Review

Management of black pod rot in cacao (*Theobroma cacao* L.): a review

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Management of black pod rot in cacao (*Theobroma cacao* L.): a review.

Abstract — Introduction. *Theobroma cacao* L. is economically speaking the most important species of the genus *Theobroma*. Cacao is cultured in tropical regions and its yield is affected by several diseases, such as black pod. **Black pod rot in cacao**. Cacao black pod, particularly, is an economically serious problem in all areas of the world where cacao is grown, causing significant pod losses of up to 30% and killing up to 10% of the trees annually. The disease is caused by different species of the stramenopile genus *Phytophthora* and, once it has infected a cacao field, its control is fairly difficult. **Black pod rot control strategies**. Several approaches are used to manage black pod: chemical control, phytosanitary and cultural methods, genetic resistance, and biological control. Losses in yield due to black pod could be reduced through integrated management practices, although the results may vary for each cacao-growing region. **Main challenges and new approaches**. Black pod control could be achieved if an integrated management strategy is established, with the combination of biological and chemical methods, genetic control, and adequate cultural methods in an integrated program.

Cuba / *Theobroma cacao* / plant diseases / *Phytophthora* / rots / disease control / alternative methods

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Gestion de la pourriture brune des cabosses du cacao (*Theobroma cacao* L.) : une revue.

Résumé — Introduction. *Theobroma cacao* L. est économiquement parlant l'espèce la plus importante du genre *Theobroma*. Le cacao est cultivé dans les régions tropicales et son rendement est affecté par plusieurs maladies, dont la pourriture brune des cabosses. **La pourriture brune des cabosses du cacao**. La pourriture brune des cabosses est un problème économique sérieux dans toutes les régions du monde où le cacaoyer est cultivé ; elle cause des pertes significatives allant jusqu'à 30 % de cabosses et tue jusqu'à 10 % des arbres par an. La maladie est causée par différentes espèces du genre straménopile *Phytophthora* et, une fois qu'elles ont infecté un champ de cacao, son contrôle est assez difficile. **Stratégies de contrôle de la pourriture brune de la cabosse**. Plusieurs approches sont utilisées pour contrôler la pourriture brune de la cabosse : la lutte chimique, les méthodes phytosanitaires et de culture, la résistance génétique et la lutte biologique. Les pertes de rendement dues à la pourriture brune pourraient être réduites par l'utilisation de pratiques de gestion intégrée, bien que les résultats puissent varier en fonction de la zone de croissance du cacaoyer. **Principaux défis et nouvelles approches**. Le contrôle de la pourriture brune de la cabosse ne pourrait être obtenu qu'en adoptant une stratégie de gestion intégrée, combinant des méthodes de luttes chimiques et biologiques, le contrôle génétique, des méthodes culturales adéquates inclus dans un programme intégré.

Cuba / *Theobroma cacao* / maladie des plantes / *Phytophthora* / pourriture / contrôle de maladies / méthode alternative

1. Introduction

Theobroma cacao L. is economically the most important species from the genus *Theobroma*, and it is cultivated in the humid tropical regions of the world, although it probably originated in the upper Amazon basin [1]. Over 80% of all cacao is produced by smallholder farmers, providing employment in many rural communities [2, 3]. Smallholder cacao is grown mostly under shade trees, being either inter-cropped or in a semi-natural agro-forestry system. Farmers have been selecting cacao genotypes for years, based on disease tolerance and cacao bean quality. Cacao was traditionally classified into two main groups: Criollo and Forastero, based on morphological traits and geographical origins, recognizing a third group, Trinitario, as the hybrids between Criollo and Forastero genotypes [4]. However, in 2008 a new classification based on genetic data was achieved, recognizing up to 10 genetic groups (Amelonado, Criollo, Contamana, Curaray, Guiana, Iquitos, Marañon, Nacional, Nanay and Purús) [1]. Genetic differences among groups may result in differences in yield and size of the pods, as well as in disease susceptibility [5, 6]. However, all varieties of cacao are affected by several diseases that can affect worldwide production by up to 40% [7, 8], such as black pod caused by *Phytophthora* spp. [9]; witches' broom caused by *Moniliophthora perniciosa*; swollen shoot caused by the Cacao Swollen Shoot Virus (CSSV); Vascular-Strike Dieback (VSD) caused by the fungus *Oncobasidium theobroma*, and frosty pod rot caused by *Moniliophthora roreri* [7, 8].

Cacao black pod is a particularly economically serious problem in all cacao-producing regions of the world [9–14]. Annual yield losses due to black pod may range from 20% to 30%, although individual farms may suffer from 30% to 90% [7], being especially severe in West and Central Africa, causing up to 64% of losses in plantations [10, 11], although it is reported to also be one of the main causes of pod losses in Southeast Asia [12].

The main strategies for cacao black pod control involve using resistant varieties, fungicide applications, phytosanitary measures and biological control, but none of them have completely controlled the disease so far [8, 9]. The aim of our work is to describe the occurrence of black pod in cacao and the main strategies used for its control and management, focusing on the major results and perspectives of black pod management.

2. Black pod rot in cacao

The cacao black pod disease is caused by several species of the stramenopile *Phytophthora* genus, with varied geographical distribution. *Phytophthora megakarya* along with *P. palmivora* are considered to be the most important cacao pathogens in Central and West Africa [9, 10], and most of the studies concerning black pods refer to these species. However, *Phytophthora megakarya*'s presence has not been reported in America, where the species *P. capsici* and *P. citrophora* cause significant losses in favorable environments [15]. *Phytophthora palmivora* seems to be a species with a worldwide distribution, since it is present in Africa, Asia and America [9, 15].

The most recognizable symptom of *Phytophthora* infection in a cacao field is the apparition of black pods [7]. Though pods or cherelles can be infected at any location, infection occurs most often at the tip or stem end and more frequently on pods close to the soil [16]. The main symptoms are firm, spreading, chocolate-brown lesions that eventually can cover the whole pod. When husk infection is achieved, *Phytophthora* invades the internal pod tissues and causes discoloration and shrivelling of the cacao beans. Diseased pods eventually become black and mummify [7], causing the main economic loss and a secondary source of inocula [17, 18]. When infection of the stem and young leaves occurs in nursery stages it causes seedling blight, compromising the start point of the cacao culture [7, 19]. Additionally, *Phytophthora palmivora* and *P. megakarya* can infect bark, flower cushions and chupons, causing cankers that are often hidden by the bark [20, 21]. Unlike pod infections, canker effects on the root, stem and leaves are rather indirect and difficult to measure, but it has been observed that cankers reduce tree vigor and frequently girdle them, killing up to 10% of the trees annually [10, 13, 21].

The inocula that initiate black pod can come from the soil and/or infected roots, stems, flowers and leaves [21–23]. Although root infection from residual soil inocula is not usually an economic concern, it can become a source of spores that could infect the pods and the same is true for infected bark and stem cankers [21, 22]. When pods are infected, they can produce a massive amount of inoculum to infect other pods; it is especially abundant in the infections caused by *P. megakarya* [24]. In addition, as *Phytophthora* can persist in soil and debris for months to several years [13, 15], and susceptible pods may be present on the trees most of the year, the pathogen may always be present in the canopy, ready to cause major epidemics when environmental conditions become favorable for sporulation and dispersal [16]. In addition, factors such as rain and wind, as well as biotic elements such as ants, beetles and insects in general should be considered of importance for black pod spread [13, 15, 17]. Therefore, management of the disease should be approached from different angles.

3. Black pod rot control strategies

Once black pod has infected a cacao field, its eradication is very difficult, although its control is easier to achieve. Several approaches are used to manage black pod: the use of chemical compounds, genetically resistant trees, biological control and phytosanitary methods.

Chemical compounds have been the method of choice for the control of cacao black pod for many years. These substances may have multiple sites of action (systemic, semi-systemic or contact) and have different active compounds [25]. Numerous field trials have been conducted to evaluate the efficiency of chemical fungicides [16, 25–28] with varied results. Their efficiency depends on the application method, dosage and time of the year [16, 28–30]. Copper-based fungicides can reduce *Phytophthora* incidence in pods by using protective sprays and trunk injections [25, 28], and they can also be useful in the control of cankers when applied directly onto the oozing canker. The systemic fungicide metalaxyl (alone or combined with copper compounds) is a popular choice, and it should be applied at three- or four-week intervals to control black pods, although the cost-benefit ratio is not very favorable and the producer should decide the moment of application [29]. The application of fungicides by spraying is often impeded by tree height (sometimes the fungicide cannot reach the higher branches and infected pods remain on top), labor (it requires special safety measures for the farmer) and rainfall, that requires frequent reapplication. To overcome these problems, the application by injection into the trunk has become an attractive alternative. Annual injection of phosphonates into tree trunks has proven to be a cost-effective solution for the reduction of black pod, particularly cankers [27]. Nevertheless, as cacao is mainly grown by smallholder farmers, the application of commercially available fungicides for *Phytophthora* control is often limited due to their high costs [31]. On the other hand, some of these substances have been proven not only to be sometimes unsatisfactory, but also hazardous to the environment [32].

For many years, obtaining cacao resistant to black pod has become the goal of many breeding programs. Many surveys in cacao fields have been made in order to isolate naturally resistant clones against black pod and methodologies to assess such resistance have been developed [33–42]. It is impractical and risky to inoculate attached pods, since spores could be spread through wind and rain and could infect other plants; therefore, simple tests that can accurately assess the resistance, such as leaf, twigs and/or pod inoculation have been developed [35, 36, 38–44]. These results have been confirmed by field observations [33, 36, 39, 40, 42, 44] and, although the observation of symptom development and severity assessment cannot be directly related to specific resistance genes, the search for those is led by the study of the genotypes that show field resistance to black pod.

Black pod resistance is considered polygenic and Quantitative Trait Loci (QTL) may be used to identify genome regions implicated in the resistance of cacao genotypes, opening up the possibility of selection assisted by specific genetic markers [45–47]. Once a resistant genotype is identified or obtained in a genetic breeding program [48], field tests will have to provide conclusive results [49] before propagating the most promising genotypes. Despite all the breakthroughs in this research line, fully resistant cacao genotypes are currently not available.

As the application of chemical inputs for disease control and prevention may be costly and hazardous to the environment, there is an increasing tendency to consider the use of microorganisms as an alternative for plant disease management [16, 50]. In cacao, there are several works concerning the use of microorganisms for the control of black pod.

For example, *Trichoderma* species have beneficial effects on plant growth and inhibit *Phytophthora* growth both *in vitro* and *in vivo* [16, 50–52]. A recent and important research project demonstrated that *Trichoderma* species are capable of colonizing the aboveground tissues of *T. cacao* and several *Trichoderma* species have been identified that occur as endophytes in cacao [53]. The beneficial effect of an endophytic *T. hamatum* has been demonstrated on cacao [54]. Moreover, *Trichoderma martiale* caused a reduction in black pod rot of cacao caused by *Phytophthora palmivora* in *in situ* field assays. This species has potential for incorporation into integrated pest management schemes for the control of diseases of cacao [50].

Actinomycetes are another microbial group with antagonistic potential against black pod. Barreto *et al.* [55] characterized *in vitro* cellulolytic, xilanolytic and chitinolytic activity, indolacetic acid production, and phosphate solubilization activities of actinomycete strains, isolated from the rhizosphere of cacao. Some authors isolated actinomycetes from the cacao phylloplane (pod surface) and subsequently assessed their antagonistic effect *in vitro* against *P. palmivora* and *M. perniciosa* [56].

Moreover, some Plant Growth-Promoting Bacteria have been used as antagonists against *Phytophthora*, such as *Pseudomonas aeruginosa* [57] and *Pseudomonas fluorescens* [58]. In addition, two strains isolated from the rhizosphere of annual crops, *Azospirillum brasilense* and *Bacillus subtilis*, were tested as antagonists against black pod [59, 60]. In general, although some field tests have been carried out, the use of microorganisms as the sole control strategy has not been extended, due to variations in the results [16, 60, 61].

On the other hand, phytosanitary strategies have proven to be efficient in the elimination of secondary inocula and improvement in the yield of cacao [18, 19]. There are many measures that contribute to an efficient phytosanitary management, such as shade management, appropriate spacing, pruning, weed control and frequent and complete harvesting, sanitation, and proper disposal of infected pods and pod husks. Pruning and the removal of basal chupons open up the cacao canopy for more light to penetrate and thereby increase yield [30]. It is well known that *P. megakarya* is sensitive to light, so the correct management of shading and pruning could help to reduce the incidence of this pathogen in cacao fields [30]. In the case of *P. palmivora*, it has been proven that leaf litter mulches reduce its survival in the soil, since they are natural barriers to rain splash and promote microbial decomposition of *Phytophthora*-infected debris [62]. Although cultural control has been shown to be effective in countries as Peru, Ghana and Cameroon [16, 18, 19], its application alone has not been able to control black pod.

4. Main challenges and new approaches

Up to this point, the strategies for the control of black pod transcend chemical, phytosanitary or varietal control, highlighting biocontrol as an eco-friendly promising alternative. The use of microorganisms as biological control agents is attractive to producers, since the use of antagonistic microorganisms is frequently considered as one of the safest and most affordable control strategies. However, field results may vary with different agro-ecological conditions and the complete control of the disease is not achieved [19]. Besides, it is necessary to evaluate the real economic benefit derived from biocontrol strategies *versus* chemical control regarding cacao yield. There is also little knowledge of the molecular dialog involving genes and metabolites that is established during the interactions between the antagonists, the plant and the pathogen. Particularly, the work by Melnick *et al.* opened up a very interesting alternative for black pod control in cacao, since the strain of *Bacillus subtilis* seemed able to induce systemic resistance responses in the plant, achieving plant protection against black pod [60]. The determination of the genes involved in such interactions should be the next step to characterize the defence mechanisms in cacao.

Taking everything into consideration, the best alternative for a sustainable management of cacao black pod disease would be the combination of biological and chemical methods, genetic control, and adequate cultural methods in an integrated program.

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Manejo de la pudrición negra en cacao (*Theobroma cacao* L.)

Resumen — Introducción. *Theobroma cacao* L. es, desde el punto de vista económico, la especie más importante del género *Theobroma*. El cacao se cultiva en regiones tropicales y su rendimiento es afectado por varias enfermedades, tales como la pudrición negra del fruto. **La pudrición negra en cacao**. La pudrición negra es un problema económico serio en todas las regiones del mundo donde se cultiva el cacao, causando pérdidas significativas de bellotas de hasta 30% y la muerte de hasta el 10% de los árboles anualmente. La enfermedad es causada por diferentes especies del género *Phytophthora* (Stramenopile) y, una vez que ha infectado a un campo de cacao, su control es bastante difícil. **Estrategias de control de la pudrición negra**. Se utilizan varios enfoques para el manejo de la pudrición negra: control químico, métodos fitosanitarios y culturales, resistencia genética y control biológico. Las pérdidas de rendimiento debidas a la pudrición negra pueden reducirse cuando se usan prácticas de manejo integrado, aunque los resultados pueden variar para cada región de cultivo de cacao. **Principales retos y nuevos enfoques**. El control de la pudrición negra podría lograrse si se establece una estrategia de manejo integrado, con la combinación de métodos químicos y biológicos, control genético y métodos culturales adecuados dentro de un programa integral.

Cuba / *Theobroma cacao* / enfermedades de las plantas / *Phytophthora* / podredumbres / control de enfermedades / métodos alternativos