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History, dissemination, and field control strategies of cocoa witches' broom

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Abstract

The world demand for cocoa beans has increased, but the spread of fungal diseases of the cocoa tree (*Theobroma cacao*) has become an obstacle. Witches' broom is one such disease, caused by *Moniliophthora perniciosa*, a pest that devastates cocoa production. Thus, this review aims to address the historical description and verify the spread and field control strategies of witches' broom in cocoa trees. Studies reveal that in various countries the disease has led to crises in cocoa production. The history of the disease shows a long fungal parasite–plant relationship and the first scientific studies indicate the Amazon Rainforest as the epicentre. In the field, attempts to control witches' broom involve different strategies, such as genetic control, culture management, and chemical and biological control, which together form integrated management, an approach with good disease control results and perspectives for increased production. Nevertheless, there are economic and technical difficulties to be overcome. Records of occurrence indicate that witches' broom is restricted to Central and South America, distributed across 14 countries. However, it is necessary to adopt measures that prevent the disease from spreading to other parts of the world, which could trigger a global crisis in cocoa production.

KEYWORDS
fungal infections, *Moniliophthora perniciosa*, pest management, pest plant, plant disease, *Theobroma cacao*

1 | INTRODUCTION

The cocoa tree (*Theobroma cacao*) is native to the Americas, specifically South America, in the region of the Amazon Rainforest (Ploetz, 2007). Among the indigenous peoples inhabiting tropical America, the plant has such importance that it became known as the food of the gods (de Souza et al., 2018). The cocoa tree is from the Malvaceae family, which is composed of the former families Sterculiaceae, Bombacaeae, Malvaceae sensu lato, and Tiliaceae (Ploetz, 2007). The fruits of the tree, called cocoa, appear along the trunk of the plant. The beans, considered the most commercially profitable part of the plant, are inside the pods. Currently, the international trade in cocoa beans has made cocoa farming an important activity for several countries (Fiorin et al., 2018).

Cocoa bean production is the basis of the billion-dollar industry of cocoa transformation (Moretti-Almeida et al., 2019). Various products are obtained from the beans, chocolate being the most important and well known (Pimenta Neto et al., 2018; de Souza et al., 2018). Cocoa is produced in countries in Africa, Asia, South America, and Central America among others; however, Africa is the largest producer in the world (Pimenta Neto et al., 2018). Among the cocoa-producing countries, Ivory Coast (Côte d'Ivoire), Ghana, and Indonesia stand out, as they are responsible for more than half of the world production of cocoa beans (Campos-Vega et al., 2018).

The world demand for cocoa has increased in the last 15 years, leading to a growth in the areas of cultivation and intensification of production (Beg et al., 2017; Tothmihaly et al., 2019). However, cocoa production is influenced by various factors, including fluctuation of international prices, climate change, government policies, technical assistance, and the spread of diseases or pests (Mujica Mota et al., 2019; Ploetz, 2016). Despite increasing demand, cocoa productivity has decreased in many countries due to plantation aging, soil degradation, climate change, and the incidence of diseases (Blaser et al., 2018; Effendy et al., 2019). Among the diseases, those caused by fungi are considered the most important. In the Americas, the most evident diseases are witches' broom and frosty pod rot, which are responsible for high rates of loss in cocoa production (ten Hoopen et al., 2016; Pimenta Neto et al., 2018; Ploetz, 2007).

The *Moniliophthora perniciosa* fungus is the agent that causes witches' broom disease, one of the most devastating for the cocoa tree (Moretti-Almeida et al., 2019; Pimenta Neto et al., 2018; Ploetz, 2016). In addition to the genus *Theobroma* (Sterculiaceae), other hosts of *M. perniciosa* include *Solanum* spp. (Solanaceae), and *Arrabidaea* spp. (Bignoniaceae) (Evans & Barreto, 1996). This fungus was named by Stahel (1915) as *Marasmius perniciosa*. Singer (1942) transferred the pathogen to the genus *Crinipellis*, calling it *Crinipellis perniciosa*. At the end of the 20th century, the genus *Moniliophthora* was proposed, to which *Monilia roreri*, which causes frosty pod rot, and *C. perniciosa*, which came to be called *M. perniciosa*, were transferred (Aime & Phillips-Mora, 2005).

In Brazil, the introduction of witches' broom in the state of Bahia at the end of the 1980s contributed to the decline of Brazilian cocoa production and the loss of its position in the world ranking, as the state of Bahia was the main cocoa producer in Brazil (de Souza et al., 2018). In Latin America, hundreds of hectares of cocoa plantations and production have been abandoned, and the ineffectiveness of control methods has resulted in expansion to neighbouring farms, further spreading *M. perniciosa* (Armengot et al., 2020; Medeiros et al., 2010). Among cocoa-producing countries in South America and the Caribbean, where witches' broom has occurred on plantations, average reductions of 70% in cocoa bean production have been recorded (Moretti-Almeida et al., 2019).

Globally, losses of 30% were estimated in cocoa production due to the three main pathogens, *M. perniciosa* causing witches' broom, *M. roreri* causing frosty pod rot, and *Phytophthora* causing black pod rot (Fiorin et al., 2018; Tirado-Gallego et al., 2016). Witches' broom does not only affect cocoa pods; as with frosty pod rot, *M. perniciosa* has the power to debilitate and influence the allocation of nutrients in the plant, being considered a parasite with devastating capacity (Pimenta Neto et al., 2018; Ploetz, 2016). Thus, to measure the impact of the witches' broom, the amount of nutrients diverted by the fungus should also be verified, an important factor because the nutrients are linked to the plant's defence functions.

According to the panorama described above, cocoa cultivation is an important activity for the economy of several countries around the world. However, the growth of world production of cocoa beans, to supply global demand, is being offset by production and productivity losses caused by fungal diseases. Witches' broom is one such disease that has spread across various countries of the Americas, causing extensive damage to cocoa cultivation. If the disease were to affect other parts of the world, it could damage cocoa cultivation on an alarming scale. Thus, it is of fundamental importance to list the strategies for the control of witches' broom in the cocoa tree and, subsequently, know more about possible successful solutions.

In light of the above, this review aims to address the historical description and verify spread and field control strategies of witches' broom in cocoa trees.

2 | REVIEW METHODOLOGY

To verify the viability and structure of the topics of this review, research on the Scopus database was carried out using three key terms: *Theobroma cacao*, witches' broom, and *Moniliophthora perniciosa*. However, no review was found in the last 5 years that covered the proposed theme, and, as such, this review was subsequently developed. In the second stage, a new search using the same three terms was conducted, resulting in 146 articles on the database. To guarantee the relevance of the theme, the articles were selected manually by keywords, title, abstract, and, in the case of uncertainty, inspection of the complete text. Although most of the cited articles are from the database, it was particularly useful to collect other information from specialized books and articles that were significant for the theme addressed in this review. Finally, after excluding publications not related to the approach to the historical record of the presence of the witches' broom, dissemination, and field control, 43 publications were considered relevant.

3 | THE HISTORY OF WITCHES' BROOM

Witches' broom was first described in 1795, in the Amazon Rainforest, when malformations called *lagartão*, or "big lizard", were observed on cocoa trees (Meinhardt et al., 2008). The first scientific investigation to identify the disease occurred in Suriname, at the end of the 19th century (Purdy & Schmidt, 1996). It was found that witches' broom was caused by a fungus that was capable of infecting the cocoa tree and morphologically modifying the vegetative sprouts and flowers, generating vegetative brooms (Hedger et al., 1987).

In Peru, Bolivia, and Venezuela, the occurrence of witches' broom has been mentioned since the period of antiquity (Purdy & Schmidt, 1996). In Peru, fungal diseases of the cocoa tree are one of the biggest problems for production, and better management of witches' broom would increase cocoa productivity in the country (Soberanis et al., 1999).

Between the end of the 19th century and the beginning of the 20th century, there are records of witches' broom influencing a serious, sudden drop in cocoa production in Suriname, which generated a decline in the country's cocoa industry and abandonment of the crop (Evans & Barreto, 1996). This crisis contributed to the forced diversification of crops in Suriname, with the plantation of bananas and coffee. Survival of the cocoa crop in the country was only possible after the implementation of techniques to control witches' broom and the introduction of resistant cocoa tree varieties (Evans, 2016).

In Ecuador, the incidence of witches' broom dates from the beginning of the 20th century, when the disease was recorded in the west of the country, from where it is speculated to have initiated contamination of the cocoa plantations (Villavicencio Vásquez et al., 2018). The disease was considered responsible for cocoa production losses of around 60% to 70%, contributing to the acceleration in the decline of the national cocoa industry (Villavicencio Vásquez et al., 2018).

In Trinidad, during the 20th century, in the years of economic recession and a fall in the international price of cocoa beans, the implementation of witches' broom control was impaired. As a result, cocoa production was reduced from 30,000 to 8000 tonnes (Evans, 2016). Research began on the management and especially the planting of cocoa selections resistant to witches' broom. The focus of research in this country was on cocoa trees selected from other countries, for example, Peru and Ecuador, which exhibited resistance to the disease (Evans, 2016).

In Panama, there are two different records for the first occurrence of witches' broom in the cocoa tree, in 1978 and 1989. In 1978 it was reported in the south, where Panama shares a border with Colombia, a country that had been recording witches' broom since 1917 (Purdy & Schmidt, 1996). The other occurrence from 1989 suggests that the disease was recorded in the centre of the country, in the main cocoa production region (Evans, 2016).

In Brazil, witches' broom was first recorded in the 18th century in the Amazon, during the age of Portuguese colonization (Evans & Barreto, 1996). In north-east Brazil, in the south of the state of Bahia, the first occurrence of witches' broom on cocoa farms was recorded in 1989 (Purdy & Schmidt, 1996). The incidence and spread of the disease on cocoa plantations in Bahia negatively affected cocoa activity. In 1989, production was approximately 600,000 tonnes of cocoa per year, decreasing to around 150,000 tonnes in the last decade (Evans, 2016). The consequences of this drop in production had social and economic impacts, compromising the employment of cocoa managers (Evans, 2016). It is mentioned that about 200,000 jobs were lost and rural areas with diseased cocoa plantations depopulated (Ploetz, 2016). The incidence of the disease in Bahia serves as a warning regarding the contribution of anthropic interventions, accidental or intentional, to the propagation of diseases in crops. This is because, geographically, the state of Bahia is thousands of kilometres away from the Amazon region, where witches' broom previously existed.

4 | PATH OF THE SPREAD OF THE DISEASE

Studies describe witches' broom as a serious problem for world cocoa production, as the disease can cause various negative effects on plantations, as found in countries in which the disease has occurred (de Andrade Silva et al., 2020; Hedger et al., 1987; Meinhardt et al., 2008). The literature reports that of all the continents in the world, the disease is restricted to the Americas and the Caribbean, constituting a bottleneck for cocoa production in these areas (Fiorin et al., 2018; Marelli et al., 2019).

The epicentre of the occurrence of witches' broom disease points to the region of the Amazon Rainforest, where the cocoa tree is native. Tracing a probable route of disease propagation, based on records in scientific studies, the chronological order of countries would be Suriname, Guyana, Ecuador, Trinidad and Tobago, Colombia, Grenada, Panama, Brazil, and St Lucia (Evans, 2016; Kelly et al., 2009; Meinhardt et al., 2008; Purdy & Schmidt, 1996). The spread of witches' broom managed to affect cocoa tree cultivations in a wide geographic strip, overcoming natural barriers, and even affecting Caribbean islands (Figure 1). This demonstrates that the spread of witches' broom could reach other parts of the world, places in which the occurrence of the cocoa tree disease is yet to be verified.

The disease has reached cocoa trees in a total of 14 countries in Central and South America: Bolivia, Brazil, Colombia, Ecuador, Grenada, Guyana, Panama, Peru, St Lucia, St Vincent and the Grenadines, Suriname, Trinidad and Tobago, and Venezuela (Calle et al., 1982; Cronshaw & Evans, 1978; Hedger et al., 1987; Kelly et al., 2009; Medeiros et al., 2010; Ploetz, 2007; Purdy & Schmidt, 1996). In South America, witches' broom has spread through all the countries that produce cocoa. This is a threat to the maintenance of cocoa production levels in this part of the world, as the disease causes a decrease in production and productivity in cultivation areas.

As already mentioned, the incidence of witches' broom can contribute to the abandonment of areas of cocoa cultivation and culminate in substitution for other crops. This constitutes a worrying problem, as millions of small producers depend on the crop for subsistence (Fiorin et al., 2018). In Ecuador, Colombia, Brazil, and the Dominican Republic, properties where cocoa is cultivated are generally smaller than 5 ha. Throughout the world, most cocoa producers are small-scale farmers, who produce 90% of all traded beans (Tirado-Gallego et al., 2016). The need to change cultivation practices to achieve high levels of production, added to the implementation of strategies against cocoa diseases, represent particular challenges for small-scale subsistence farmers.

Given the world scenario of globalization, where goods and services cross physical borders, there is no guarantee that witches' broom will not reach other nations producing cocoa on continents where there is still no record of the disease. Cocoa-producing countries in Africa, Asia, and the northernmost part of Central America need to take precautions to protect the cocoa crop throughout their lands, anticipating a possible incidence of witches' broom and the damage that occurs. It would therefore be relevant to analyse measures of combat and control adopted in countries already affected by the disease in order to evaluate what has produced beneficial results, with the possibility of replication.

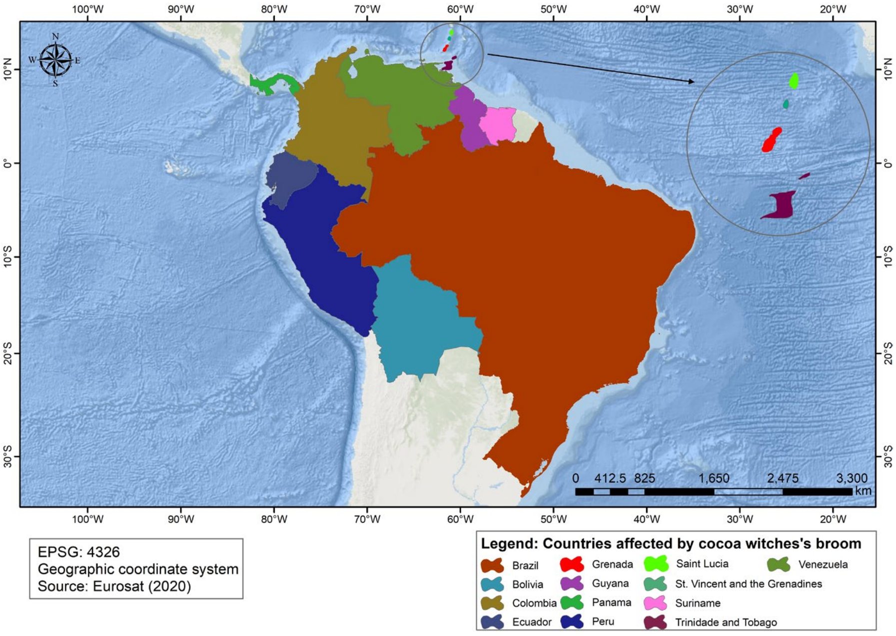

FIGURE 1 Illustrative map of the worldwide occurrence of witches' broom disease (*Moniliophthora perniciosa*) in the cocoa tree (*Theobroma cacao*) [Colour figure can be viewed at wileyonlinelibrary.com]

In recent years, much has been revealed about the life cycle of *M. perniciosa*, and the disease control strategies that could facilitate prevention. The prevention of an outbreak in cocoa plantations in countries where the disease does not yet exist would avoid problems for farmers, due to the damage caused by the witches' broom. Preventive measures can be seen in Brazil, which has been trying to take precautions in relation to the arrival of *M. roreri*, the pathogen that causes frosty pod rot, a devastating disease in cocoa. After the experience with the witches' broom outbreak in the state of Bahia, anticipating the frosty pod rot, CEPLAC (Comissão Executiva do Plano de Lavoura Cacaueira [Executive Commission of the Cocoa Tree Plantation Plan]) researchers are working on the Brazilian preventive breeding programme. This programme aims to launch cultivars resistant to frosty pod rot (Pimenta Neto et al., 2018). In the case of *M. perniciosa*, this could be a plausible preventive initiative to be adopted by countries free of witches' broom.

5 | CONTROL STRATEGIES

The search for solutions to combat witches' broom disease, making it possible to overcome the impacts on cocoa production and productivity, has led to various studies being carried out (Ahnert et al., 2018; Armengot et al., 2020; ten Hoopen & Krauss, 2016; Niether et al., 2018; Tothmihaly et al., 2019). In recent years, results have indicated different field control strategies for witches' broom, with possible increases in production (Table 1).

Among other aspects, cultural management deals with managing the pests and diseases of a crop. In the case of witches' broom, the proposed combat measures are removal of the brooms and infected fruits on the plantation, shade tree maintenance, cocoa tree pruning, and drainage system maintenance (Mortimer et al., 2018; Niether et al., 2018). Such control practices have proven efficacy in the reduction of witches' broom infestation rates, although this form of management is time-consuming and labour intensive to implement, which would encumber production with increased costs and could make it economically unviable (Armengot et al., 2020; Soberanis et al., 1999). Another relevant fact is the frequency with which the brooms are removed. *M. perniciosa* spreads in the form of spores produced by basidiocarps, which arise from dry brooms over a certain period of time and under certain climatic conditions. It is therefore necessary to remove and carry the brooms away from the cocoa plantations.

Research indicates that the cocoa production system can also influence the incidence of disease (Mortimer et al., 2018; Niether et al., 2018). Agroforestry systems (AFS) with cocoa, for example, create different microclimates to monocultures. The results of studies demonstrate that the AFS microclimate stimulates sporulation of disease-causing fungi, as well as their antagonists, which contribute to the control of fungal parasites through ecosystem mechanisms (Armengot et al., 2020). A study suggests that there are benefits in the control of pests and diseases in AFS with cocoa that have around 30% or more plant coverage, with records of production levels similar to those of monocultures (Blaser et al., 2018). The effect of shade trees on 15- to 25-year-old cocoa plantations in Ghana showed that agroforestry with approximately 30% shade cover can have production levels close to cocoa monocultures and reduce pest and disease pressure (Blaser et al., 2018). This shows the link between the maintenance of shade trees and AFS with cocoa disease incidence, which in theory could be tested for the reduction of witches' broom in this type of system.

TABLE 1 Field strategies used in the control of witches' broom (*Moniliophthora perniciosa*) in cocoa (*Theobroma cacao*)

Strategy	Practice	Difficulty	References
Cultural management	Periodic removal of infected fruits; adequate tree shade, drainage system maintenance; removal of witches' brooms	Increased labour costs; recommendation of removal frequency	Armengot et al. (2020); Medeiros et al. (2010); Mortimer et al. (2018); Niether et al. (2018); Soberanis et al. (1999); Tirado-Gallego et al. (2016)
Agroforestry production systems (AFSs)	Benefit from ecosystem mechanisms in the control of fungal parasites of the cocoa tree	Understanding how biodiversity mechanisms of AFS interact and benefit cocoa production	Armengot et al. (2020); Blaser et al. (2018); Kieck et al. (2016); Mortimer et al. (2018); Niether et al. (2018)
Chemical control	Use of fungicide on the cocoa tree; periodically apply to the plants with recommended frequency and dosage	High cost of defences; development of pathogen resistance; adherence to the fruits; maintaining application frequency; labour costs; recommendation of effective dose	Barsottini et al. (2019); Medeiros et al. (2010); Moretti-Almeida et al. (2019); Soberanis et al. (1999); Tirado-Gallego et al. (2016); Tothmihaly et al. (2019)
Biological control	Use of microbiological fungicide, based on *Trichoderma stromaticum*; application of the biofungicide on crop remains of cocoa tree pods, removed witches' brooms and infected fruits	Developing and commercializing a biocontrol product; carrying out only biocontrol is not efficitive	ten Hoopen and Krauss (2016); Krauss and Soberanis (2002); Medeiros et al. (2010); Villavicencio Vásquez et al. (2018)
Genetic enhancement	Plantation of cocoa tree saplings genetically resistant/tolerant to *M. perniciosa*; grafting of varieties resistant/tolerant to the fungus on traditional cocoa trees	Cost of substituting and/or cloning traditional varieties; genetic incompatibility; long time required for the identification of resistance; breeding and selection of such cultivars takes a lot of time	Ahnert et al. (2018); Evans (2016); Pimenta Neto et al. (2018)
Integrated management	Combination of the practices used in cultural management, chemical control, biological control, and genetic enhancement	Associating practices and overcoming the added difficulties	Armengot et al. (2020); Evans (2016); ten Hoopen and Krauss (2016); Villavicencio Vásquez et al. (2018)

A trial applied to an AFS using only cultural management practices of regular pruning twice a year, weed removal, infected fruit removal, and periodic harvest demonstrated that the occurrence of witches' broom was lower in AFS than in monoculture (Armengot et al., 2020). In another study, it was also shown that in AFS there is a close relationship between biodiversity, the occurrence of pathogens, and the secondary metabolism of cocoa trees infected with *M. perniciosa*, as the analysed beans had high concentrations of polyphenols and caffeine, compounds with a relevant function in resistance to fungi (Kieck et al., 2016). However, there remains a lack of understanding of the many mechanisms through which AFS biodiversity interacts and benefits agricultural production (Kieck et al., 2016).

Chemical control is a combat strategy against witches' broom used on cocoa farms in Central and South America, where copper-based fungicides that demonstrate a certain efficiency against *M. perniciosa* are generally used (Tirado-Gallego et al., 2016). However, the general principle of fungicide action is to attack the cellular membrane or respiration of the fungus, which are routes that have not been effective against *M. perniciosa*; studies indicate that this fungus is able to use an alternative mitochondrial oxidase enzyme, which performs an essential function in survival against fungicides (Barsottini et al., 2019). Furthermore, there are difficulties with chemical control related to adherence to fruits and application frequency and dosage (dos Santos Silva et al., 2020; Soberanis et al., 1999). The high cost of fungicides is another relevant factor that makes chemical control of cocoa tree diseases difficult (Medeiros et al., 2010; Tothmihaly et al., 2019).

Chemical control agents alone do not provide a definitive solution, as they may induce microorganism resistance and loss of effectiveness, as occurs with strobilurin fungicides, to which *M. perniciosa* is resistant (Moretti-Almeida et al., 2019). In a study identifying promising new molecules for fungicides, 74 were tested and one showed effectiveness against witches' broom (Barsottini et al., 2019). The discovery of promising molecules, adequate application methods, and, finally, the development of a viable commercial product capable of eradicating the fungus, are still important challenges (de Andrade Gonçalves et al., 2019; Barsottini et al., 2019).

Biological control of witches' broom is based on the use of natural agents that act against *M. perniciosa*, using ecological mechanisms such as parasitism, antibiosis, and competition. This results in the reduction of the disease-causing fungus, promoting cocoa tree resistance. Biological control applied to the cocoa tree has been developed as a sustainable and efficient technique based on the use of fungal antagonists, which produce metabolites used by plants as a defence against pathogens (Villavicencio Vásquez et al., 2018).

Trichoderma stromaticum is an endophytic fungus of the cocoa tree that has been used experimentally in the biological control of witches' broom since the end of the 20th century. Field trials using *T. stromaticum* and copper-based fungicides resulted in the reduction of green brooms and a greater number of fruits per cocoa tree. The recommendation is integration of biological control, chemical control, and cultural management (Medeiros et al., 2010). *T. stromaticum* colonizes dead brooms and diminishes production of basidiocarps of *M. perniciosa*, resulting in a reduction in the quantity of inoculum on the plantation. In Brazil, the Ministry of Agriculture, through CEPLAC, has developed a biocontrol product using *T. stromaticum* (ten Hoopen & Krauss, 2016).

The genetic improvement of cocoa is another strategy used to control witches' broom. The tactic aims to develop disease resistant cultivars, with high productivity, low fruit content, and beans with organoleptic, physical, and chemical characteristics that meet commercial demands. These are some desirable agronomic characteristics that may be obtained by breeding (Ahnert et al., 2018).

The first records of hybrid cocoa trees occurred in Trinidad, between the 17th and 18th centuries (Ahnert et al., 2018). Between 1933 and 1935, cocoa trees with interesting agronomic characteristics were selected in Trinidad, for example, large fruits and seeds, high production, and resistance to diseases and pests. This collection is known worldwide as the Imperial College Selection (ICS) and these cocoa genetic resources were shared with several countries and used in breeding programmes (Ahnert et al., 2018). One of the problems of genetic improvement is the incompatibility in cocoa or cocoa clones, as incompatible plants in the field generate reduced production (Akoa et al., 2021; López et al., 2021). Other difficulties are related to the identification of resistance in the field and the time to develop genetically improved cultivars (Ahnert et al., 2018).

Research shows that genetic enhancement of the cocoa tree has managed to progress in the selection of cultivars resistant to witches' broom (Ahnert et al., 2018; Marssaro et al., 2020). In the state of Bahia, Brazil, the first cultivars with specificity of resistance to witches' broom were launched in 1997 by CEPLAC; however, they lost resistance to witches' broom in a short space of time, were incapable of self-fertilization, and there were problems with low productivity. Since 2000, new, self-competitive cultivars have been launched that demonstrate prolonged resistance to witches' broom (Ahnert et al., 2018).

Genetically enhanced cloned cultivars were implemented in the field on various farms in Bahia. This technology is accessible to farmers and enables rehabilitation of production, as these plants have been demonstrating high yield (Medeiros et al., 2010; Pimenta Neto et al., 2018). Besides being resistant to witches' broom, these new varieties of cocoa tree have superior agronomic characteristics (fruit weight, seed weight, and quantity of seeds per fruit) compared to traditional, local cultivars, which are affected by *M. perniciosa* (Ahnert et al., 2018).

Integrated management of witches' broom involves the associated strategies of cultural management, chemical control, biological control, and genetically enhanced cultivars. The integrated approach to disease management has been recommended by CEPLAC on cocoa farms in the state of Bahia, Brazil, which has enabled a certain stability in production and continuity of the cocoa crop (Evans, 2016). Studies indicate that integrated management is promising for the reduction of the incidence of cocoa tree diseases and increased production (Armengot et al., 2020; ten Hoopen & Krauss, 2016).

In Ecuador, field experiments demonstrated that integrated management using biological control (*Trichoderma* spp.), chemical control, and cultural management was the most satisfactory strategy against witches' broom (Villavicencio Vásquez et al., 2018). However, to increase productivity it is necessary to go beyond integrated management of the disease, to include an adequate fertilization plan, especially on neglected cocoa plantations (ten Hoopen & Krauss, 2016).

6 | CONCLUSIONS

The history of *M. perniciosa* with *T. cacao* demonstrates a parasitic fungus–plant relationship, with the first scientific records pointing to the Amazon Forest as the epicentre. The witches' broom coincided with a decrease of cocoa production in countries where the disease was present, causing great losses to farmers and national economies. The control of witches' broom requires the adoption of different strategies: genetic improvement of cultivars, and cultural, chemical, and biological control; measures that together form an integrated management approach with good results in fighting the disease and prospects for increasing production, when combined with an appropriate fertilization plan. However, to implement the field practices of these strategies, there are economic and technical difficulties to be overcome.

It is possible to learn from the experiences of regions where witches' broom occurs, specifically in 14 countries in Central and South America. The genetic improvement of cocoa and disease management measures have enabled the survival of cocoa plantations in these regions. However, the best way to control the spread of *M. perniciosa* to other cocoa-producing regions would be prevention. At this point there is a gap in studies, and it will be necessary over the next few years to look for potential ways of preventing the spread of fungal diseases in cocoa. In theory, the spread of witches' broom to countries in Africa and Asia could cause a crisis in world cocoa production, with the capacity to affect the industry and cause economic losses.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no data sets were generated or analysed during the current study.

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