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Crown Rot of Bananas

Preharvest Factors Involved in Postharvest Disease Development and Integrated Control Methods

Bananas are grown in more than 120 countries and rank second in world fruit production, after oranges and before grapes. The banana industry, which is based on a small number of cultivars belonging to the Cavendish subgroup, is a vital source of income, employment, and export revenue for most exporting countries, which are mainly developing countries in Latin America, the West Indies, Southeast Asia, and Africa. However, major losses often occur during shipping of bananas to their final market, mainly because of ripening during shipping (bananas should reach ripening rooms unripe), appearance defects, and storage decay such as anthracnose and crown rot that occur during shipping. Such postharvest diseases negatively impact the market value of bananas, especially when they are assessed at the port of arrival or in ripening facilities, thus contributing to banana quality depreciation and constraining export trade. Anthony et al. (9) reported that postharvest diseases were responsible for 20% of harvest losses in Sri Lanka in 1997.

Crown rot affects export bananas in all banana-producing countries and is considered to be one of the main export banana postharvest diseases (62,85). This became a major problem in the banana industry during varietal reconversion initiatives in the 1960s. Up until 1960, only Gros-Michel subgroup cultivars were cropped for export, and for economic and practical reasons bananas were shipped in complete bunches consisting of double layers of fruits called hands, which are arranged helicoidally around a central axis called the stalk. These cultivars were, however, susceptible to Panama disease (*Fusarium oxysporum* f. sp. *cubense*) and thus were replaced by Cavendish subgroup cultivars because of their resistance to Panama disease. However, Cavendish bananas are more fragile during shipping (34), and this triggered a revolution in the banana industry as bunch shipping was discontinued. Bananas were instead cut into clusters consisting of several banana fruits joined by the crown tissues (Fig. 1A) and boxed for shipping. The crown became a prime site for infection by different pathogens (42,53,66). The incidence of crown rot periodically increases during the rainy season, and losses of over 10% have been recorded in the United Kingdom in bananas coming from the Windward Islands that were harvested during this period (62). Losses of up to 86% have also been reported in non-chemically-treated bananas from the Philippines (6).

The first studies on crown rot focused on the etiology of the disease, especially on the identification of the most pathogenic fungal species involved, and on postharvest control methods, mainly chemical. Nevertheless, these studies provided neither a good understanding of the conditions most conducive for disease expression nor adequate control of the disease at all spatio-temporal scales. There is now some evidence that fruit physiology at harvest influences crown rot development and that all interactions among the microorganisms implicated should be considered. Taking these into account, a new concept of "banana quality potential at harvest" and a model of elaboration of this quality potential were proposed (Fig. 2). In this model, the fruit quality potential at harvest is presented as a key factor in crown rot development (18). The quality potential develops during banana growth in the field and depends on two components: (i) a fruit physiological component, which determines the fruit susceptibility to the disease; and (ii) a parasitic component, which reflects a level of crown contamination by the fungal complex, as well as the pathogenicity of this complex. The influence of environmental and agrotechnical preharvest factors on these two components of the fruit quality potential is a new approach in postharvest disease research, and we will discuss their importance in this review.

Crown Rot Symptoms

Crown rot affects tissues of the so-called crown, which unites the peduncles (Fig. 1). The rot is not visible when the bananas are boxed, and symptoms generally appear only after maritime shipping. The rot begins with mycelial development on the surface of the crown (Fig. 1B), followed by an internal development (Fig. 1F)

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doi:10.1094/PDIS-94-6-0648

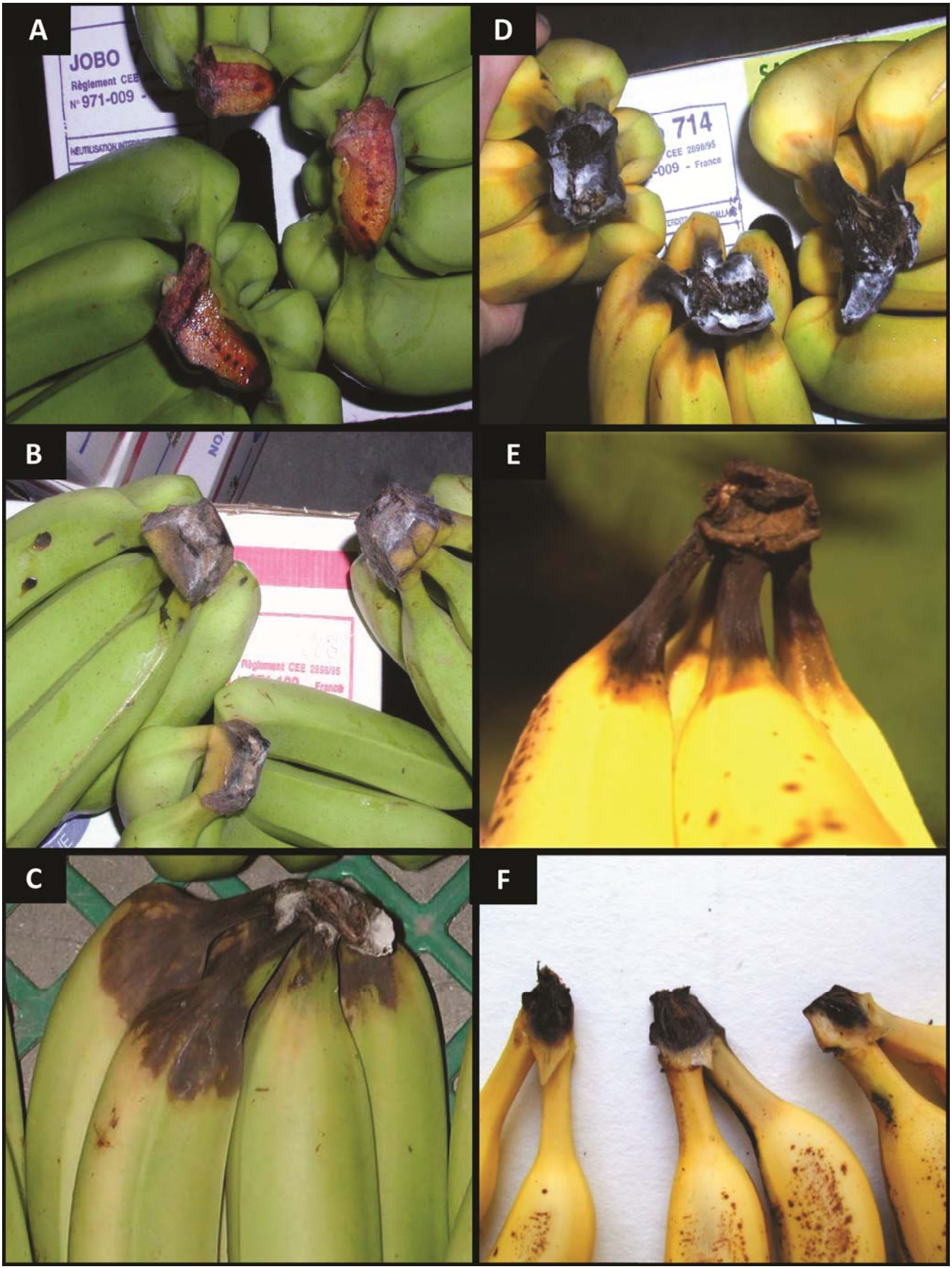

Fig. 1. Crown rot symptoms. **A,** Healthy crowns after maritime shipping before being placed in ripening rooms. **B,** Crowns diseased with a superficial mycelium after maritime shipping. **C,** Rot noted on bananas after maritime shipping. **D,** Rot on the peduncles inducing banana ripening upon their arrival after maritime shipping. **E,** External crown rot symptoms after fruit ripening. **F,** Internal crown rot symptoms after fruit ripening.

that might later affect the peduncle (Fig. 1D) and the fruit (Fig. 1C). The bananas may detach from the peduncle in cases of severe infection. Crown rot results from the development in the crown of several common fungi, which constitute a fungal complex, and leads to softening and blackening of tissues at the site of the wound left when the cluster was cut from the bunch. The role of bacteria in the complex (66) has not been confirmed by detailed research. The symptoms develop rapidly during ripening when the physiology of the fruit undergoes modifications that facilitate fungal development (47).

Crown rot affects fruit quality because of the development of necrosis on the fruit, and it can also trigger early ripening of bananas during shipping (79) (Fig. 1D). Ripening may be caused by ethylene released by stressed and necrotic tissues (32,67,91), but also by ethylene produced by mycelia of fungi such as *Colletotrichum musae* (24,80). Onset of the disease cannot be predicted, and it spreads in an irregular pattern on all clusters in a shipping box. The same box may contain both healthy and infected clusters.

Fruit Quality Potential as a Key Factor in Crown Rot Infection Patterns

Geographical and seasonal variations have been noted in the incidence of crown rot disease of bananas (62,66,89). Lukezic et al. (66) showed that the incidence of this disease varied throughout the year in Honduras. It is generally higher during the summer (March to September) and declines during the coldest period (October to February). They also demonstrated that this pattern did not seem to be correlated with variations in the fungal complex isolated from banana crowns. Moreover, in Jamaica, a high disease incidence was found to be correlated with periods during the year when temperatures were highest (89), whereas in the Windward Islands, incidence was reported to be highest during the rainy period (62). These spatio-temporal fluctuations reflect the variations in the banana fruit quality potential that depends both on a parasitic and a physiological component (Fig. 2).

Parasitic component of the fruit quality potential. In crown rot, the parasitic component reflects a level of crown contamination by the fungal complex, as well as the pathogenicity of this complex.

Etiology of crown rot and pathogenicity of the fungal complex. Crown rot is the result of the activity of a fungal complex. The microorganisms most commonly isolated in crown rot are: *Musicillium theobromae, Colletotrichum musae, Ceratocystis paradoxa, Lasiodiplodia theobromae, Nigrospora sphaerica, Cladosporium* sp., *Acremonium* sp., *Penicillium* sp., and *Aspergillus* sp., as well as many *Fusarium* spp., including *F. semitectum, F. verticillioides, F. sporotrichoides, F. oxysporum,* and *F. solani* (9,40,42,52,66,68, 73,78,87,98,99).

Several organisms may be involved in disease development. Moreover, disease severity and the nature of the complex may vary substantially, depending on the production area (Table 1) and season. Lukezic and Kaiser (65) showed that fungal populations may differ between banana plants and even between crowns.

Fungi of the complex do not all have the same pathogenicity, and variations have been reported among regions (Table 1). Knight (58) considered that *F. oxysporum, F. verticillioides,* and *F. graminearum*, which have been isolated frequently from crowns of Windward Island bananas, are primary pathogens, whereas *L. theobromae, M. theobromae,* and *N. sphaerica* are considered to be relatively nonpathogenic species. According to the findings of Marin et al. (68) in Costa Rica, *F. verticillioides* and *F. semitectum*

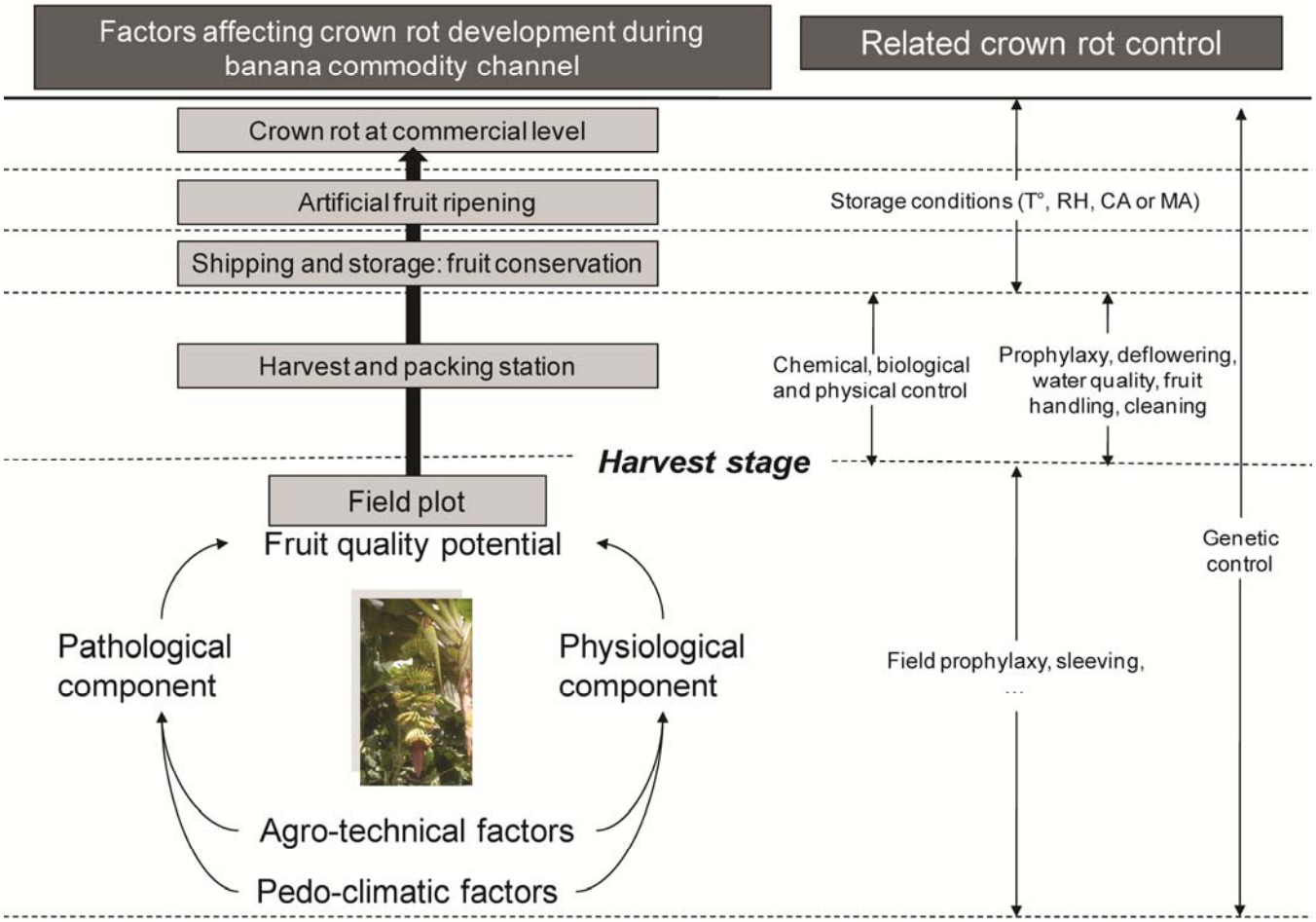

Fig. 2. Diagram representing different key factors that arise throughout the commodity channel concerning crown rot development at the commercial stage, and related control methods. T° = temperature; RH = relative humidity; CA = controlled atmosphere; MA = modified atmosphere.

are the most pathogenic species. According to Griffee (41), *C. musae, L. theobromae, C. paradoxa, F. semitectum,* and *F. graminearum* are major pathogens involved in this disease. However, many authors agree on the strong pathogenicity of *C. musae*, which may trigger an infection from a very small amount of inoculum (35,40,64,66,87). Other pathogens require larger amounts of inocula to induce crown rot symptoms (35,41,60,61,64).

A wide range of fungal complex compositions have been noted in natural contaminations. The nature of this complex, the specific pathogenicity of the different microorganisms involved, as well as interactions among them, may alter the pathogenicity of the complex. *C. musae* was more pathogenic when it was inoculated alone than when it was coinoculated with other species (64); however, Anthony et al. (9) found that *L. theobromae, F. verticillioides*, and *C. musae* were more highly pathogenic when coinoculated than when inoculated separately.

The respective roles of the different species that could belong to the fungal complex have been thoroughly studied, whereas little information is available on the antagonistic or synergistic relationships among these different species. It is essential to gain greater insight into these interactions in order to better characterize the pathogenicity of the fungal complex.

Factors influencing the level of crown contamination by the fungal complex. Very little information is available on the epidemiology of crown rot. The fact that the characteristics of each species involved in the disease complex differ complicates studies on the infection cycle. There are nevertheless some general features. Badger (11) showed that the relative humidity generally has to be over 86% for germination of conidia of most fungi involved in the complex. In banana plantations, this group of fungal species sporulates abundantly on all putrescent organs such as leaves (70,90), floral parts (2,29), and bracts (27,65). *C. musae* and some *Fusarium* species are primary colonizers of decomposing leaves (71) and floral parts (27). Banana contamination by spores of *C. musae* and various *Fusarium* spp. mainly occurs during the first 40 days following bunch emergence, and these are gradually replaced by another fungal complex (29). Spores of some species such as *Colletotrichum* spp. are mainly disseminated by rainwater (27,29,48), whereas others are airborne (65).

The fungus *C. musae*, which is also the causal agent of anthracnose, establishes quiescent infections in the field during the first month following banana flowering (27). These quiescent infections could also contribute to the onset of crown rot if the pathogen has an opportunity to colonize the crown region (43); however, for the other pathogens, even though field infections cannot be excluded, infections mainly occur during harvest and when clusters are trimmed from bunches (72). Contamination generally takes place when hands are cut with a contaminated knife (36,40,96,98), or when clusters are cleaned with contaminated washing water (88). At harvest, the fruits and senescent floral organs bear high quantities of spores that could potentially contaminate the crowns. Some of these spores could be removed by washing and then accumulate

Table 1. Bibliographic data on the fungal species isolated from crown rot in different banana-producing regions[a]

References / Countries		*Colletotrichum musae*	*Fusarium semitectum*	*Fusarium verticillioides*	*Fusarium sporotrichoides*	*Fusarium oxysporum*	*Fusarium solani*	*Lasiodiplodia theobromae*	*Musicillium theobromae*	*Glyocladium roseum*	*Nigrospora sphaerica*	*Acremonium sp.*	*Penicillium sp.*	
Honduras	64	3%	80%	14%					12%	81%			93%	
Central and South America	39	F	MF	X					R	F		R		
	66	0-10%	4-50%	0-28%							0-30%		0-8%	0-33%
Windward Islands (WI)	97	23-33%								5-7%	5%			
	41	36%	27%	6%					2%	8%		<1%		
	96	24%	18%	3%			3%	2%	2%	3%	2%	<1%	2%	<1%
	51	26-44%	7-23%	6-21%					3-9%	4-18%	0-10%	24-26%	0-10%	
	62	I		I									I	
	34	X	X	X					X					
	58	I	I											
	57	I	I	I			I		I	I		I		
	40	I	I	I			I		I	I		I		
Jamaica	85	11%	F	X			X		3%	13%		1%	3%	
Sri Lanka	9	X		X					X					
Nigeria	76	27%	3%	10%			4%	6%	26%	2%				
Somalia, WI, Guatemala	71	38%	X	X	20%					2%			4%	

[a] Percent values correspond to isolation frequencies when given by the authors. X indicates that the pathogen was identified on the crown by the author(s), but without providing any isolation frequency data. F, frequently isolated; MF, most frequently isolated; R, rarely isolated. I indicates that authors evaluated fungal pathogenicity without information about isolation frequencies. Information about pathogenicity is shown when given by authors. ■ = Highly pathogenic; ■ = medium pathogenicity; ■ = slightly or nonpathogenic.

in the washing water (93), while others, such as *C. musae* appressoria, may adhere tightly to the fruit surface (86). The washing tanks are the main source of inocula according to Shillingford (88). After the banana clusters are dipped in the washing water, the spores can penetrate passively a few millimeters into the vascular vessels of the crown, and disease is then hard to control with a fungicide spray treatment (34). Greene and Goos (40) showed that a suspension of *C. musae* spores could penetrate 5 to 7 mm into the crown tissues within only 3 min. The crowns may also be contaminated by airborne spores before the fruit are placed in boxes in the packing station. The risk is especially high when the facilities are dirty or if debris (pistils, stalks, and fruits) is piled up nearby. Conidia can survive for several months under extreme temperature and humidity conditions before germination (72).

Physiological component of the fruit quality potential. The physiological component refers to the level of fruit susceptibility to crown rot, which reflects the physiological state of the fruit and is dependent on agrotechnical and pedoclimatic factors during plant growth. Only a few studies have been conducted on factors influencing the level of banana susceptibility to crown rot. In Guadeloupian conditions, it was shown that marked variations in fruit susceptibility could occur at the same production site over a period of 10 successive weeks (64). Variations in crown rot susceptibility among different Guadeloupian production areas during the same period have also been observed (L. Lassois, *unpublished*).

Fruit age as expressed in accumulated degree day (dd) (54) also seems to affect crown rot development. An intrabunch banana crown rot susceptibility gradient has been documented. Clusters growing on the first hands of a bunch, which are, on average,70 dd more advanced than the hands initiated last (55), are more susceptible than clusters developing on the last hands (63). Moreover, a linear relationship between fruit age (in dd) and the susceptibility of the fruit to crown rot was reported, with the oldest fruit being most susceptible to this disease (37).

Some agricultural practices have a bearing on crown rot development. Modifying the source-sink ratio by trimming leaves and hands (where leaves are considered as sources and fruits as sinks) may induce variations in fruit susceptibility. Severe bunch trimming leads to a sharp drop in banana crown rot susceptibility when the bananas are harvested at a constant physiological age of 900 dd (63).

The mechanisms underlying variations in fruit crown rot susceptibility have yet to be investigated. The plant mineral status has an effect on banana susceptibility to various diseases (19,46). Preformed fungitoxic polyphenolic compounds could be involved in banana resistance to postharvest diseases (1,4,20,74,76). Nevertheless, all factors potentially involved in plant resistance mechanisms could have an impact on the level of banana crown rot susceptibility. Plants are equipped with a series of defense mechanisms controlled through the expression of different genes. Genes governing observed susceptibility variations could be identified by assessing differences in gene expression between bananas with different levels of susceptibility. Studies are currently underway to identify the underlying mechanisms and key genetic factors involved in crown rot susceptibility variations using a differential expression analysis technique (L. Lassois, P. Frettinger, L. de Lapeyre de Bellaire, P. Lepoivre, and H. Jijakli, *unpublished*).

Crown Rot Control Methods

Banana crown rot, like other storage diseases, has an especially detrimental impact on export produce. A routine postharvest treatment with a fungicide is the main method currently used to control this disease. However, problems may arise from differences in fungicide efficacy associated with the level of susceptibility of the fruit to crown rot or of the pathogens to the different fungicides. Finally, discharge of fungicidal slurries can also lead to environmental pollution, and residues of fungicides may be detected in the marketed bananas. Research focused on alternative nonchemical control methods is of considerable interest in the current increasingly prohibitive social and legal setting. It is essential to implement sound integrated control strategies throughout the commodity channel considering the complexity of the disease and the difficulty of its control (34,93). We have a set of methods that can usually be implemented in an integrated way to achieve efficient crown rot control (Fig. 2).

Field control methods. *Sanitation of banana plantations.* Most species involved in the fungal complex are saprophytes that occur on senescent banana organs, especially on decomposing leaves (71). Old leaves present in the banana plantation may harbor inocula that could be responsible for severe contamination of bananas by this fungal complex (92). The inoculum pressure, and thus the disease development rate, may be reduced through regular elimination of senescent leaves around the fruit (93). Banana floral parts are also inoculum sources, especially for *C. musae* and several *Fusarium* species (29). In light of the potential role of bunch stalk contamination in the development of crown rot (36), early elimination of flower parts in the field is also essential for reducing bunch contamination by the pathogens (27).

Plastic sleeving to protect bananas. No accurate studies have been carried out to assess the impact of sleeving on the crown rot development rate. It is nevertheless known that bunch sleeving (Fig. 3) with perforated plastic film protects bunches from fungal contamination, thus especially curbing the development of pitting disease (45) and speckling disease (53). Moreover, it has been shown that sleeving can reduce contamination of banana bunches by *C. musae* by over 80% (27). These findings suggest that sleeving directly reduces crown contamination in the field, or that sleeved fruits release fewer spores in washing water during packing operations.

Controlling the banana harvest stage. Bananas are exported when they have grown to a commercial grade specified by European regulations (Commission Regulation [EC] No 2257/94 of 16 September 1994, setting quality standards for bananas) and market requirements. However, bananas should be harvested at an age that will ensure a sufficient preclimacteric life during conservation, because they should reach the ripening rooms still unripe (green). Bananas are climacteric fruits, and the period between harvest and climacteric rise, the preclimacteric life, is commonly called the greenlife. It has also been shown that the best estimator of the green life is physiological age, expressed as a sum of accumulated temperatures from flowering to harvest, rather than in days (54). It was shown that the physiological age of bananas (expressed in dd) has an impact on crown rot susceptibility (37).

The fruit physiological age should thus be taken into account at harvest. Some practices such as field trimming of false hands, some true hands, male buds, and external fruits of hands can accelerate the fruit pulp filling rate. These practices can thus reduce the physiological age that bananas need at harvest to enable them to reach a sufficient commercial grade (62,63).

Genetic control. The range of varieties grown for dessert banana export is very narrow, as all clones belong to the Cavendish subgroup (12). Moreover, breeding is complicated because triploid banana varieties are generally sterile. In the past, banana genetic improvement programs were mainly focused on obtaining varieties resistant to Sigatoka and Panama diseases. Resistance to crown rot of improved varieties has not been considered in any breeding programs to date.

According to Marin et al. (68), FHIA-01 and FHIA-02, two hybrids produced by the FHIA breeding program, are partially resistant to crown rot. Conversely, Perez Vicente and Hernandez (81) consider that these two varieties are more susceptible to crown rot caused by *F. semitectum* and *C. musae* compared with Cavendish varieties. According to these authors, only FHIA-23 is more resistant to crown rot than Grande-Naine. Finally, the first FHIA hybrids were introduced in the late 1980s, but their characteristics differ from those of Cavendish bananas, and consumers have shown little interest in them, thus limiting their distribution.

Postharvest control methods. *Chemical control.* Routine postharvest fungicide treatment is still the most efficient crown rot control method. This strategy was introduced in the late 1960s with

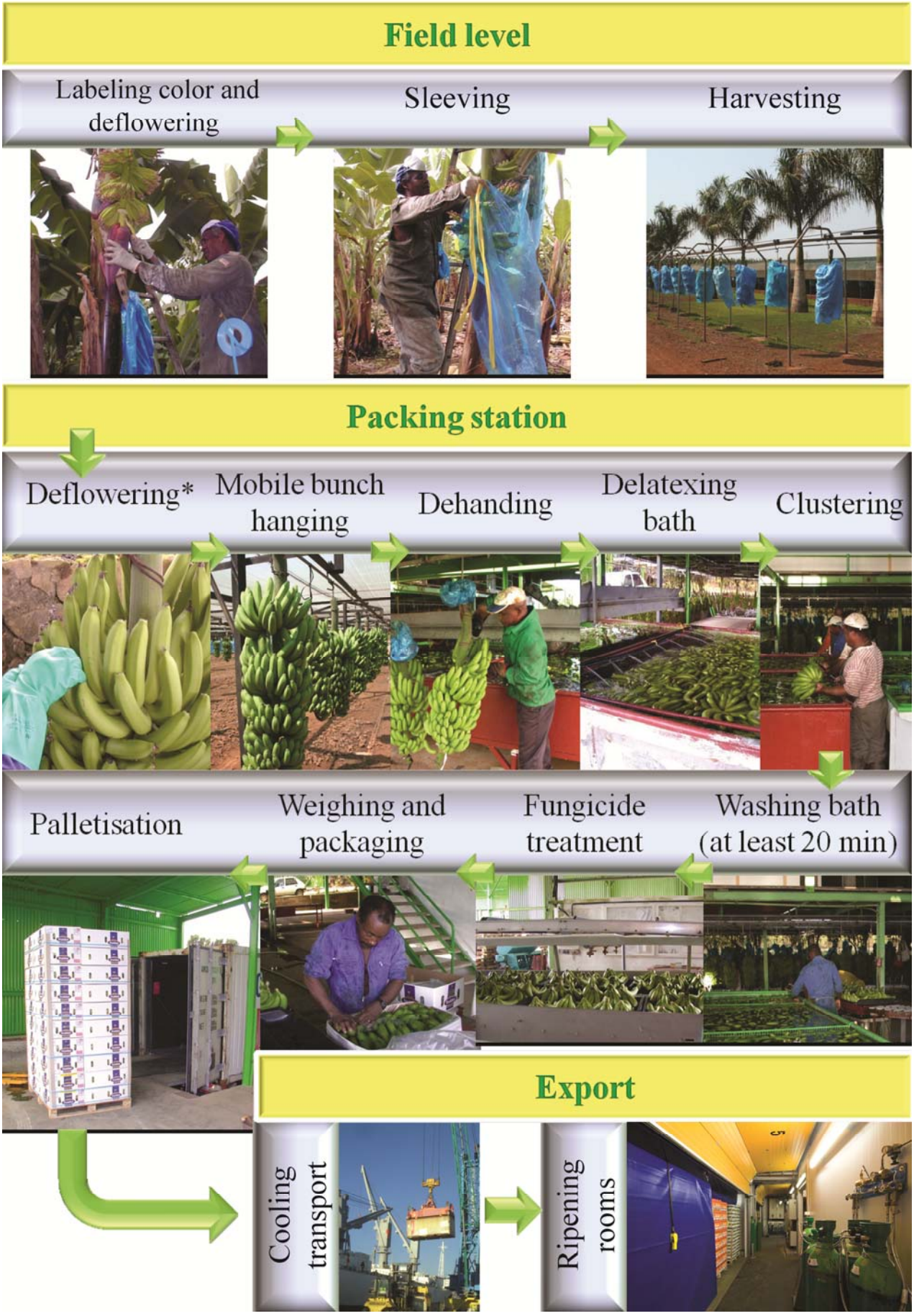

Fig. 3. Successive operations carried out from the field to the banana marketing stage. * Deflowering is done in the packing station when it has not been done in the field.

the discovery of systemic benzimidazole derivative fungicides (thiabendazole and benomyl). They are classified as antimitotic compounds. Gradually, other fungicides that inhibit ergosterol biosynthesis, such as imazalil and bitertanol, were also introduced (30,38). The application methods vary markedly, including dipping, spraying (Fig. 3), and cascade treatment, but in every case the bananas must be thoroughly wetted to ensure the fungicide treatment efficacy (30,51). Alum is often combined with fungicide slurries to neutralize latex residue remaining on crowns when the bananas are removed from the washing bath (75); however, this mixture seems to have a negative impact on the performance of some active ingredients such as thiabendazole (51). The time between crown trimming and fungicide application is critical. Crown rot severity seems to increase when fungicide application is delayed (40). Bananas are nevertheless usually treated in time in packing stations, i.e., just after they are removed from the washing bath. Problems concerning the development of resistant strains may arise with this practice. Postharvest fungicides generally have the same mode of action as those sprayed in the field to control Sigatoka disease. *C. musae* strains resistant to thiabendazole, and generally to all antimitotic compounds, have been detected in many banana-producing countries (28,47,52,62). In Guadeloupe, it has been shown that thiabendazole-resistant *C. musae* strains developed after exclusive foliar applications of benomyl over a decade (1972 to 1982) for Sigatoka disease control (28). Postharvest use of chemicals could ultimately be prohibited because the number of active substances registered for postharvest treatment has been reduced by current regulations, and legislation is becoming increasingly restrictive. Moreover, the efficacy of intensive fungicide treatments is not always adequate. In some areas where very few resistant strains are present, the efficacy of fungicides for postharvest disease control was found to vary substantially depending on season and production area (17). Finally, consumers are now highly selective with respect to food safety concerns, and demand is increasing for produce that has not undergone any postharvest chemical treatments. Alternative nonfungicide solutions are therefore being sought.

Preventive measures in packing stations. Deflowering in packing stations. Deflowering (Fig. 3) involves the removal of all floral parts that could potentially harbor inocula before the dehanding operation. When the floral parts have not been removed in the field, deflowering is done in the packing station before bunch trimming, thus reducing the risk of contamination of the washing baths (62,87).

Packing station water quality. Fruit dehanding is a risky operation because the resulting wound is the main portal for infection by crown rot pathogens. Contamination of crowns when the bananas are processed in the dehanding tanks and then in the washing tanks is a key step in the crown rot development process (Fig. 3). Spore accumulation in the water can be reduced by regularly changing the washing water in the washing and delatexing baths (93) (Fig. 3). These baths can contain a high quantity of spores, mainly *Fusarium* sp. and *Verticillium* sp., that detach from the peel surface (88), whereas *C. musae* conidia are less often found (87). Care should be taken to avoid contaminating the baths with plant debris (pistils, leaves, trimming waste, etc.), and the water should be regularly refreshed.

It is also recommended that the bath water be treated with active chlorine (10,34,93) or quaternary ammonium disinfectants in order to hamper contamination (88), but the efficacy of this disinfection procedure is controversial (34,93). The chlorine concentration should be regularly adjusted to offset the high observed losses by volatilization or through redox reactions with latex or other organic matter in the washing baths (88). It is especially hard to maintain the bath water quality when the water is recirculated in a closed system. In such situations, latex contamination gradually increases in the tanks, so it is hard to control the water quality simply through chlorine treatment. Note also that, due to changes in market standards, it is important to reduce health risks associated with the development of human pathogens in the washing baths.

Packing station sanitation. Protective measures implemented in the packing station are aimed at keeping the crowns of freshly trimmed bananas away from all inoculum sources. To ensure efficient crown rot control, it is thus essential to keep the packing station and the adjoining facilities clean. Waste (stalks, low-grade fruit, etc.) located in the vicinity of the banana packing area, which could contaminate the air in the station, must be eliminated (36,62). It has been shown that trimming clusters in a clean environment rather than in the field can reduce crown rot incidence by 50% (36).

The fruits should also be cleaned before being trimmed from the bunch. A contaminated trimming knife could spread inocula from the peel into the crown tissues (66). This may be avoided by washing the bunches in lightly chlorinated water before they are trimmed into clusters (62).

Banana and crown trimming. Bananas should be trimmed with a clean stainless steel blade. Finlay and Brown (35) showed that roughly trimming the crowns, or ripping them off the hands, significantly increased the level of fruit contamination. Tissue fragments on the surface of the crowns dry out and quickly become senescent, thus providing an ideal site for rot development (35). Moreover, banana trimming knife tips are rounded to avoid banana fruit wounds (62). It is also important to cut wide crown sections containing as much crown tissue as possible, a technique that seems to enhance crown resistance to rot and seldom leads to the spread of rot into the fruit pedicels (75).

Banana storage techniques. The temperature, relative humidity, and atmospheric composition are the main environmental factors that impact storage disease development. These factors may directly affect the biology of the pathogens, but they can also have an indirect effect by slowing down fruit metabolism. These environmental parameters can thus be modified, especially to extend the banana greenlife. The greenlife seems to be a prime factor in the development of storage diseases because a direct relationship has been noted between the degree of banana ripeness and susceptibility to disease (75). Fruit resistance also seems to decrease at the onset of the ripening process. It is therefore crucial to carefully manage these factors to ensure efficient banana crown rot control (62).

Storage temperature. One way to slow down banana metabolism, and thus to delay crown rot development, is to refrigerate the fruit in boxes at the lowest possible temperature without inducing physiological disorders. Cooling should be continuous throughout the shipping phase, which in turn should be as short as possible. Containers designed for maritime shipping of bananas are climate controlled at 13 to 14°C, because temperatures below 12°C provoke peel browning due to oxidization (75). Fungal growth is slowed down at 13°C (35), which is a good tradeoff with respect to preserving the bananas and hampering fungal colonization of the crowns. However, this is much lower than the optimal temperatures for germination and growth of fungi responsible for crown rot, but it is not low enough to slow down the activity of these fungi, which can take place within a broad temperature range, i.e., 8 to 36°C (92). As a result, crown rot incidence and severity are higher in bananas exposed to temperatures over 16°C (93).

Relative humidity. Although most pathogens require a high relative humidity for their in vitro development (11), bananas are less susceptible to crown rot under these conditions. A high relative humidity seems to hinder transpiratory water loss from the fruit, which is essential to ensure a long greenlife. Indeed, banana greenlife is markedly reduced under low relative humidity atmospheric conditions (30 to 40%) as a result of ethylene production from the fruit peel (79). The senescence of banana crown tissues, which is conducive to crown rot development, can be hampered by maintaining their turgidity (75).

Atmosphere composition. The composition of the atmosphere around bananas during shipping can be manipulated to slow down metabolic activity. Modified atmospheres (MA) can be achieved by packing bananas in sealed plastic bags (polybags), and controlled atmospheres (CA) are obtained by injecting nitrogen into the storage rooms. It was shown that crown rot can be partially controlled by packing bananas in MA (15). For MA, the balance of an atmos-

phere with a lower O_2 and a higher CO_2 content depends on the extent of fruit respiration, bag permeability, and the composition of the air outside the bag (97). The O_2 and CO_2 contents generally range from 1 to 10% and from 2 to 14%, respectively, depending on the quality and thickness of the plastic packaging (69,97). This modification in the gas composition reduces the fruit respiratory intensity and hampers endogenous ethylene synthesis, which can considerably increase the length of the preclimacteric phase. MA also inhibits the metabolism of some pathogenic agents. These plastic bags must also have a high mechanical strength because even small punctures will upset the MA (17).

High CO_2 (>15%) and low O_2 (<1%) levels are toxic to many fungi (3,39). Unfortunately, bananas cannot be stored under these conditions because major alterations generally occur during ripening when the atmospheric CO_2 level is above 7 to 12% or when the O_2 level is below 1 to 2% (23,97,102).

Another way to modify gas exchange is to coat the peel with a wax composed of sucrose esters combined with cellulose or fatty acids. This wax blocks the stomatal pores, thus reducing gas exchange (14). The fruits have higher permeability to CO_2 than to O_2, and wax coatings accentuate this difference. This leads to a substantial decrease in the fruit internal O_2 content without increasing the CO_2 to an excessively high level, thus creating an ideal atmosphere for preserving bananas without alterations (13).

Physical control methods. Hot water treatments. Hot water treatments destroy the pathogens (16) and modify the fruit environment by activating antimicrobial compounds in the peel (25). De Costa and Erabadupitiya (25) showed that the optimal temperature and exposure time for controlling crown rot was 50°C for 3 min. Higher temperatures lead to pale fruit, and exposure times of over 5 min reduce Brix values (25) and damage the fruit peel (103). A 20 min longer treatment at a temperature under 45°C is effective for controlling *C. paradoxa*, with the percentage of infected bananas decreasing from 100% to less than 15% (85). However, commercial tests on naturally infected fruit have not achieved crown rot control, and ripening delays have also been noted. There has been no commercial adaptation of this technique to date, except in other tropical fruits such as papaya (22,77) and mango (21,94). Hot water treatments have also been combined with the application of antagonistic bacteria in order to increase the biological control efficacy (25).

UV and gamma radiation treatment. Ultraviolet light (UV) treatments have considerable potential for fruit and vegetable postharvest disease control. Stevens et al. (95) discussed the possibility of inducing apple resistance to *Colletotrichum gloeosporioides* through UV-C treatments. In bananas, however, the peel seems to be too sensitive to UV for the use of this technique for postharvest control of pathogens of the complex such as *C. musae* (50).

Kanapathipillai et al. (56) pointed out that gamma ray treatment (38 min at 4 kGy) inhibited spore germination, the formation of *C. musae* appressoria, and all fungal development on the surface of fruit pieces. However, these authors did not investigate the effects of gamma rays on whole fruit, or on their complex components. Although dosages of around 0.5 kGy can extend banana greenlife (69,101), Marriott and Palmer (69) noted that irradiation can alter the banana peel; the maximum dose tolerated by the fruits is likely around 0.5 kGy (101). Finally, the development of postharvest fruit irradiation has been hampered especially by the high cost of such treatments and their low consumer acceptance (101).

Biological control. Postharvest biological control is very promising because the crown rot infection site on the fruit is limited, the environmental conditions during storage are clearly defined and stable, and bananas have a high added value (49). The results of many studies have suggested that the use of microorganisms such as fungi, bacteria, and yeasts could provide partial crown rot control (8,25,26,33,44,61,64,82,100). It has also been shown that biological control efficacy increases with the antagonistic agent concentration and with the incubation time between the application of the antagonist and crown contamination by the fungal complex (64,82). Antagonists can be used to significantly reduce lesions induced by the fungal complex that causes crown rot, but the control efficacy is limited and variable (64). This type of control, when used alone, cannot provide total crown rot control, and so should be combined with other control tactics such as calcium additives and MA packaging (15).

The impact of several natural substances or nonsynthetic fungicides, such as preparations of calcium, plant extracts, or organic acids, on crown rot development has also been evaluated. *Allium sativum* extracts (62) and essential oils of *Cinnamomum zeylanicum*, *Syzygium aromaticum* (83,84), *Cymbopogon nardus*, and *Ocimum basilicum* (9) have also been found to have fungicidal activity. Win et al. (103) showed that cinnamon extracts reduced crown rot, increased greenlife, and had no negative effects on postharvest banana quality. These plant extracts have fungistatic and fungitoxic activity and inhibit conidial germination and mycelial growth of *C. musae, Fusarium* spp., and *L. theobromae*. However, cases of phytotoxicity have been reported, and the level of control provided by these natural substances is not sufficient to meet market requirements. The use of antioxidants (57) and organic salts (5), sometimes combined with surfactants (7), can also enhance crown rot control. Finally, treatments with Biocto 6 (seed extract from citrus) (Productos Biogenicos S.A., San Jose, Costa Rica) combined with a wax-based additive (Verdiol, Productos Biogenicos S.A., San Jose, Costa Rica) was found to provide the same level of crown rot control as fungicide treatments of export bananas (31).

Conclusion

Crown rot studies and control are especially complex because of the observed diversity and variability in the composition and pathogenicity of the complex involved in the development of this disease. The broad range of possible situations complicates studies on both the parasitic and physiologic components of fruit quality. Further studies are thus required to gain better insight into this disease, especially because little documentation is available on certain aspects such as the epidemiology of crown rot. It is also very important to enhance the overall understanding of banana physiological mechanisms involved in the induction of fruit resistance to crown rot pathogens with the aim of improving control.

There is considerable growing interest in alternative methods to reduce or even completely eliminate fungicide treatments. To be efficient, these alternative control methods should not be too specific considering the broad spectrum of pathogens involved in the complex. No alternative methods to chemical control are currently efficient enough by themselves to match the efficacy of fungicide treatments. However, the results of some experimental trials have shown that crown rot can actually be managed by combining different nonchemical control methods. Crown rot research should enhance the overall understanding of this disease and thus lead to the development of an effective integrated control strategy.

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