



## **SUSTAINABLE AND PRACTICAL APPROACHES FOR THE CONTROL OF ANTHRACNOSE IN COMMERCIAL MANGO (*MANGIFERA INDICA* L.) PRODUCTION**

### **INTRODUCTION**

Anthracnose is one of the most significant and widespread diseases affecting mango worldwide, particularly in regions characterized by high humidity and high rainfall climates. In these environments, the disease can be extremely destructive both before and after fruit harvest leading to substantial yield losses of up to 100% in orchards that are not properly managed (Arauz, 2000; Dofuor et al., 2023). While fruits are the primary focus of anthracnose damage in mango trees, the disease can also be a serious problem on other parts of the tree, such as stems, leaves, inflorescences or flowers, causing a range of symptoms such as blossom blight, leaf blight, and, in severe cases, tree dieback (Ploetz and Prakash, 1997).

The impact of anthracnose extends beyond mature trees, affecting young plants in nurseries as well as newly established orchards, where it can severely limit plant growth and establishment. In addition to the visible damage, the fungus can also infect the plant systemically, making management and control particularly challenging. Managing mango anthracnose requires a multifaceted approach that includes early detection, the use of tolerant cultivars, effective cultural practices, and timely chemical or biological interventions. Effective disease management is critical because untreated infections can spread rapidly through an orchard, leading to significant crop losses both in the short term and over subsequent growing seasons.

### **GEOGRAPHICAL DISTRIBUTION**

Mango anthracnose is present in most mango producing regions worldwide, including some of the main mango producers and exporters, in different continents: Africa (Ethiopia, Ghana, Ivory Coast, Nigeria or South Africa), Oceania (Australia), Asia (Bangladesh, China, India, Indonesia, Malaysia,

Philippines, Taiwan, Thailand or Vietnam), America (Brazil, Colombia, Cuba, Dominican Republic, Ecuador, Mexico, Peru or the US (Florida, Hawaii and Puerto Rico) (Dofuor et al., 2023).

The presence of anthracnose is not limited to humid, tropical climates. It has also been reported in Mediterranean regions, where generally low or no rainfall occurs during the critical period from the flowering stage to the fruit harvest season, conditions typically considered the least favorable for the development of this disease. One such example is southern Italy (Ismail et al., 2015). In recent years, the spread of mango anthracnose to previously unaffected regions has accelerated, likely due to the global movement of plant material, both for trade and cultivation. Examples include Indonesia (Benatar et al., 2021), Vietnam (Li et al., 2020) and Cuba (Manzano León et al., 2018). The international trade of mangoes, coupled with the exchange of planting material, has facilitated the rapid introduction of the disease to new areas, creating growing concerns about the vulnerability of mango production in these regions. This spread further underscores the importance of comprehensive quarantine measures and the need for global cooperation to prevent the introduction and dissemination of mango anthracnose.

## **CAUSAL AGENT AND PATHOGEN LIFE CYCLE**

The causal agents of mango anthracnose are several species of the *Colletotrichum* genus (Fungi, Ascomycota) that affect a wide range of crops worldwide. The form-genus *Colletotrichum* Corda (form-order *Melanconiales*; form-class *Coelomycetes*; subdivision *Deuteromycotina*) includes imperfect fungal species, which exist in their sexual (teleomorphic or perfect) form as *Glomerella* (subdivision *Ascomycotina*). According to Weir et al. (2023), the *C. gloeosporioides* complex consists of 22 species and one subspecies. At the molecular level, phylogenetic relationships among *Colletotrichum* species have been analyzed through sequencing of different genomic regions, such as the Internal Transcriber Spacer (ITS) region of the nuclear ribosomal RNA gene cluster which is the official barcoding gene for fungi (Freeman et al., 2000; Weir et al., 2012). However, in some cases other genome regions such as actin (ACT),  $\beta$ -tubuline (TUB2), chitin synthase 1 (CHS-1) or the glyceraldehyde 3-phosphate

dehydrogenase (GAPDH) have been used to resolve phylogenetic relationships (Weir et al., 2012; Sharma et al., 2013; Pardo de la Hoz et al., 2016, Mo et al., 2018).

Among the key *Colletotrichum* species associated with mango anthracnose are *C. gloeosporioides*, *C. asianum*, *C. fructicola*, *C. scovillei*, and *C. siamense*. The most common species responsible for mango anthracnose in most mango-producing regions, is *Colletotrichum gloeosporioides* Penz. whose sexual form is *Glomerella cingulata* (Stonem.) Spauld. and Schrenk. (Cook, 1975; Snowdon, 1990; Ploetz, 2003). However, other species play secondary roles in specific geographic regions. For example, *Colletotrichum acutatum* Simmonds (sexual stage or teleomorph: *Glomerella acutata*) is prevalent in areas such as Australia, Florida (USA), India, Japan, and Taiwan (Fitzell, 1979; Prakash, 1990; Weng and Chuang, 1995; Taba et al., 2004). Additionally, *Colletotrichum boninense* J. Moriwaki, Toy. Sato, and T. Tsukiboshi has been reported in Colombia (Afanador-Kafuri et al., 2003). In addition, several additional *Colletotrichum* species have been identified associated with mango in China (Li et al., 2019; Sudheeran et al., 2021; Zheng et al., 2025).

A typical life cycle of mango anthracnose is described in Paudel et al. (2022). One of the key stages in this cycle is the dissemination of asexual spores (conidia) from primary inoculum sources. These inoculum sources can include soil, plant debris (such as rotten fruits), and infected plant parts like leaves, twigs, panicles and fruits still hanging on the tree. Conidia production is particularly favored by wet or humid conditions, and conidia dispersal is facilitated by rain splashes, irrigation water, and wind. As a result, mango anthracnose is particularly prevalent in tropical climates, where humidity and rainfall, combined with warm temperatures, are abundant. When rainfall is frequent during the flowering and fruit set stages, anthracnose can cause significant damage by destroying inflorescences and/or resulting in the premature drop of young developing fruitlets.

Thus, the pathogen's cycle of infection begins with the release of conidia, which adhere to the plant tissue surface via a hemicellulosic mucilage, facilitating the germination and infection of the fungus often by means of specialized structures, such as appressoria that aid in penetration of the plant tissue producing

subcuticular hyphae allowing the pathogen to invade and establish an infection. The development of hyphae and the colonisation of the mango tissues are closely correlated with the secretion of cell wall-degrading enzymes, such as polygalacturonases and pectate lyases, which degrade the host cell wall and promote further fungal development (Meng et al., 2022). The disease progresses through the development of fruiting bodies (acervuli) on the infected tissues, where new conidia are produced, completing the cycle. This cycle is characterized by the continual dissemination of spores, infection of new host tissues, further disease progression, reproduction of the pathogen, and survival of pathogen on infected plant material (Jeffries et al., 1990; Paudel et al., 2022).

Mango fruits can also be infected by *Colletotrichum* conidia that originate from other tropical and subtropical host fruit crops such as avocado, banana, coffee, guava, papaya or citrus (Freeman and Shabi, 1996; Freeman et al., 1998; Moraes et al., 2013; Zakaria, 2021). This cross-infection between different crops further complicates disease management, as the broad host range of *Colletotrichum* spp. allows the pathogen to spread across various agricultural systems. This highlights the need for comprehensive management strategies that consider the pathogen's ability to infect multiple crops and environments.

## **DETECTION OF ANTHRACNOSE**

Traditional methods for detecting mango anthracnose have primarily relied on the observation of specific morphological features of the pathogen such as mycelial growth, conidia size, colony color, texture, and the presence and absence of setae (Freeman et al., 1998; Ashraful et al., 2017). While these methods remain widely used, they have notable limitations. They are time-consuming and require skilled taxonomic expertise to accurately identify *Colletotrichum* species. Moreover, distinguishing between *Colletotrichum* species based solely on morphological features can be challenging, as many species exhibit overlapping characteristics, making it difficult to differentiate them at the species level (Weir et al., 2012). Furthermore, these techniques can be less effective at detecting the pathogen in its early stages of infection, where symptoms may be subtle or not yet visible, hindering effective disease management.

In recent years, molecular techniques have increasingly become the preferred method for detecting *Colletotrichum* spp. and diagnosing mango anthracnose. Strategies based in PCR (Polymerase Chain Reaction) and DNA sequencing have proven to be more precise and reliable, enabling the detection of the pathogen at various stages of its lifecycle, even when it is in a latent or asymptomatic phase (Kamle et al., 2013; Zakaria et al., 2015). These molecular approaches are based on the identification of specific genetic markers within the genome of the pathogen, offering a high degree of sensitivity and accuracy, which is especially beneficial in detecting infections that may not yet show visible signs on the fruit or plant (Weir et al., 2012; Sharma et al., 2013; Pardo de la Hoz et al., 2016, Mo et al., 2018).

In addition to molecular methods, other innovative detection tools are also being explored to improve early diagnosis and facilitate rapid identification at the field level. One such approach is camera-assisted image analysis (Corkidi et al., 2006). This technique employs high-resolution cameras to capture detailed images of mango plants and fruits, analyzing the visual patterns associated with anthracnose symptoms, such as lesions and discoloration. These images can be processed using specialized software to detect and quantify the extent of infection, even before the symptoms become visible to the naked eye. More recently, the integration of computer vision, deep learning and artificial intelligence (AI) methodologies are gaining popularity for analyzing fungal diseases. AI algorithms can be trained to recognize fungal infections by analyzing large datasets of images and identifying subtle changes in plant morphology. These approaches offer great potential for automating the detection process and increasing the speed and accuracy of anthracnose diagnosis. Examples of different approaches using these technologies to analyze mango anthracnose include Khan et al. (2019), Singh et al. (2019), Prabu et al. (2022), Ramírez et al., (2022), Velásquez et al., (2023) or Patiño et al. (2026). While these modern detection methods offer great promise, challenges remain in terms of cost, scalability, and integration into field-level diagnostic practices.

## **DAMAGE**

Anthracoze can significantly damage multiple parts of the mango tree, including fruits, leaves, panicles, peduncles, pedicels, stems, twigs. The extent of the damage is closely linked to the stage of infection and prevailing environmental conditions, such as humidity, rainfall and temperature.

### **Panicles**

In the panicles, anthracnose affects both the flowers and the inflorescence stalk (Arauz, 2000; Fitzell and Peak, 1984). Infected panicles show necrotic flowers that eventually detach, leaving behind the peduncles. The pedicels and peduncles develop small, round, dark spots that can enlarge and merge into larger, dark brown, necrotic patches. The disease significantly reduces fruit set and overall yield, as the affected flowers fail to develop into fruits. On the inflorescence stalks, dark gray to black, elongated lesions appear. The affected flowers dry out, with the color ranging from brown to black (Arauz, 2000; Fitzell and Peak, 1984). In high-humidity environments, especially during periods of prolonged rainfall, fungal fruiting bodies can appear on infected panicle tissues. These fungal structures may appear salmon- to orange-colored, contributing to further dispersion of the pathogen. The widespread infection of panicles, coupled with the premature detachment of flowers, is one of the primary reasons for significant yield losses in mango orchards affected by anthracnose.

### **Leaves**

On mango leaves, anthracnose manifests as irregular, dark brown necrotic spots, usually surrounded by yellowish halos, with the lesions having irregular, rounded edges, often extending beyond the leaf veins. These lesions typically range from 0.5 to 1.0 cm in diameter on mature leaves, but they can be larger on younger, more susceptible leaves. The infection affects both sides of the leaf, and the lesions often coalesce to form large necrotic areas, typically along the leaf margins (Fitzell and Peak, 1984; Arauz, 2000; Dofuor et al., 2023). Severely infected leaves may curl. The disease primarily targets young tissue, with conidia produced visible in lesions at any stage of infection. Older, mature leaves typically

show latent infections, where the pathogen remains dormant until the tissue begins to senesce. Over time, large necrotic patches appear, causing the leaf to wither, dry out, and, ultimately, fall off. In cases of extensive leaf loss, the tree may exhibit a ragged, tattered appearance, affecting photosynthesis and overall tree health.

## **Fruits**

Although anthracnose causes significant damage in the trees in the field, it is the main cause of postharvest mango fruit rot and can severely impact fruit quality and yield. The disease can affect both immature and mature fruits; small, immature fruits may become infected and fail to develop, while larger fruits may become mummified. These mummified fruits are subsequently invaded saprophytically by the fungus, which sporulates abundantly on them, serving as a secondary source of inoculum (Arauz, 2000; Dofuor et al., 2023). In mature mangoes, black lesions with undefined borders, often greater than 2 cm in diameter, are common (Arauz, 2000; Dofuor et al., 2023). The incidence of anthracnose is nearly 100% in mangoes produced in regions with high humidity and heavy rainfall, where the fungus thrives. Temperatures ranging from 20°C to 30°C favor infection, although there is considerable variation in the optimal temperature requirements for conidia germination and appressorium formation among different isolates of the fungus from different locations (Arauz, 2000).

In the early stages, anthracnose lesions are typically limited to the skin, but, as the fruit ripens, the pathogen can invade the pulp, causing further fruit degradation. At harvest, many fruits contain latent infections, where the pathogen, exists as appressoria attached to the fruit's epithelial cells, even if the infective hyphae have not penetrated the cellular layer. In immature fruits, the development of the fungus is inhibited by endogenous fungicidal metabolites produced in the fruit itself. As the fruit begins to ripen, these fungicidal compounds dissipate, and the pathogen continues to colonize the fruit. The infectious structures of the pathogen are found on or very close to the surface of the fruit during the latent phase of the infection cycle. In harvested fruits, anthracnose lesions appear as rounded, brown to black spots with indefinite borders on the fruit surface (Arauz, 2000). These lesions can vary in size and may coalesce to

cover extensive areas of the fruit's surface, usually restricted to the peel. However, in severe cases the fungus can invade the pulp (Arauz, 2000) leading to further decay. In advanced stages of the infection, the fungus produces acervuli, and abundant orange to salmon pink masses of conidia appear on the lesions (Arauz, 2000).

Thus, on immature fruits and young tissues, spores of the fungus germinate and penetrate both the cuticle and epidermis, extending throughout the tissue layers whereas on mature fruits, infections penetrate the cuticle but remain dormant, only becoming active fruits start to ripen.

## **DISEASE CONTROL**

Effective control of anthracnose is crucial for successful mango production, especially in regions characterized by warm and humid climates. A well-integrated holistic approach that combines multiple strategies, from orchard planning and design to postharvest management, is essential for controlling the disease. Preventive measures should always be prioritized as they can significantly reduce the need of curative interventions, which are typically more expensive and less sustainable. These preventive strategies have gained importance in recent years, aiming to make mango production more cost-effective and environmentally sustainable.

### **Before planting strategies**

The first line of defense against anthracnose begins even before planting. Crowded and moist conditions in nurseries are particularly problematic leading to significant damage to young leaves. After planting with infected plants, entire new orchards can be devastated by the disease. To combat this, the first step of a proper plan of fight against this pathogen, especially in areas with high disease pressure, is selecting an appropriate orchard site and choosing resistant or tolerant mango varieties.

Key factors in orchard site selection include well-drained soils, ample sunlight, and good air circulation. Ideally, the orchards should be located in areas with a

distinct dry season, especially from flowering to fruit harvest, as this reduces the risk of disease during the crucial stages of fruit development. In regions with a high risk of disease, avoiding areas that experience frequent rains during flowering and fruit set can help minimize the spread of the pathogen. In some cases, intercropping mango with other fruit tree crops that are not hosts of anthracnose could be an interesting option.

While commercial mango cultivars are susceptible to anthracnose, several studies in various producing regions have shown that different varieties have varying levels of susceptibility to the disease (Vitale et al., 2020; Gong et al., 2013; Karunanayake et al., 2014; Supriya et al., 2020; Grice et al., 2022), although even the most resistant cultivars must be treated against the fungus in humid tropical environments. Some known cultivars with partial tolerance/resistance includes Zill, Rapoza, Fairchild, Palmer, Carrie, Kensington Pride (Grice et al., 2022; Dofuor et al., 2023; although the results are not always consistent in different countries and often cultivars that perform well under natural field conditions develop symptoms when artificially inoculated (Grice et al., 2022). In any case, this variability means that natural disease resistance can be used as a control against anthracnose (Gong et al., 2013), and, therefore, the selection of appropriate mango varieties can facilitate, mango production with fewer incidences of anthracnose, resulting in an increased yield and better fruit quality (Dofuor et al., 2023). In fact, screening of mango progenies for resistance to anthracnose is a goal in breeding programs (Bally et al., 2010).

The use of molecular markers linked to resistance can accelerate breeding programs focused on developing more resistant mango cultivars to anthracnose. Examples include the report of a Single Nucleotide Polymorphism (SNP) marker linked to the defense-related  $\beta$ -1,3-glucanase 2 ( $\beta$ -1,3-GLU2) gene (Felipe et al., 2022). Moreover, the development of omic strategies will provide new information on resistance genes that could be used to accelerate breeding programs (Gómez-Ollé, et al., 2023). Promising results have already been reported using high-throughput next-generation sequencing technologies to develop transcriptomic data or preharvest (Sudheeran et al, 2021) and postharvest (Hong et al., 2016) mango fruits against *C. gloeosporioides*.

Several mango varieties have been shown to exhibit higher resistance due to the presence of antifungal compounds such as resorcinols (Hassan et al., 2007; Karunanayake et al., 2011; 2014), mainly present in unripen fruits. For example, 'Kensington Pride', showed higher concentration of 5-n-pentadecyl resorcinol in fruit peel extracts than more susceptible varieties as 'Badami' and 'Raspuri' (Supriya et al., 2020). Other substances may also be involved. Examples include hydrogen peroxide, lignin or phenolic compounds that have been reported in fruits of 'Keitt' during development and storage when compared to those of 'Zill', that was more susceptible to the disease (Gong et al., 2013). Other example are galloannins,  $\beta$ -glucanases and chitinases present in the mango fruit peel and latex (Karunanayake et al., 2011; Jiménez-Maldonado et al., 2024).

### **Cultural techniques**

Cultural management practices are fundamental in controlling mango anthracnose. Since humidity favors the development of the disease, orchards should preferably be established in areas that present a distinct dry season so fruit development can take place in the most unfavorable conditions for disease development (Arauz, 2000). Main key strategies that should be included in this program are:

- **Tree spacing.** Proper tree spacing is crucial to avoid overcrowding, which can lead to poor airflow and sunlight penetration. This helps in reducing humidity around the trees and prevents conditions favorable for fungal growth.
- **Pruning.** Regular and appropriate pruning is necessary to maintain canopy health. Underpruned trees can have dense canopies that inhibit light penetration, reduce new leaf development, and increase relative humidity, all of which create favorable conditions ease for the development of the disease (Asrey et al., 2013). Ideally pruning should be performed during dry weather when the fungus causing anthracnose is less likely to infect the pruning wounds.
- **Flowering management.** In seasonal tropical regions, a strategy can include management of flowering with the goal that fruit development

takes place during the driest period (Arauz, 2000). This is more challenging in subtropical regions, where the main stimulus for flowering in mango are low temperatures.

- **Water and nutrient management.** Proper irrigation schedules and balanced fertilization are essential to keep trees healthy. Over-watering or improper irrigation practices can increase the tree's susceptibility to anthracnose, while nutrient deficiencies can weaken the plant's natural defenses.
- **Sanitary field measures.** Regular monitoring for early signs of anthracnose and the timely removal of infected plant material (such as leaves, branches, fruits, and panicles) can help reduce disease spread. In some cases, when the market value of the fruit is high, bagging individual fruits could be a viable option to protect them from the disease (Arauz, 2000; Senghor et al., 2007) but it also could affect the red color of the fruit of some varieties, which could reduce consumer appeal in some markets (Hofman et al., 1997).
- **Forecasting systems.** Different anthracnose forecasting models have been developed to schedule fungicide applications with the goal of reducing the number of applications, enabling growers to apply proper control measures at the right time (Fitzell et al., 1984; Dodd et al., 1991; Estrada et al., 1996). However, caution should be taken when using a model in a different region from which it was developed (Akem, 2006).

### **Chemical control**

Chemical control has traditionally been the most common method for managing anthracnose in mango, especially in humid environments where the disease pressure is high. While some mango cultivars may exhibit partial resistance, fungicide treatments are often necessary to control the disease (Lim and Khoo, 1985; Jefferies et al., 1990). However, fungicide use is limited by the low number of available effective products, and by the regulations present in both producing and importing countries. Therefore, the choice of fungicides depends on both local regulations and the final destinations of the fruits. The treatments have to

take into account that the Maximum Residue Limits (MRLs) are below target market limits established by the importing countries. In the case of the U.S., all mangos sold in the country must comply with all applicable agricultural regulations, including The Plant Protection Act that gives the USDA's Animal and Plant Health Inspection Services (APHIS) the authority to inspect imported fruits and vegetables. In addition, the U.S. Environmental Protection Agency (EPA) regulates the use of pesticides, fungicides and other chemicals that may be used in the production of mangos sold in the U.S. Consequently, imported mangos grown outside of the U.S. must comply with both the regulations of their countries of production and those of the U.S. In addition, extended use of chemical treatments can result in the development of resistant genotypes of the pathogen, which can be present for several years after discontinued use of the products (Sanders et al., 2000).

Non-systemic fungicides such as dithiocarbamates (mancozeb, maneb, zineb), captan or copper-based compounds are widely used to control anthracnose. Overall, copper fungicides are the most commonly used, although they often present low efficacy (Arauz, 2000), and they are usually applied in conjunction or alternated with other fungicides, especially if disease pressure is high (Thind and Hollomon, 2018). Dithiocarbamates are also very popular and show good control, but in the presence of water they are readily transformed into ethylenethiourea (Downing, 2000), a carcinogen linked to various human health concerns (Mutic et al., 2017; van Wendel de Joode et al., 2016; Mora et al., 2018). Other contact fungicides that show high effectiveness against this disease, such as chlorothalonil, may also cause phytotoxic effects. In this kind of preventive programmes, application frequency, key to the effectiveness of the interventions, may vary according to crop phenological stage (Sardrood and Goltapeh, 2018), disease pressure (Thind and Hollomon, 2018) or climatic conditions (Akem, 2006).

Systemic fungicides, although few are available, may also be included in the scheduled application programs against mango anthracnose; in fact, most of them are described as fungicides with both preventive and curative effects. Benzimidazoles, imidazoles and strobilurins are the main available groups. Benzimidazoles (e.g. benomyl and carbendazim), were highly used in the past

due to their excellent anthracnose control until pathogen resistance was developed (Akem, 2006). Imidazoles, such as prochloraz and imazalil, are moderately effective against this disease for pre- and post-harvest applications, respectively. Strobilurins are also effective against anthracnose and other post-harvest diseases, but they should be limited to no more than three applications per season to avoid resistance buildup, preferably alternating or combining with fungicides with a different mode of action (Brent and Hollomon, 2007).

The overuse of chemical fungicides has resulted in the development of resistant pathogen strains, which can persist even after the fungicides are no longer used (Torres-Calzada et al., 2015). Thus, rotating fungicides with different modes of action and using them in combination with other control methods is essential to minimize the risk of resistance.

### **Biological control**

Biological control methods are increasingly being explored as a sustainable alternative or complement to chemical fungicides to control mango anthracnose (Choudhary et al., 2025). The use of microbial consortia based on bacteria, fungi and yeasts that protect mango trees from pathogens is an emerging approach that focuses on improving plant health and resilience without relying on chemicals (Peralta Ruiz et al., 2023). Examples include some species of yeasts, such as *Debaryomyces nepalensis* (Luo et al 2015), *Metschnikowia pulcherrima* (Tian et al., 2018; Shao et al., 2019), *Meyerozyma caribbica* (Bautista-Rosales et al., 2013; Aguirre-Güitrón et al., 2022) or *Meyerozyma guilliermondii* (López-Cruz et al., 2024). Fungi such as *Cryptococcus laurentii* (Bautista-Rosales et al., 2014), *Papiliotrema aspenensis* (Konsue et al., 2020), *Rhodotorula minuta* (Patiño-Vera et al., 2005) or several species of *Trichoderma* (de los Santos-Villalobos et al., 2013; Alvinida, 2018) have also shown promising results. All these fungi show different antagonistic mechanisms of action against the causal agents of mango anthracnose such as competition for space and nutrients, production of hydrolytic enzymes, parasitism or biofilm formation. In addition to fungi, several reports have also demonstrated that postharvest treatments with antagonistic bacteria, particularly species of the genus *Bacillus*, show good results. Examples include *Bacillus subtilis* (Senghor et al., 2007), *Bacillus licheniformis* (Silimela and

Korsten, 2007), *Bacillus pumilus* (Zheng et al., 2013), *Bacillus amyloliquefaciens* (Alvandia and Acda, 2014; Liang et al., 2022), *Bacillus velezensis* (Reyes-Estebanez et al., 2020), *Bacillus siamensis* (Jiang et al., 2022) or *Bacillus thuringiensis* (Zheng et al., 2013). Other bacteria that have shown promising results in controlling anthracnose in mango fruits belong to the genera *Streptomyces*, known to secrete a diverse repertoire of secondary metabolites and extracellular enzymes (Evangelista-Martínez et al., 2022; Cheng et al., 2023), *Pseudomonas*, such as *Pseudomonas putida* (Archana et al., 2021; Janamatti et al., 2022) or *Stenotrophomonas*, such as the marine bacterium *Stenotrophomonas rhizophila* (Reyes-Pérez et al., 2019).

### **Postharvest control**

In addition to conventional postharvest control of anthracnose using synthetic fungicides typically applied through immersion treatments, hot water treatment is a widely used practice in quarantine protocols for mangoes to prevent the introduction of pests and diseases, including the pathogen causing anthracnose. Optimal temperatures for infection range from 20°C to 30°C (68°F to 86°F), although they vary depending on the specific strain of the pathogen (Aruaz, 2000). However, pathogen development is inhibited or prevented at temperatures outside of this range. Thus, the development of the causal agents of mango anthracnose is sensitive to high temperatures (>30°C/86°F). However, while high temperatures can be lethal to the pathogen, they may also cause damage to the surface of the mango fruit, causing sunken lenticels, superficial scalding, starch layers in the pulp, sunken shoulders, and the formation of internal cavities.

The commonly used quarantine hot water treatment, which involves maintaining a constant temperature of 46.1°C (115°F), provides only partial control of mango anthracnose, particularly when infection levels are low (McGuire, 1991). However, this treatment is often insufficient to fully control the disease under conditions of high infection pressure. Consequently, several alternative or complementary postharvest treatments have been explored to enhance control of the disease. Several of them include the use of various coatings. Thus, promising results have been reported with the application of propionic acid combined with bee-carnauba wax (Thinn and Kunasakdakul, 2013), hydroxypropyl methylcellulose and beeswax (Sousa et al., 2021) as well as with

chitosan-based coatings (de Oliveira et al., 2017; Limon et al., 2021; Li et al., 2024) or copper nanoparticles (Nguyen et al., 2020). Additionally, plant essential oils such as those derived from *Mentha piperita* (de Oliveira et al., 2017) and other plant extracts have shown antifungal activity against *Colletotrichum spp.* in mango fruits (Imtiaj et al., 2005; Dahn et al., 2021; Khan et al., 2021; Alvindia and Mangoba, 2022; Choudhary et al., 2025, Worku et al., 2025) as well as volatile compounds such as Dimethyl trisulfide (DMTS) (Tang et al., 2019, 2024), nitric oxide (NO) (Hu et al., 2014; Ren et al., 2020), 1-methylcyclopropene (1-MCP) (Xu et al., 2017) or phenylalanine (Patel et al., 2023).

Emerging non-chemical technologies, such as non-thermal atmospheric pressure plasma (NTP) and plasma-activated water (PAW) have also shown significant potential as innovative postharvest treatments for reducing anthracnose severity while minimizing thermal damage to the fruit (Boonmee et al., 2026). Furthermore, the elicitation of plant defense mechanisms by the fruits after the application of exogenous biological, chemical and physical agents is becoming a promising approach for controlling mango anthracnose and other postharvest diseases; examples include the non-protein amino acid  $\beta$ -aminobutyric acid (BABA) (Zhang et al., 2013), salicylic acid (He et al., 2016), putrescine (Song et al., 2023) or melatonin (Lu et al., 2025). Some promising results have been obtained using irradiation to control mango anthracnose although better results are obtained when combined with other treatments (Sultana et al., 2021).

## **RESEARCH AND FUTURE DIRECTIONS**

Ongoing research efforts are critical in advancing our understanding of mango anthracnose and developing more effective, sustainable management strategies. As the global demand for mangoes increases and the impact of climate change intensifies, these innovations are essential for ensuring long-term crop productivity and fruit quality. Current research focuses on several key areas:

- **Genetic resistance:** One of the most promising directions in anthracnose management is the development of mango varieties with inherent resistance to the disease. Ongoing genetic studies aim to further dissect the molecular pathways involved in anthracnose resistance, providing a

deeper understanding of the host-pathogen interaction and enabling breeders to develop more resilient mango varieties. Researchers are exploring both traditional breeding methods and advanced genetic technologies to achieve this goal. Among them, the use of cutting-edge genetic tools, such as CRISPR/Cas9 gene editing, holds significant potential in accelerating the development of anthracnose-resistant mango cultivars. Recent advances in genome sequencing will provide new information on resistance genes that could be used to accelerate breeding programs (Gómez-Ollé, et al., 2023). By precisely targeting and modifying genes involved in the mango's immune response, researchers aim to enhance the plant's natural defenses against pathogens.

- **Enhanced biocontrol methods:** As the negative environmental impacts of chemical fungicides become more evident, researchers are increasingly focused on developing more effective biocontrol strategies for managing anthracnose in mango orchards. Biocontrol agents, such as beneficial fungi, bacteria, and yeasts, which can naturally suppress pathogen growth, offer an environmentally friendly alternative to chemical treatments.
- **Climate adaptation strategies:** With the ongoing effects of climate change, rainfall patterns and temperatures are becoming more erratic, which poses additional challenges for mango production. Research is now focusing on developing mango cultivars better suited to these changing environmental conditions.
- **Improved diagnosis and early detection.** Advancements in diagnostic tools are essential to improve the early detection of anthracnose and enable more timely interventions. While molecular techniques like PCR and DNA sequencing have greatly improved diagnostic accuracy, further research is needed to develop rapid, cost-effective, and easy-to-use diagnostic tools for mango growers. These tools could potentially be integrated into field-based diagnostic kits that would allow farmers to quickly identify and manage anthracnose outbreaks before they cause significant damage. Emerging technologies, such as computer vision, machine learning, and remote sensing, are also being explored for their potential in monitoring and predicting disease outbreaks. By combining data from weather

forecasts, crop monitoring systems, and pathogen detection methods, researchers are working on integrated platforms that can provide real-time disease predictions and guide management practices.

Mango anthracnose remains one of the most significant challenges for mango production, severely affecting both the quality and yield of the fruit. However, the future of managing this disease looks promising with the ongoing development and application of integrated management strategies. By combining cultural practices, chemical treatments and advanced biological control measures, and leveraging advances in research into resistant cultivars and biocontrol solutions, there is considerable hope for reducing the impact of this disease on global mango production.

As research into mango anthracnose evolves, the development of sustainable management solutions will become more feasible. The integration of genetic resistance, advanced biocontrol techniques, and climate-adaptive strategies is expected to be the cornerstone of future disease management approaches. These methods will not only minimize the dependency on chemical fungicides but will also contribute to more environmentally sustainable farming practices.

The collaboration between breeders, plant pathologists, climate scientists, and biotechnologists will be crucial in driving these innovations forward. This collective effort will ensure that mango production remains viable and adaptive in the face of shifting global climatic conditions.

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