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Mango Anthracnose: Economic Impact and Current Options for Integrated Management

The mango (*Mangifera indica* L.) is native to India and Southeast Asia. It is grown throughout the tropics and subtropics worldwide. India is the world's largest producer (29; Fig. 1), but Mexico is the largest exporter (48). Until recently, mango fruit was considered an exotic, specialty item in import markets such as the United States and Europe (37). Currently, many countries are shipping large volumes of fruit to these markets, and they must compete on the basis of price and quality.

Postharvest diseases can reduce fruit quality and cause severe losses, sometimes because they yield completely unmarketable fruit, and in many cases because blemished fruit does not meet the cosmetic standards for first-quality fruit in the major import markets (18). Although blemished fruit can often be sold in the less demanding local markets, this practice results in important economic losses due to the considerable differences in export and local prices (Fig. 2).

Among the postharvest diseases of mango, anthracnose is the most prevalent in humid growing areas. The incidence of this disease can reach almost 100% in fruit produced under wet or very humid conditions. Other common postharvest diseases of mango in humid areas are stem-end rot, caused by *Lasiodiplodia theobromae* (Pat.) Griffon & Maubl. (9) and *Dothiorella dominicana* Petrak. et Cif. (45), and black-mold rot, caused by *Aspergillus niger* v. Tieghem. Mango black spot, caused by *Alternaria alternata* (Fr.:Fr.) Keissl. (25), is prevalent in dry countries.

Mango anthracnose is caused by *Glomerella cingulata* (Stoneman) Spauld. & H. Schrenk (anamorph: *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. in Penz.), *C. gloeosporioides* Penz. var. *minor*

J.H. Simmonds (31), and *C. acutatum* J.H. Simmonds (34). The pathogen also causes blossom blight, leaf blight, and in severe cases, tree dieback (61,62). The postharvest phase is the most economically significant throughout the world (63). This paper deals primarily with postharvest anthracnose. The other phases of the disease are treated as they relate to the postharvest phase. Some of the disease management strategies described here were developed for postharvest anthracnose in Costa Rica, but they are applicable to other tropical mango growing areas with a well-defined dry season.

Symptoms

Leaf anthracnose appears as irregular-shaped black necrotic spots on both sides

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Fig. 1. Distribution of world mango production. Source FAO (29).

of the mango leaf. Lesions often coalesce and form large necrotic areas, frequently along the leaf margins (Fig. 3). Lesions develop primarily on young tissue, and conidia are formed in lesions of all ages. Under favorable conditions, the fungus can invade the twigs and cause dieback (62).

Panicle anthracnose or blossom blight can affect both the inflorescence stalk and the individual flowers (Fig. 4). In the stalk, elongated dark gray to black lesions appear. Blighted flowers are dry, and their color varies from brown to black. Fruit smaller than pea-size can be infected and aborted. Larger fruit that are aborted because of normal self-thinning or due to other physiological causes are usually mummified. Mummies are invaded saprophytically by *C. gloeosporioides*, and the fungus sporulates abundantly on them (Fig. 5).

Postharvest anthracnose appears as rounded brown to black lesions with an indefinite border on the fruit surface. Lesions larger than 2 cm are fairly common. Lesions of different sizes can coalesce and cover extensive areas of the fruit, typically in a tear-stain pattern developing from the basal toward the distal end of the fruit (Fig. 6). Lesions are usually restricted to the peel, but in severe cases the fungus can invade the pulp. In advanced stages of the disease, the fungus produces acervuli, and abundant orange to salmon pink masses of conidia appear on the lesions.

Epidemiology

Disease cycle. Ascospore production in dry leaves on the ground has been reported

(1,40), but the role of the sexual stage in the disease cycle is unclear (31). Since conidia are formed abundantly in the mango canopy (31), this is considered to be the primary source of inoculum. In the field, *C. gloeosporioides* produces conidia on lesions on leaves, twigs, panicles, and mummified fruit (6,31). Conidia can be rain-splashed to other leaves or flowers and cause secondary infections; thus the disease is polycyclic in these organs. Developing fruit can be infected, and some isolates can cause preharvest fruit loss (38). In the case of postharvest anthracnose, developing fruit are infected in the field, but infections remain quiescent until the onset of ripening, which occurs after harvest. Once the climacteric period of the fruit starts, lesions begin to develop. There is no fruit-to-fruit infection; hence postharvest anthracnose is a monocyclic disease (Fig. 7).

A study of genetic diversity in the population of the mango anthracnose pathogen in Florida showed there may be exceptions to this general pattern of the disease cycle. Pectic zymogram analysis of isolates from different mango tissues revealed pectic zymogram groups (PZGs) of *C. gloeosporioides* that occurred only in specific tissues as well as PZGs that were present in several mango tissues (38). These researchers concluded that members of some PZGs may have a greater propensity to colonize and to cause disease in some tissues than in others.

Mango fruit can be infected with conidia from isolates of *Colletotrichum* spp. from

other host plants such as avocado, papaya, banana, coffee, and citrus (34,35,56). The epidemiological significance of these potential inoculum sources on the disease cycle has not been assessed.

Fig. 3. Anthracnose symptoms on mango leaves. Left: mature leaf with old lesions. Right: young leaf with new lesions.

Fig. 2. Prices of mango in international (39) and local (54) markets.

Fig. 4. Anthracnose symptoms on mango panicles. (A) Mild symptoms. (B) Severe symptoms.

Termination of fungal quiescence on climacteric fruits appears to be related to the reduction of antifungal compounds (64) or the production of ethylene by the ripening fruit (33). As mango fruit ripens, there is a reduction in the concentration of phenolic compounds, which are active against *C. gloeosporioides* in vitro (20). Similar systems have been found with mango black spot (*Alternaria alternata*) and avocado anthracnose (*C. gloeosporioides*) in Israel

Fig. 5. Mummified mango fruit attached to the tree, showing sporulation of *Colletotrichum gloeosporioides*.

(67). The change in nutritional status of the host upon ripening has also been suggested as a factor in quiescence termination, but experimental evidence is contradictory (64).

Regardless of the mechanisms that are involved in the onset and termination of quiescence, quiescent infection appears to be a case of coevolution, as it is advantageous to both pathogen and host in a natural ecosystem. In relation to the pathogen, quiescent infection of climacteric fruits by *C. gloeosporioides* represents an example of pathogen adaptation to host physiology. Flaishman and Kolattukudy (33) indicate that the involvement of ethylene in the termination of quiescence strongly suggests that *Colletotrichum* spp. must have coevolved to develop a mechanism to use the host's ripening hormone as a signal to reactivate the infection process. This mechanism prevents contact of the pathogen with host tissues that have high levels of antifungal compounds (Fig. 8). On the other hand, resistance to the pathogen in mango fruit tissue is advantageous to the host during seed development, but not

afterward because invasion of ripe fruit by saprophytes and weak pathogens can help eliminate the ripe pulp, thus liberating the seed, which will, in turn, germinate in a rich organic substrate. Therefore, there is evolutionary value in allocating chemical defenses to the immature fruit but not to the ripe fruit, which seems to be the case in mango (20,67). Hence, a mechanism indicative of coevolution of host and pathogen seems to be taking place in this system.

Temperature and moisture requirements for infection. Most research on the effects of weather on the *C. gloeosporioides*-mango interaction has been done in Australia (32) and the Philippines (24,26). *C. gloeosporioides* requires free water or relative humidity above 95% for conidial germination and appressorium formation (24,32). However, conidia can survive for 1 to 2 weeks at humidities as low as 62% and then germinate if placed in 100% relative humidity (26). In general, infection is favored at temperatures ranging from 20 to 30°C. Within this range, there is considerable variation in the optimal temperature requirements for germination and appressorium formation among isolates of *C. gloeosporioides* from different locations. Dodd et al. (24) suggested that differences among locations may be due to ecotypic variation.

Temperature and moisture requirements for infection have been used to build forecasting systems for mango anthracnose. The details and application of these systems will be discussed in the following section.

Management

Control of postharvest anthracnose can be achieved by field management, after-harvest treatments, or a combination of both. Management must be efficient and cost-effective, as well as safe to consumers, agricultural workers, and the environment.

Field control. Management of mango anthracnose in the field involves cultural and chemical practices, as well as cultivar selection.

Cultural control. Since the development of mango anthracnose is dependent on wetness or high relative humidity, ideally orchards should be established in areas with a well-defined dry season to allow for fruit development in conditions unfavorable for disease development. In the tropics, mango flowering usually occurs during dry seasons. However, within a given area, mango trees can flower at any moment during the dry season, depending on factors such as maturity of the shoot (21), temperature (72), and nutritional status of the tree (68). If flowering occurs early, before the dry season is well established, flowers and young fruit can be infected. From an anthracnose management standpoint, the worst-case scenario occurs when trees flower late in the dry season and the last part of fruit

Fig. 6. Anthracnose symptoms on mango fruit. (A) Typical lesions. (B) Advanced lesions. (C) Growth of anthracnose lesions into mango pulp. (D) Sporulation of *Colletotrichum gloeosporioides* on anthracnose lesion.

development takes place when the rainy season has already started. In this case, severe fruit infection is likely. Anthracnose incidence over 90% is common in fruit that developed during the rainy season (9).

In seasonal tropical areas, a plausible disease avoidance strategy is to manage flowering so that fruit develop during the least rainy time of the year (2). The incidence and severity of mango anthracnose

can be close to zero in fruit developed completely in the dry season, without the application of any other control measure (42). This strategy is not necessarily applicable to subtropical mango-growing areas,

Fig. 7. Anthracnose cycle on mango. Solid lines represent disease cycle. Dotted lines represent mango phenology.

where the stimulus for flowering is low temperature (58,72) rather than water deficit, and flowering is not necessarily followed by dry periods. An additional advantage of fruit production under dry conditions is that populations of mango fruit flies (*Anastrepha* spp.) are lower during the dry season (11). Also, in some tropical countries, fruit developed in the dry season will be harvested when mango prices in international markets are high (Fig. 2). Considerable effort has been made to understand and manage mango flowering. Mango flowering can be advanced by several weeks with potassium nitrate sprays on mature foliage (57). The growth retardant paclobutrazole can also be used to advance flowering, used alone (58) or followed by potassium nitrate sprays (53).

Field sanitation involving the collection and incineration of fallen fruit and tree trash has been recommended for anthracnose control (47). Sanitation of the tree itself is difficult to practice. Elimination of dry panicles and mummified fruit is time-consuming, and the possible benefits have not yet been fully evaluated. In one ex-

periment (L. F. Arauz, *unpublished data*), no difference was found in anthracnose severity in fruit from trees where dry panicles were eliminated, compared with trees without panicle elimination; leaf inoculum was probably sufficient to result in high levels of disease.

Wrapping of developing fruit in paper bags has been investigated in Australia (41) and the Philippines (15). Bagging resulted in reduced anthracnose severity, but it also reduced the red color of the fruit, which may have a negative impact on consumer appeal. Depending on market conditions and disease pressure, this could be outweighed by the benefit of reduced disease (41) or reduced use of fungicides. The cost effectiveness of this practice will depend on the market price of the fruit.

Resistant varieties. Although all commercial mango cultivars are susceptible to anthracnose, some are less susceptible than others. The cultivars Tommy Atkins and Keitt are less susceptible than others such as Irwin, Kent, or Edward (16,59). The popular cultivar Haden is highly susceptible to anthracnose (16). Because of market

cosmetic standards, the level of anthracnose that develops under high disease pressure in less susceptible varieties such as Tommy Atkins is still unacceptable in a commercial situation, even in the less demanding local markets.

Chemical control. In extreme situations, where fruit develops completely under disease-favorable conditions, up to 25 sprays of protectant and systemic fungicides have been reported (25). Few fungicides are approved for use on mango in importing countries. The European Union uses the guidelines of the FAO/WHO Codex Alimentarius, and the U.S. Environmental Protection Agency provides different guidelines (Table 1). Therefore, the choice of fungicides depends on the intended destination of the fruit.

Dithiocarbamate fungicides are highly effective for anthracnose control. Because ethylene thiourea (ETU) is a by-product of their degradation, ethylene-bisdithiocarbamates such as maneb or mancozeb are no longer labeled for mango shipped to the United States, but they can be used on fruit shipped to some European countries. The methyl dithiocarbamate fungicides such as ferbam do not produce ETU and are an alternative for anthracnose control on fruit grown in or shipped to the United States. Copper fungicides are recommended, but their efficacy is lower than that of dithiocarbamates under high disease pressure (22,44). Also, phytotoxicity of copper on mango flowers has been reported (25).

Fungicides with after-infection activity for mango anthracnose include benzimidazoles and the imidazole prochloraz. Benomyl has been used in calendar-based schedules, usually in a mix with protectant fungicides to delay the buildup of resistance in the pathogen population (44). It has also been applied as an eradicant spray following infection periods (27). Prochloraz has been used as a protectant or as an eradicant spray (27).

Resistance of *C. gloeosporioides* to benzimidazole fungicides has been reported in many cases (10,12,73). Resistance of *C. gloeosporioides* to prochloraz has not been reported yet, but it is a distinct possibility, based on two facts. First, resistance to prochloraz in other fungi has been reported (19), and second, there is considerable variation in sensitivity to prochloraz among isolates of *C. gloeosporioides* from mango (49). Currently, prochloraz is the only fungicide that can be used for post-harvest treatments in mango. For this reason, Costa Rican growers are advised not to use this fungicide in the field to avoid resistance development.

Forecasting systems. Two predictive models based on temperature and moisture requirements for infection of mango by *C. gloeosporioides* have been developed. These models have been the basis of two forecasting systems for mango anthracnose, which have been used in the field to time fungicide applications.

Fig. 8. Pathogen and host events in quiescent infection of fruit by *Colletotrichum gloeosporioides*.

Table 1. Fungicides labeled for anthracnose control on mango^a

Fungicide	Maximum residue limits	
	Codex (FAO/WHO)	EPA (U.S.A.)
Benomyl	2.0 ^b	3.0
Prochloraz ^c	2.0	Not labeled
Captan	Not labeled	50.0
Ferbam	Not labeled	7.0
Thiabendazole	2.0 ^d	10.0
Copper fungicides	No data	Exempt

^a Sources: FAO (28); U.S.-Environmental Protection Agency (75).

^b As carbendazim.

^c Allowed in postharvest use.

^d As carbendazim.

In Australia, Fitzell et al. (32) studied the requirements of temperature and wetness duration for production of dark appressoria from conidia applied to detached young mango leaves under laboratory conditions. They obtained the following equation:

$$Y = \ln P/q = -16.114 + 1.120T - 0.0225T^2 + 1.0862 \ln t \quad (1)$$

where P = percentage of conidia forming dark appressoria, T = temperature (C), t = wet period (h), and $q = 100 - P$. This equation was built into a microprocessor-based forecasting system. This system was used to time applications of prochloraz during the mango flowering period in Australia. Infection levels were estimated from temperature and wetness duration following at least 0.2 mm of rain. Prochloraz (0.6 mg/ml) was applied if the model predicted that 10, 20, or 40% of conidia would form dark appressoria, which were the thresholds defined by the authors for low, medium, or high levels of anthracnose infection, respectively. Wetness periods separated by less than 6 h were combined. The fungicide was not reapplied if an infection period took place within 7 days after an application. The three thresholds used resulted in similar levels of anthracnose severity. Depending on the threshold, use of the model resulted in a reduction of four to eight fungicide sprays per season to control flower anthracnose in Australia compared with weekly spraying, which was the commercial recommendation (60).

A similar system was developed in the Philippines based on the studies by Dodd et al. (24). It differs from the Australian system, in that it was developed using combined data from fruit and leaf inoculations and it includes relative humidity in addition to wetness and temperature. Two equations were obtained from laboratory studies:

$$Y = \ln P/q = -1,172.6 + 2.08T - 0.004T^2 + 3.91 \ln t + 22.8H - 0.115H^2 \quad (2)$$

$$Y = \ln P/q = -40.8 + 2.08T - 0.039T^2 + 3.91 \ln t + 0.217(100 - H) - 0.115(100 - H)^2 \quad (3)$$

In both equations, Y , P , q , T , and t have the same meaning as in equation 1. The term H in equations 2 and 3 is the percent relative humidity. It should be noted that if data are obtained from wetness sensors, then the humidity term $(100 - H)$ in equation 3 becomes zero, and the model form approaches that of Fitzell et al. (32) (equation 1).

The model of Dodd et al. (24) was tested under field conditions for the control of postharvest anthracnose in the Philippines. Benomyl, prochloraz (both at a rate of 0.47 mg/ml), or triforine (0.375 mg/ml) was applied following a predicted infection period with a threshold of 40% of conidia forming dark appressoria. One timed application of benomyl or prochloraz was as

effective as six calendar-based sprays of either fungicide (27).

A comparison of the two models is shown in Figure 9. There are important differences between the models in level of infection predicted from a given combination of temperature and wetness duration. For example, at 25°C, 10% of conidia would form dark appressoria in approximately 1 h according to the Australian model and in approximately 16 h according to the Philippine model. Such a discrepancy indicates that weather-based forecasting systems for mango anthracnose should not be extrapolated from one region

to another, and the infection criteria should be elucidated locally. The difference between the two models may also reflect differences in the experimental methods, especially in the plant tissues used to develop them. Tissue specificity can occur in different isolates of *C. gloeosporioides* (38), and this factor should be considered in the development and application of mango anthracnose forecasting systems.

The forecasting systems can be simplified in certain tropical areas. For example, under the seasonal tropical conditions of the Costa Rican mango growing areas, the temperature of a given location does not

Fig. 9. Comparison of the wetness duration requirements for appressorium formation at 25°C, as predicted by the Australian model (32) and the Philippine model (24).

Fig. 10. Mean temperature during periods with relative humidity above 95% at the Fabio Baudrit Experiment Station, University of Costa Rica, Alajuela, Costa Rica, 1992.

vary considerably from one wetness or high humidity period to another, and it is usually close to the optimum for infection (Fig. 10). Also, most wetness periods are long, because rain usually falls in the afternoon. Thus, it can be assumed that if a wetness period occurs, it is likely that infection will take place. Therefore, it is should be possible to time fungicide sprays based on the mere occurrence of a wetness or high humidity period. Working under that assumption, a considerable reduction in the number of fungicide sprays was achieved, compared with a calendar-based program for postharvest anthracnose control (42).

The use of these forecasting systems to program fungicide applications based on predicted infection levels following individual wetness periods (27,60) is appropriate for leaf or flower anthracnose. However, the quiescent infections that result in postharvest anthracnose on mango fruit accumulate over several infection periods of varying durations and temperatures

throughout fruit development. Therefore, disease should be forecast on the basis of accumulated infection rather than on individual wetness periods. Otherwise, several below-threshold infection periods could result in enough infection to account for high disease severity. Conversely, one application of a fungicide with after-infection activity could be sufficient to reduce significantly an infection level resulting from several infection periods.

An anthracnose forecast based on accumulated infection would also be useful for optimizing postharvest disease control. Several postharvest treatments are available, with varying degrees of cost and efficacy (see next section). Thus, a forecast of cumulative infection could be used to decide which postharvest treatment would be most cost-effective for a given level of infection. One such approach to anthracnose forecasting would be the monitoring of latent infections to determine the need for postharvest treatments, as proposed by Prusky et al. (66) for *A. alternata* in Israel.

Several monitoring methods are possible: direct plating of sections of mango epidermis on culture media (66), fruit treatment with herbicide to force the rapid expression of quiescent infections (13), or correlation of accumulated weather conditions or cumulative predicted infection periods with final disease severity (70).

Forecasting systems are useful for diseases that are important but sporadic (36). An anthracnose forecast in the seasonal tropics would be most useful in dry seasons, when sporadic rain is possible, or during transitional periods between dry and wet seasons. Once the rainy season is established, calendar-based fungicide applications are the best strategy for chemical control, since conditions are usually favorable for disease development. The most advisable strategy would depend on the time of flowering of a given orchard (Fig. 11).

The choice of fungicides to be used for after-infection sprays in the field should be determined by the target market and by the

Fig. 11. Strategies for chemical control of mango anthracnose, according to weather conditions during fruit development. Rainy and dry months correspond to tropical areas in the Northern Hemisphere. The upper mango development sequence represents early flowering. In this situation, panicle anthracnose is likely. The middle sequence represents intermediate flowering, with the entire development of the fruit taking place in the dry season. Low levels of anthracnose would be expected in panicles and fruit. Lower sequence represents late flowering. In this case, fruit maturation occurs in the rainy season, and a high level of fruit anthracnose would be anticipated if no control actions are taken.

fungicides that will be used in postharvest treatments. Field and after-harvest application of the same fungicide, or of fungicides with a risk of cross resistance, should be avoided. Benomyl and prochloraz give good after-infection control of mango anthracnose (27), but prochloraz is the only fungicide registered for postharvest use. Therefore, its use in the field should be restricted to situations where no other options are available.

Prospects for biological control. A number of microorganisms with in vitro or in vivo activity against *C. gloeosporioides* have been isolated (43), but none have been used commercially in the field. Most of the literature reports attempts at post-harvest rather than field control, possibly because of the well-known limitations of biological control under field situations compared with controlled-environment situations (77).

Postharvest control. Traditionally, post-harvest control of mango anthracnose has aimed at reducing the level of quiescent infections on the fruit. Recent research (67) suggests the possibility of prolonging the period of fruit resistance and delaying the onset of anthracnose development until the fruit ripens.

The elimination of quiescent infection is achieved commercially by thermal and chemical treatments, or a combination of both (52). Dips of fruit in hot water alone are moderately efficient (Table 2). Temperatures between 50 and 55°C for 3 to 15 min have been recommended, with the higher temperatures corresponding to the lower exposure times. Fruit from Latin America entering the U.S. market must undergo a quarantine hot water treatment to eliminate larvae of fruit flies (*Ceratitis capitata* and *Anastrepha* spp.). Fruit is immersed in water at 46°C for 90 to 120 min, depending on variety and fruit size. The efficacy of the fruit fly quarantine treatment varies from 60 to 85% for elimination of anthracnose infections (50). Hot water treatments leave no chemical residue on the fruit and could be a good anthracnose control option for organic mango or for mango targeted for markets in the United States, where no fungicides are currently labeled for postharvest use. Temperature and time control are critical, because fruit can be easily damaged by over-exposure to heat.

Several fungicides have been applied after harvest to control mango anthracnose. Benomyl was used in the past as a postharvest dip at rates varying from 500 to 1,000 ppm, but its use is no longer permitted. Thiabendazole (1,000 to 2,000 ppm) is also effective, and there is interest in its registration for postharvest use in mango, as it is used in many other fruits. Prochloraz can be used at rates up to 1,000 ppm in fruit shipped to the European Union. Efficacy of this fungicide varies from 65% at very high disease pressure to 94% under

moderate disease pressure (3) (Table 2). A similar fungicide, imazalil, has shown variable efficacy. It has been effective in trials conducted in the United States (51), but not in Costa Rica (23). It is not labeled for use in mango. One advantage of benzimidazole fungicides such as benomyl or thiabendazole is that they are also effective for the control of stem-end rot caused by *L. theobromae*, which is the second most important postharvest disease of mango in tropical areas. Imidazoles like prochloraz or imazalil are not effective against *L. theobromae* on mango (23,27).

The combination of hot water and fungicides is the most effective commercial postharvest treatment for the control of mango anthracnose. Both rate of fungicide and duration of exposure to hot water are lower, and efficacy is higher than with either treatment considered separately. Even at very high levels of infection, efficacies over 95% can be achieved (3,8) (Table 2). Hot water and fungicides can be applied sequentially or together.

Irradiation of fruit to control anthracnose has been attempted. Gamma irradiation was not successful (74). Recently, a short-wave infrared radiation treatment developed in South Africa resulted in anthracnose levels similar to the commercial hot water treatment, and was much faster and less expensive (71).

Disease control through maintenance of host resistance is an interesting approach. Climacteric fruits such as mangos, avocados, and bananas typically exhibit a rise in respiration rate during ripening, called the

climacteric rise. The climacteric rise occurs simultaneously with the production of ethylene and with changes in external and internal color, flavor, aroma, and firmness (78), and with a reduction in fruit resistance to fungal attack (67). Postharvest practices such as cold storage and controlled atmosphere maintain resistance to decay by delaying the ripening process, but there are two limitations to the potential benefit of this approach in mango. First, mangos, as well as many other tropical and subtropical fruits, are sensitive to chilling and are injured at temperatures lower than 10 to 13°C, depending on variety and duration of exposure (78). Second, once the fruit are allowed to ripen under ambient conditions, disease develops normally. Nevertheless, some progress has been made toward anthracnose control through maintaining fruit resistance beyond the onset of ripening. In the last decade, a better understanding of the physiological basis of quiescent infections on tropical and subtropical climacteric fruit has been achieved, mainly through the pioneering work of D. Prusky and his collaborators in Israel (67). Their research has shown that antifungal compounds are present in immature avocado and mango fruit, and that the concentration of these compounds decreases as the fruit ripens. The decline in antifungal compounds, which is brought about by oxidative processes, can be delayed so that it occurs closer to full ripeness. In avocado, the decline of the concentration of antifungal compounds was delayed by exposure of fruit to an atmos-

Table 2. Efficacy of commercial treatments for anthracnose control

Treatment	Severity in untreated fruit ^a	Percent efficacy ^b	Reference
Preventive sprays in the field (benomyl + copper oxychloride)	5.1	58	22
Preventive sprays in the field (benomyl + mancozeb)	6.4	89	42
Preventive sprays in the field (benomyl + mancozeb)	11.5	92.5	42
Preventive sprays in the field (ferbam + copper hydroxide)	12.9	92.7	17
Eradicant sprays in the field (750 ppm prochloraz, following six low-level infection periods) ^c	1.15	69.6	7
Postharvest dip in water, 53°C, 3 min	0.514	82.1	3
Postharvest dip in water, 53°C, 3 min	12.5	48.3	3
Postharvest dip in 750 ppm prochloraz, ambient temperature	12.5	94	3
Postharvest dip in 750 ppm prochloraz, ambient temperature	27.7	43.2	3
Postharvest dip in 250 ppm prochloraz, 53°C, 3 min	0.514	98.8	3
Postharvest dip in 250 ppm prochloraz, 53°C, 3 min	12.5	98.5	3
Postharvest dip in 500 ppm prochloraz, 53°C, 3 min	27.7	96.6	3

^a Average percent fruit area diseased.

^b Percent disease reduction relative to control.

^c Estimated 10% of conidia forming dark appressoria, according to the model developed by Fitzell et al. (32).

phere containing 30% CO₂ for 24 h, or by treatment of fruit with the antioxidant compound butylated hydroxy anisole (BHA) (67). The delay resulted in less disease in ripe fruit. In Costa Rica, post-harvest treatments with BHA resulted in reduced severity of mango anthracnose, although the level of reduction achieved was less than that obtained with a prochloraz dip (69).

Postharvest biological control of mango anthracnose has been attempted. In an investigation with a strain of *Bacillus* sp. that exhibited in vitro activity against *C. gloeosporioides*, it was found that disease control in vivo was obtained when fruit were inoculated with the bacterium 24 h prior to inoculation with the fungus, but not when fruit were inoculated with the pathogen first (30), which indicated that the quiescent phase of the fungus was not affected by the antagonist.

It is not clear whether the quiescent structure in mango is a dormant appressorium or a subcuticular hypha, and this information could be critical to the successful postharvest application of biological control agents (43). If quiescence is dependent on an appressorium, an effective biocontrol agent could possibly act by antibiosis, competition, or parasitism on the fruit surface, or by inducing resistance. If the quiescent phase is a subcuticular hypha, an effective biocontrol agent should produce an antibiotic that penetrates the cuticle, or the antagonist itself should be capable of cuticular penetration. The latter mechanism seems more promising because there is concern about antibiotic production on edible commodities (77). Prusky et al. (65) found a nonpathogenic strain of *Colletotrichum magna* that colonizes the fruit endophytically and prevents infection by *C. gloeosporioides*. The only other example of successful postharvest application of a biocontrol agent for mango anthracnose is the application of isolate 558 of *Pseu-*

domonas fluorescens by Koomen and Jeffries (46). The bacterium significantly reduced anthracnose development compared with the control fruit, but the mode of action involved was not clear.

Economics of anthracnose control. Several different economic analyses have been proposed to aid in the disease control decision-making process (55). Net profit analysis allows for a comparison of several treatments but does not allow for optimization. Marginal analysis (14) can be used to compare various levels of a treatment under conditions conducive to disease development to obtain the optimum level of treatment. These two methods do not take into consideration the variation in disease level and its effect on crop loss.

The economic threshold model, widely used in the management of insect pests, considers disease-loss relationships. It could be adapted for a disease such as fruit anthracnose if an estimate of cumulative infection, such as accumulation of favorable weather periods, could be used in a manner analogous to the use of degree-day accumulation to predict insect pest outbreaks (76). For example, the model developed in the Philippines for anthracnose prediction (24) could be used in a cumulative way, instead of considering wetness periods independently. The independent variable *P* in equation 3 (i.e., percent conidia forming appressoria during individual wetness periods) could be reinterpreted as an "anthracnose infection degree." An eradicant fungicide would be applied once disease reaches a threshold number of "infection degrees." After each fungicide application, the number of accumulated "infection degrees" should be reset according to the efficacy of the fungicide. Such an approach has not been used in the mango anthracnose pathosystem. The economic threshold model does not allow for comparison among several control methods and does not consider the variation in efficacy of different disease control

tactics under varying disease potential (i.e., weather conditions or inoculum level).

A different approach, which combines elements of both the net profit analysis and the economic threshold model, has been taken for mango anthracnose (5). This method allows for the comparison of different control tactics, taking into consideration the varying efficacy of each tactic in relation to infection potential. The method requires the following information:

(i) An estimation of the efficacy of control tactics in relation to infection levels. This can be obtained from results of disease control trials, where disease severity in the untreated controls (*Su*) provides an estimate of the infection potential under which the test was conducted. Thus, the efficacy (*Ef*) of different treatments for several infection potentials can be estimated as the percent reduction in severity on treated fruit (*St*) relative to severity of the control (Table 2).

$$Ef = (Su - St) \times 100 / (Su) \quad (4)$$

Conversely, the expected infection level (% severity, *Se*) can be calculated for different treatments under levels of infection potential similar to those of the original experiments (equation 5).

$$Se = Su - (Su \times Ef / 100) \quad (5)$$

(ii) The expected percent loss (*EL*) for different expected infection levels, calculated from disease-loss relationships. In the case of mango anthracnose, the relationship between disease severity and exportable fruit was estimated by the following equation (5):

$$E = 67.4 - 20.3 \ln(S) \quad (6)$$

where *E* = percent exportable fruit (fruit with less than 1% of surface area diseased), and *S* = severity of anthracnose (% diseased surface area). In this case, *EL* = (100 - *E*).

(iii) The expected monetary loss (*EML*), in dollars per ton, calculated as *EL* × price of fruit/100. With this method, the expected monetary losses to disease are determined for different control tactics (including no control) under varying conditions that result in different expected infection levels (Table 3). The Total Expected Loss (*TEL*) is then calculated as the sum of the *EML* and the cost of the control tactic. The *TEL* for the different control tactics is compared to determine which is most cost-effective for a given expected disease level. To be used as an optimization method, this technique could be modified to allow for the variation in revenues or losses, and the variation of control tactic efficacies, over a continuum of infection potentials (4) (Fig. 12). Infection potential could be estimated from weather-infection relationships by modifying existing models or developing local criteria.

Conclusions

Integrated management of postharvest mango anthracnose under tropical conditions requires knowledge of the biology of the pathosystem and the technologies

Table 3. Expected monetary loss (\$/ton) due to reduction of percent exportable mango fruit because of anthracnose, under different levels of infection at harvest, and treated after harvest with hot water, prochloraz, or a combination of both

Treatment	Treatment cost (\$/ton)	Infection level		
		Low ^a	Moderate	High
No treatment	0.00	378.00 ^b	1,678.00	2,000.00
Hot water, 53°C, 3 min	5.00	0.00 ^c	1,410.00	nd
		(82.1) ^d	(48.3)	
Prochloraz, 750 ppm, ambient temperature	7.50	nd	536.00	1,770.00
			(94.0)	(43.2)
Prochloraz + hot water	12.50	0.00	0.00	628.00
		(98.8)	(98.5)	(96.6)

^a Low: 0.51% diseased area on untreated fruit. Moderate: 12.5% diseased area on untreated fruit. High: 27.7% diseased area on untreated fruit.

^b Estimated percent loss is calculated as 100 - *E*, *E* as defined in equation 6. Expected monetary loss is based on price of \$2,000/ton, i.e., every 1% loss is equivalent to \$20/ton.

^c Numbers in italics represent the most profitable control tactic for each infection level, after adding together the expected monetary loss and the treatment cost.

^d Numbers in parentheses are percent efficacies of control tactics for each infection level, according to Table 2.

available for control, their economical feasibility, and ecological acceptability. Successful integrated management of mango anthracnose must take into account the following key points from the previous discussion: (i) the system is rain-moisture driven, and infection criteria have been elucidated so that they can be used to time fungicide applications; (ii) severity of postharvest anthracnose is the result of cumulative quiescent infections that develop after harvest, as fruit ripens, and which are subject to eradication by post-harvest treatments; (iii) flowering can be managed so that susceptible tissue is produced during the drier months of the year, reducing the probability of fruit infection; (iv) several preharvest and postharvest treatments are commercially available; and (v) the efficacy of the various treatments is dependent on infection level.

Most areas in the Americas that produce mango for export are located in regions with pronounced dry seasons. In these areas, management of mango flowering so that fruit are produced under dry conditions

is the cornerstone of integrated anthracnose control. Other treatments are complementary and might not be necessary at all. Fruit from the American tropical countries destined for the U.S. market must be heat-treated to meet quarantine requirements for the control of fruit flies, especially *Ceratitis capitata* (the Mediterranean fruit fly) and *Anastrepha* spp. (the Mexican fruit fly and related species). Hot water treatment for fruit flies provides acceptable anthracnose control under low infection potential, and it may not be necessary to apply any other control measure to fruit produced under dry conditions. A few eradicator field treatments with benomyl during fruit development, as indicated by a weather-based forecast, could be reserved for sporadic episodes of rain or high relative humidity during the dry season. A hot water treatment for anthracnose control may be necessary in fruit destined for the European market. The decision whether to apply a postharvest fungicide (prochloraz) would depend on weather conditions, treatments applied during fruit development, and the market requirements (i.e., organic or conventional).

Fruit development during rainy seasons should be avoided since numerous preventive fungicide applications in the field are necessary to obtain acceptable fruit, even for the low-standard local markets.

Fig. 12. Hypothetical expected monetary losses due to disease for different management options: x (dotted line), y (short-dashed line), and z (long-dashed line), or with no control (solid line). Upper graph (A) illustrates expected loss in income over a range of expected infection levels, without disease control and for each of the control options, without considering the cost of each option. Lower graph (B) illustrates the same disease-loss relationships but adds to the loss the cost of each control option, i.e., points c_x , c_y , and c_z on the y axis, which correspond to cost of control options x, y, and z, respectively. The lowest line on the graph at any given expected infection level indicates the most profitable control tactic for that infection level. For example, for infection levels between 1 and 2, option x would be the most profitable (4).

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