Sadgrove *et al.,* 2022).

Essential oils: Marin *et al.* (2024) evaluated the antibacterial activity, effect on the bacterial membrane, and citrus fruit sanitization potential of essential oils derived from the *Cymbopogon* species. The results showed that the bactericidal concentration of EOs from *C. schoenanthus* and *C. citratus*, which was 312 mg L−1, was surpassed by the bacterial concentration for *C. martini* and *C. winterianus,* which was the highest at 625 mg L−1. This proves that EOs with higher concentrations had greater potency. Fruit exposed to *C. shoenanthus* and *C. martini* showed a 68% reduction in the recovery of viable bacterial cells. Essential oils from fresh and dry leaves of Schinus molle (EO-FL and

EO-DL, respectively) were assessed for their activity in an experiment by Silva *et al.* (2024). Using 96-well culture plates, the broth microdilution technique was used to screen these activities. They demonstrated how GC-MS and GC-FID were used to identify three main ingredients in both EO-DL: β-caryophyllene, caryophyllene oxide, and spathulenol. The outcome demonstrated the effectiveness of spathulenol (MIC= 200mg/mL), EO-FL (MIC= 61.5 µg/mL), and EO-DL (MIC= 31.25 µg/mL) against strains of *X. citri*. Even these results demonstrated the ability of spathulenol, EO-FL, and EO-DL to control *X. citri*. Castillo- Juárez *et al.* (2022) investigated the antibacterial activity of diluted agar/Tween 80 solutions against *Xanthomonas citri* pv. *citri* using pure Flourensia compounds, low-polarity extracts, and essential oil from *Aloysia gratissima*. Nagy *et al.* (2023) looked into how essential oils affected *Xcc*. The outcome demonstrated that *Xanthomonas citri subsp. citri* cannot multiply when exposed to any essential oil. The antibacterial test results showed that the essential oils of natural cardamom and ginger successfully suppressed the growth of pathotype A of *X. citri* subsp. *citri*, while other essential oils showed moderate to poor activity. This demonstrated the potential benefits of these eight plants' essential oils, particularly those of cardamom and ginger, for treating citrus bacterial canker. Nagy *et al.* (2023) assessed the essential oils of *Xanthomonas* species, which are phytopathogenic bacteria, and pure constituents like limonene, oc-terpineol, p-cymene, eugenol, and linalool. The essential oils were evaluated from *Pimpinella anesum, Artemisia annua, Cymbopogon martini, Mentha piperita,* and *Apium graveolens*. The most significant growth inhibition against Xanthomonas citri demonstrated in vitro by pure ingredients such as a-terpineol and eugenol, as well as essential oils of *Apium graveolens*, was 84, 86, and 84%, respectively. Additionally, they demonstrated that *X. citri's* growth may be suppressed by essential oils from *Cymbopogon martini* and p-cymene by up to 81 and 53%, respectively. According to the study, the pure constituents a-terpineol and eugenol, as well as the studied extracts from A graveolens, may naturally suppress the growth of *Xanthomonas* species.

CONCLUSION AND FUTURE RECOMMENDATIONS

The future of citrus canker management lies in a multifaceted approach combining technological innovations, genetic research, and environmentally friendly practices. One promising avenue is the development of citrus cultivars with enhanced genetic resistance to *X. axonopodis* pv. *citri*. Advances in molecular breeding techniques, such as CRISPR/Cas9, can accelerate the development of resistant citrus varieties by targeting specific genes associated with pathogen resistance. In addition, research into biocontrol agents and natural plant-based antimicrobials can potentially reduce dependence on chemical treatments. Essential oils and plant extracts like clove, neem, and cinnamon have demonstrated antibacterial activity and could be more significant in integrated disease management (IDM) strategies. More rigorous field trials and formulations are needed to assess their practical application in large-scale citrus farming. Nanotechnology-based solutions, including copper and silver nanoparticles, may offer more precise and effective disease control with lower environmental impact. At the same time, RNA interference (RNAi) approaches targeting essential genes of *Xcc* could provide innovative, sustainable control methods (Ali *et al.,* 2024a, Ali *et al.,* 2024b).

Emerging plant diseases management options, such as gene editing, microbiome manipulation, and biopesticides, are revolutionizing how we approach plant health. These technologies have immense potential to offer more targeted, efficient, and eco-friendly alternatives to traditional chemical treatments. Harnessing the power of beneficial microbes in the soil, for example, could enhance plant resilience against various pathogens, including citrus canker. Another critical aspect is enhancing quarantine and regulatory measures to prevent the spread of citrus canker into new areas. Implementing stricter surveillance systems and rapid diagnostic tools such as real-time PCR can enable early detection and containment. Collaboration among international research institutions will be vital in overcoming the global threat of citrus canker and ensuring the sustainability of citrus production.

REFRENCES

Ali F., M. Atiq, N.A. Rajput, I. Ahmad, M.A. Latif, M.A. Aslam, M.J. Matloob, M. Mehtab, A. Ijaz and M. Qasim. 2024. Intervention of Bacterial Leaf Spot of Bell Pepper through Neem Mediated Copper and Zinc Hybrid Nanoparticles. Phytopathogenomics and Disease Control, 3(2): 251-259.

Ali, A., F. Ölmez, M.A. Zeshan, M. Mubeen, Y. Iftikhar, A. Sajid, and M.K. Solanki. 2024c. Yeast-Based Solutions in Controlling Plant Pathogens. Biocatalysis and Agricultural Biotechnology, 103199. https://doi.org/10.1016/j.bcab.2024.103199

Ali, A., I. Tabbasum, H. Azeem, F. Ölmez, G. Deveci, B. Khalid, and M. Mehtab. 2023a. Bacterial endophytes, a resilient way toward sustainable agriculture: provide plant growth promotion and biocontrol of plant pathogens. Journal of Global Innovations in Agricultural Sciences, 11(2): 153–174

Ali, A., M. Aasim, K. Çelik, M.A. Nadeem, and F.S. Baloch. 2024a. Frontiers in bacterial-based green synthesized nanoparticles (NPs): A sustainable strategy for combating ınfectious plant pathogens. Biocatalysis and Agricultural Biotechnology, 68 https://doi.org/10.1016/j.bcab.2024.103293

Ali, A., M. Shahbaz, F. Ölmez, N. Fatima, U.U.D. Umar, M.A. Ali, and F.S. Baloch. 2024b. RNA interference: a promising biotechnological approach to combat plant pathogens, mechanism and future prospects. World Journal of Microbiology and Biotechnology, 40(11):339

Ali, A., M.A. Zeshan, Y. Iftikhar, M. Abid, S.F. Ehsan, M.U. Ghani, and A.A. Khan. 2020. Role of plant extracts and salicylic acid for the management of chili veinal mottle virus disease. Pakistan Journal of Phytopathology, 32(2), 147–157

Ali, A., U.U.D. Umar, S. Akhtar, M.T. Shakeel, A.U. Rehman, M.N. Tahir, S. Atta, M. Moustafa, F. Ölmez, and R. Parveen. 2022b. Identification and primary distribution of Citrus viroid V in citrus in Punjab, Pakistan. Molecular Biology Reports, 49(12): 11433–11441 https://doi.org/10.1007/s11033-022-07677-7

Ali, A., U.U.D. Umar, S.A.H. Naqvi, M.T. Shakeel, M.N. Tahir, M.F. Khan, M.T. Altaf, F. Ölmez, A.A. Dababat, Z.U. Haq, M.A. Nadeem, R. Hatipoğlu, F.S. Baloch, and Y.S. Chung. 2023b. Molecular characterization of divergent isolates of Citrus bent leaf viroid (CBLVd) from citrus cultivars of Punjab, Pakistan. Frontiers in Genetics, 13https://doi.org/10.3389/fgene.2022.1104635

Ali, A., Y. Iftikhar, M. Mubeen, H. Ali, M.A. Zeshan, Z. Asad, M. Zafar-ul-Hye, M.A. Rehman, M. Abbas, M. Rafique and M.U. Ghani. 2022a. The antagonistic potential of bacterial species against fungal plant pathogens (FPP) and their role in plant growth promotion (PGP): A review. Phyton-International Journal of Experimental Botany, 91(9): 1859–1877

Ali, S., A. Hameed, G. Muhae-Ud-Din, M. Ikhlaq, M. Ashfaq, M. Atiq, F. Ali, Z.U. Zia, S.A.H. Naqvi and Y. Wang. 2023c. Citrus canker: A persistent threat to the worldwide citrus industry—an analysis. Agronomy, 13(4): 11–12

Aslam N., M. Atiq, N.A. Rajput, A. Akram, A.M. Arif, G.A. Kachelo, A. Nawaz, M.M. Jahangir, A. Jabbar and A. Ijaz. 2024. Explicating botanical bactericides as an intervention tool towards citrus canker. Plant protection, 08(01): 25-32.

Ayilara, M.S., B.S. Adeleke, S.A. Akinola, C.A. Fayose, U.T. Adeyemi, L.A. Gbadegesin, R.K. Omole, R.M. Johnson, Q.O. Uthman, and O.O. Babalola. 2023. Biopesticides as a promising alternative to synthetic pesticides: A case for microbial pesticides, phytopesticides, and nanobiopesticides. Frontiers in Microbiology,14 https://doi.org/10.3389/fmicb.2023.1040901

Azeem, H., A. Ali, R. Perveen, U.U.D. Umar, M. Zakaria, F. Ölmez, and M.U. Azeem. 2024. Molecular characterization of cotton leaf curl Multan beta-satellite occurance on chili plants in Multan, Pakistan. Journal of Plant Protection Research, 64(2):139-148 https://doi.org/10.24425/jppr.2024.150248

Behlau, F. 2021. An overview of citrus canker in Brazil. Tropical Plant Pathology, 46(1): 1–12.

Behlau, F., N.L. Barelli, and J. Belasque. 2014. Lessons from a case of successful eradication of citrus canker in a citrus-producing farm in São Paulo state, Brazil. Journal of Plant Pathology, 96(3): 561–568

Bhatti, A.M., H.M. Usman, A. Iffat, M. Tatar, M.M. Karim, M.I. Zafar, A. Ali and T. Shafique. 2024. Deciphering the Current Scenario and Prospective Outlook of Citrus Gummosis in Pakistan. Düzce Üniversitesi Ziraat Fakültesi Dergisi, 2(1): 46–59

Caglayan, K., M. Gazel, and D. Škorić. 2019. Transmission of phytoplasmas by agronomic practices. In Assunta Bertaccini, Phyllis G Weintraub, Govind Pratap Rao, Nicola Mori (Eds.), Phytoplasmas: Plant pathogenic bacteria-II: Transmission and management of phytoplasma-associated diseases (pp. 149–163)

Caicedo, J.C., & S. Villamizar. 2021. Xanthomonas citri ssp. citri pathogenicity, a review. In M. S. Khan & I. A. Khan (Eds.), Citrus-research, development and biotechnology.

Castillo-Juárez, I., B.E. Blancas-Luciano, R. García-Contreras, and A.M. Fernández-Presas. 2022. Antimicrobial peptides properties beyond growth inhibition and bacterial killing. PeerJ: Life and Enviroment, 10: Article e12667. https://doi.org/10.7717/peerj.12667

Cheema, I.A. and H.K. Jamali. 2020. Growth of citrus fruits in Pakistan. Amazonia Investiga, 9(35): 74–81. https://doi.org/10.34069/AI/2020.35.11.6

Cheema, I.A., H.K. Jamali, and A. Sarwar. 2020. Pakistan citrus exports break record in 2020–21 season. Trade Development Authority of Pakistan.

Chuang, S.C., S. Dobhal, K. Pal, T.D. Amore, A.M. Alvarez, and M. Arif. 2024. Xanthomonas Strains Isolated from Hosts in the Family Araceae Reveal Diverse Phylogenetic Relationships and Origins. Phytopathology, 114(8), 1963–1974

Constantin, E.C., A. Haegeman, J. Van Vaerenbergh, S. Baeyen, C. Van Malderghem, M. Maes, and B. Cottyn. 2017. Pathogenicity and virulence gene content of Xanthomonas strains infecting Araceae, formerly known as *Xanthomonas axonopodis* pv. *dieffenbachiae*. Plant Pathology, 66(9): 1539–1554 https://doi.org/10.1111/ppa.12694

Das, A.K. (2003). Citrus canker: A review. Journal of Applied

Horticulture, 5(1): 52–60
Dhiman, M.R., R. Kumar, and S. Kumar. 2021. Postharvest Handling and Disease Management of Cut Flowers. In D. Singh, R.R. Sharma, V. Devappa, D. Kamil (Eds.), Postharvest handling and diseases of horticultural produce (pp. 415–430).
Dia, N.C., L. Morinière, B. Cottyn, E. Bernal, J.M. Jacobs, R. Koebnik, E. Osdaghi, N. Potnis and J.F. Pothier. 2022. *Xanthomonas hortorum* – beyond gardens: Current taxonomy, genomics, and virulence repertoires. Molecular Plant Pathology, 23(5): 597–621 https://doi.org/10.1111/mpp.13185
Ference, C.M., A.M. Gochez, F. Behlau, N. Wang, J.H. Graham and J.B. Jones. 2018. Recent advances in the understanding of *Xanthomonas citri* ssp. *citri* pathogenesis and citrus canker disease management. Molecular Plant Pathology, 19(6): 1302–1318 https://doi.org/10.1111/mpp.12638
Gabriel, D.W., M.T. Kingsley, J.E. Hunter, and T. Gottwald. 1989. Reinstatement of *Xanthomonas citri* (ex-Hasse) and *X. phaseoli* (ex-Smith) to species and reclassification of all *X. campestris* pv. *citri* strains. International Journal of Systematic and Evolutionary Microbiology, 39(1): 14–22
Gmitter, F.G., C. Chen, M.A. Machado, A.A. De Souza, P. Ollitrault, Y. Froehlicher, and T. Shimizu. 2012. Citrus genomics. Tree Genetics & Genomes, 8: 611–626
Goto, M. (2012). Fundamentals of bacterial plant pathology.
Graham, J.H., E.G. Johnson, M.E. Myers, M. Young, P. Rajasekaran, S. Das, and S. Santra. 2016. Potential of nano-formulated zinc oxide for control of citrus canker on grapefruit trees. Plant disease, 100(12): 2442–2447. https://doi.org/10.1094/PDIS-05-16-0598-RE
Graham, J.H., T.R. Gottwald, J. Cubero, and D.S. Achor. 2004. *Xanthomonas axonopodis* pv. *citri*: factors affecting successful eradication of citrus canker. Molecular Plant Pathology, 5(1): 1–15
Guarnaccia, V., J.Z. Groenewald, G. Polizzi, and P.W. Crous. 2017. High species diversity in Colletotrichum associated with citrus diseases in Europe. Persoonia-Molecular Phylogeny and Evolution of Fungi, 39(1): 32–50 https://doi.org/10.3767/persoonia.2017.39.02
Hameed, A., N.A. Rajput, R. Binyamin, F. Ali, M. W. Alam, H. M. U. Aslam, H. Riaz, and S. Ali. 2023. Epidemiological Markers for Citrus Canker caused by *Xanthomonas citri* pv. *citri*. International Journal of Phytopathology, 12(3): 295–302
Haq ZU, A. Ali, S. A. H. Naqvi, F. S. Baloch, and U. U. D. Umar. 2024. Primary distribution and RT-PCR based detection of citrus dwarfing viroid (CDVd) in citrus cultivars of Pakistan. Turkish Journal of Botany 48: 1-11. https://doi.org/10.TJBOT-2024-00200R1.
Hughes, T., J. Dall'Asta, and S. Turner. 2022. Integrated Disease Management and its impact on young seedling cases of citrus canker. Journal of Integrated Pest Management, 13(1): 19–27. https://doi.org/10.1093/jipm/pmac015
Iftikhar, Y., M. Mubeen, Q. Shakeel, I. Lalarukh, A. Ali, M. Aasim, M.A. Zeshan, T. Zulfiqar, S. K. Alhag, and L.A. Al-Shuraym. 2024. Spatial distribution and molecular characterization of huanglongbing and its vector in various citrus cultivars. Pakistan Journal of Agricultural Sciences, 61(2): 685–694 https://doi.org/10.21162/PAKJAS/24.155
Jabeen, T., H.M.I. Arshad, K. Saleem, S. Ali, E. Ullah, S. Naureen and M.M. Babar. 2016. Morphological and biochemical characterization of *Xanthomonas axenopodis* pv. *citri* isolates causing citrus canker disease in Pakistan. PSM Microbiology, 1(1), 10–17
Jamil, Z., M. Tariq, M.U. Raja, M. Shahbaz, J.S.S. Seelan, M. Tatar, A. Ali, N. Fatima, R. Bejaoui, and A.U. Bozhüyük. 2024. Utilization of phytogenic silver nanoparticles and bacterial agents for the management of citrus canker disease. Turkish Journal of Agriculture and Forestry, 48: 1-13
Jyothi, V., and M.E. Shilpa. 2020. Citrus Diseases and Their Management. In G. Chand, N. Akhtar and S. Kumar (Eds.), Diseases of Fruits and Vegetable Crops (pp. 41–63).
Kebede, M., and K. Bamud. 2023. Assessment of major fruit diseases and insect pests in silte, gurage and yem special woreda, southern Ethiopia. Ukrainian Journal of Ecology, 13(3): 20–26 https://doi.org/10.15421/2023_435
Khan, A., M. Ikram, J.R. Hahm, and M.O. Kim. 2020. Antioxidant and anti-inflammatory effects of citrus flavonoid hesperetin: Special focus on neurological disorders. Antioxidants, 9(7). https://doi.org/10.3390/antiox9070609
Khan, M.A. and M. Abid. 2007. Effect of environmental conditions on citrus canker disease development. Pakistan Journal of Phytopathology, 19(2): 139–144
Leduc, A., C. Vernière, C. Boyer, K. Vital, O. Pruvost, Y. Niang and J.Y. Rey. 2011. First report of *Xanthomonas citri* pv. *citri* pathotype A causing Asiatic citrus canker on grapefruit and Mexican lime in Senegal. Plant Disease, 95(10): 1311–1311 https://doi.org/10.1094/PDIS-03-11-0217
Lee, R.F. 2020. Exclusion of plant viruses by certification and quarantine programs. In L.P. Awasthi (Ed.), Applied Plant Virology (pp. 763–775).
Li, W., Q. Song, R.H. Brlansky, and J.S. Hartung. 2007. Genetic diversity of citrus bacterial canker pathogens preserved in herbarium specimens. Proceedings of the National Academy of Sciences, 104(47): 18427–18432. https://doi.org/10.1073/pnas.0705590104
Luthra, J.C. and A. Sattar. 1942. Citrus canker and its control in Punjab. Punjab Fruit Journal, 6(1): 179–182

Marin, V.R., C.F.C. Zamuner, G.B. Hypolito, J.H. Ferrarezi, N. Alleoni, M.N. Caccalano, Ferreira, and D.C. Sass. 2024. Antibacterial activity of Cymbopogon species essential oils against *Xanthomonas citri* and their use in post-harvest treatment for citrus canker management. Letters in Applied Microbiology, 77(5) https://doi.org/10.1093/lambio/ovae041

Matrose, N.A., K. Obikeze, Z.A. Belay, and O.J. Caleb. 2021. Plant extracts and other natural compounds as alternatives for post-harvest management of fruit fungal pathogens: A review. Food Bioscience, 41: Article e100840. https://doi.org/10.1016/j.fbio.2020.100840

Mazhar, H. R., M. Atiq, N. A. Rajput, S. Ali, M. Usman, U. Ahmad, A. Nawaz, M. Faizan Ullah and S. Iqbal. 2021. Determination of Antibacterial Activity of Phytochemicals towards *Xanthomonas citri* Pv. *citri* Causing Citrus Canker. Agricultural Sciences Journal, 3(2): 1-12.

Moreira, L.M., N.F. Almeida, N. Potnis, L.A. Digiampietri, S.S. Adi, J.C. Bortolossi, A.C. Da Silva, A.M. Da Silva, F.E. De Moraes, J.C. De Oliveira, R.F. De Souza, A.P. Facincani, A.L. Ferraz, M.I. Ferro, L.R. Furlan, D.F. Gimenez, J.B. Jones, E.W. Kitajima, M.L. Laia, . . . J.C. Setubal. 2010. Novel insights into the genomic basis of citrus canker based on the genome sequences of two strains of *Xanthomonas fuscans* subsp. *aurantifolii*. BMC Genomics, 11(1): Article e238. https://doi.org/10.1186/1471-2164-11-238

Mubeen, M., A. Ali, Y. Iftikhar, M. Shahbaz, M.I. Ullah, Md.A. Ali, N. Fatima, J.S.S. Seelan, Y. S. Tan and U.B. Algopishi. 2024a. Innovative strategies for characterizing and managing huanglongbing in citrus. World Journal of Microbiology and Biotechnology. 40:342 https://doi.org/10.1007/s11274-024-04135-3

Mubeen, M., F. Bakhtawar, Y. Iftikhar, Q. Shakeel, A. Sajid, R. Iqbal, R.M. Aljowaie and T. Chaudhary. 2024b. Biological and molecular characterization of citrus bent leaf viroid. Heliyon. 10(7): Article e28209. https://doi.org/10.1016/j.heliyon.2024.e28209

Mubeen, M., H. M. Arshad, Y. Iftikhar, I. Bilqees, S. Arooj and H. M. Saeed. 2015a. In vitro efficacy of antibiotics against *Xanthomonas axonopodis* pv. *citri* through inhabitation zone techniques. International Journal of Agricultural and Applied Sciences. 7(1): 67–71

Mubeen, M., H. M. Arshad, Y. Iftikhar, M. U. Ullah and I. Bilqees. 2015b. Bio-chemical characterization of *Xanthomonas axonopodis* pv. *citri*: A gram-negative bacterium causing citrus canker. International Journal of Science and Nature, 6(2): 151–154

Nagy, J.K., A.M. Móricz, A. Böszörményi, A. Ambrus, and I. Schwarczinger. 2023. Antibacterial effect of essential oils and their components against *Xanthomonas arboricola* pv. *pruni* revealed by microdilution and direct bioautographic assays. Frontiers in Cellular and Infection Microbiology, 13https://doi.org/10.3389/fcimb.2023.1204027

Naqvi, S. a. H., J. Wang, M.T. Malik, U. Umar, N. Ateeq-Ur-Rehman, A. Hasnain, M.A. Sohail, M.T. Shakeel, M. Nauman, N. Hafeez-Ur-Rehman, M.Z. Hassan, M. Fatima, and R. Datta. 2022. Citrus canker—distribution, taxonomy, epidemiology, disease cycle, pathogen biology, detection, and management: A critical review and future research agenda. Agronomy, 12(5): Article e1075. https://doi.org/10.3390/agronomy12051075

Nauman, M., S. Mushtaq, M.F. Khan, A. Ali, S.A.H. Naqvi, Z. Haq and U.U.D. Umar. 2023. Morphological, biochemical, and molecular characterization of *Xanthomonas citri* subsp. *citri*, cause of citrus canker disease in Pakistan. Pakistan Journal of Botany, 55(6): 2409–2421

Nawaz, R., N.A. Abbasi, I.A. Hafiz, M.F. Khan, and A. Khalid. 2021. Environmental variables influence the developmental stages of the citrus leafminer, infestation level and mined leaves physiological response of Kinnow mandarin. Scientific Reports, 11(1): Article e7720. https://doi.org/10.1038/s41598-021-87160-8

Naz, M., D. Zhang, K. Liao, X. Chen, N. Ahmed, D. Wang, J. Zhou, and Z. Chen. 2024. The past, present, and future of plant activators targeting the salicylic acid signaling pathway. Genes, 15(9): Article e1237. https://doi.org/10.3390/genes15091237

Okoh, E.B., M. Payne, R. Lan, M. Riegler, T.A. Chapman and D.R. Bogema. 2024. A multilocus sequence typing scheme for rapid identification of *Xanthomonas citri* based on whole-genome sequencing data. Phytopathology, 114(7): 1480–1489 https://doi.org/10.1094/PHYTO-12-23-0490-R

Pathak, R., S.K. Singh, A. Tak, and P. Gehlot. 2018. Impact of climate change on host, pathogen and plant disease adaptation regime: a review. Biosciences Biotechnology Research Asia, 15(3): 529–540

Riasat, A., M.U. Ghazanfar and W. Raza. 2020. Interaction of citrus canker with *Phyllocnistis citrella* stainton. Pakistan Journal of Phytopathology, 32(1): 01-07.

Riseh, R.S., and M.G. Vazvani. 2024. Unveiling Methods to Stimulate Plant Resistance against Pathogens. Frontiers in Bioscience-Landmark, 29(5): Article e188. https://doi.org/10.31083/j.fbl2905188

Sadgrove, N.J., G.F. Padilla-González and M. Phumthum. 2022. Fundamental chemistry of essential oils and volatile organic compounds, methods of analysis and authentication. Plants, 11(6)https://doi.org/10.3390/plants11060789

Sebghatollahi, Z., M. Ghanadian, P. Agarwal, H.S. Ghaheh, N. Mahato, R. Yogesh, and S.H. Hejazi. 2022. Citrus flavonoids: Biological activities, implementation in skin health, and topical applications: A review. ACS Food Science & Technology, 2(9): 1417–1432

Shahbaz, E., M. Ali, M. Shafiq, M. Atiq, M. Hussain, R.M. Balal, A. Sarkhosh, F. Alferez, S. Sadiq, and M.A. Shahid. 2022. Citrus canker Pathogen, its mechanism of infection, eradication, and impacts. Plants, 12(1)https://doi.org/10.3390/plants12010123

Silva, A., C. Fernandes, D.D. Santos, M. Mazza, J. Silva, L. Magalhães, R. Pires, M. Miranda, and A. Crotti. 2024. Chemical composition, antileishmanial, and antifungal activities of essential oils from *Cinnamomum cassia* bark, *Schinus molle* dried leaves and their blends. ChemRxiv. https://doi.org/10.26434/chemrxiv-2024-xv7db

Sun, X., R.E. Stall, J.B. Jones, J. Cubero, T.R. Gottwald, J.H. Graham, W.N. Dixon, T.S. Schubert, P.H. Chaloux, V.K. Stromberg, G.H. Lacy, and B.D. Sutton. 2004. Detection and characterization of a new strain of citrus canker bacteria from Key/Mexican lime and alemow in South Florida. Plant Disease, 88(11): 1179–1188 https://doi.org/10.1094/PDIS.2004.88.11.1179

Tennant, P.F., D. Robinson, L. Fisher, S.M. Bennett, D. Hutton, P. Coates-Beckford, and W. McLaughlin. 2009. Diseases and pests of citrus (Citrus spp.). Tree and Forestry Science and Biotechnology, 3(2): 81–107

Testai, L., and V. Calderone. 2017. Nutraceutical value of citrus flavanones and their implications in cardiovascular disease. Nutrients, 9(5).https://doi.org/10.3390/nu9050502

Trade Development Authority of Pakistan (TDAP). (2023). Report on citrus production in Pakistan. TDAP Agricultural Reports.

Ullah, M.I., M. Riaz, M. Arshad, A.H. Khan, M. Afzal, S. Khalid, N. Mehmood, S. Ali, A.M. Khan, S.M.A. Zahid, and M. Riaz. 2019. Application of organic fertilizers affects the citrus leafminer, *Phyllocnistis citrella* (Lepidoptera: Gracillariidae) infestation, and citrus canker disease in nursery plantations. International Journal of Insect Science, 11: 1–12. https://doi.org/10.1177/1179543319858634

Vauterin, L., and P. Vauterin. 1995. Reclassification of Xanthomonas species based on DNA-DNA hybridization data. International Journal of Systematic and Evolutionary Microbiology, 45(3): 572–580

Villalta, O.N., M. Mebalds, and J. Edwards. 2018. Biosecurity tool-set: Optimising quarantine zones for eradication through consideration of Australia's success with plant pathogen eradications in horticulture. Australasian Plant Pathology, 47: 135–154

Xiao, M., Y. Dong and X. Zhao. 2021. The role of vector insects in the spread of *Xanthomonas axonopodis* pv. *citri*. Journal of Agricultural and Urban Entomology, 37(1): 45–58 https://doi.org/10.1080/10509585.2021.1898875

Yan, Q. and N. Wang. 2012. High-throughput screening and analysis of genes of Xanthomonas citri subsp. citri involved in citrus canker symptom development. Molecular Plant-Microbe Interactions, 25: 69–84. https://doi.org/10.1094/MPMI-05-11-0121

Yu, Y., H. Liu, H. Xia and Z. Chu. 2023. Double-or triple-tiered protection: Prospects for the sustainable application of copper-based antimicrobial compounds for another fourteen decades. International Journal of Molecular Sciences, 24(13) https://doi.org/10.3390/ijms241310893

Contribution of Authors:

Amjad Ali, Parnaz Mortazavi, Muhammed Tatar, Qaiser Shakeel and Meliha F. Sarıkaya.	:	Conceptualization, collecting literature, visualization, validation, project administration review & editing.
Mustansar Mubeen	:	Writing the original draft, preparation of tables and figures.