Chapter

Evaluation of Progress in Cocoa Crop Protection and Management

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Abstract

Cocoa cultivation began with the Olmecs, who were the first humans to consume chocolate as a drink in equatorial Mexico between 1500 and 400 BC. Over the centuries, commercial cocoa cultivation and trade have developed from the Mayans, Aztecs, and through Meso-America under the influence of the Spanish explorers. In 1822, cocoa was first introduced to São Tomé and Príncipe in Africa from where it spread as a plantation crop, with West Africa becoming the major centre of global production. The cultivation of selected hybrid varieties particularly have led to pest and diseases becoming major production limiting factors. This chapter evaluates crop protection techniques developed over the years, and highlights their contribution to yields, production costs, impact on farmers, and the cocoa value chain and ecosystems. We discussed the need to re-evaluate the imbalance of power in the global value chain, the colonial trading systems, and the required investments for integrated disease and pest management systems. The prospects of using modern biotechnological tools to improve cocoa, and how these approaches can reduce the negative impacts of current protection measures on the ecology and production systems are highlighted. Key recommendations have been made for all stakeholders in the cocoa industry to ensure future sustainability.

Keywords: chocolate industry, pricing, small-scale farmers, cocoa diseases, management, biotechnology

1. Introduction

Cocoa is an important crop belonging to the genus *Theobroma* in the family Malvaceae. Species of this genus are found in the wild of the Western Hemisphere rain forest from 18°N to 15°S [1]. The cultivation of cocoa, *Theobroma cacao*, L., started in equatorial Mexico between 1500 and 400 BC, and the beans were first consumed as a drink by the Mayans and Aztecs [2]. This was confirmed in earlier classical work on cocoa by van Hall [3], who emphasized that cocoa had been revered as "food for the gods," an important cultivated crop not only consumed by the native Indians as a beverage but used as a substitute for money. The revered status of cocoa was enshrined in the latinized name of "*Theobroma*" which was assigned by the botanist Linnaeus. Recent archeological records suggest that plantation-scale cultivation of cocoa occurred in the lowlands of the Mayas in the state of Chiapas and Western Belize centuries before the arrival of the Spanish [4, 5].

1.1 Spread of cocoa

Cilas and Bastide ([5], p. 2) provide a graphical timeline of the cultivation and transportation of cocoa, which began in the 1200s in Central America and then to Southern America in the sixteenth century. This was followed by cultivation in South East Asia in the first half of the 1800s and finally to the humid tropical countries of West Africa in three successive events that started in 1822. From these events, cultivation of cocoa spread through all the humid tropical lowlands and is now grown in 57 countries on three continents [6, 7]. See **Figure 1**: map of global cocoa-growing countries below [8].

1.2 Current production of cocoa

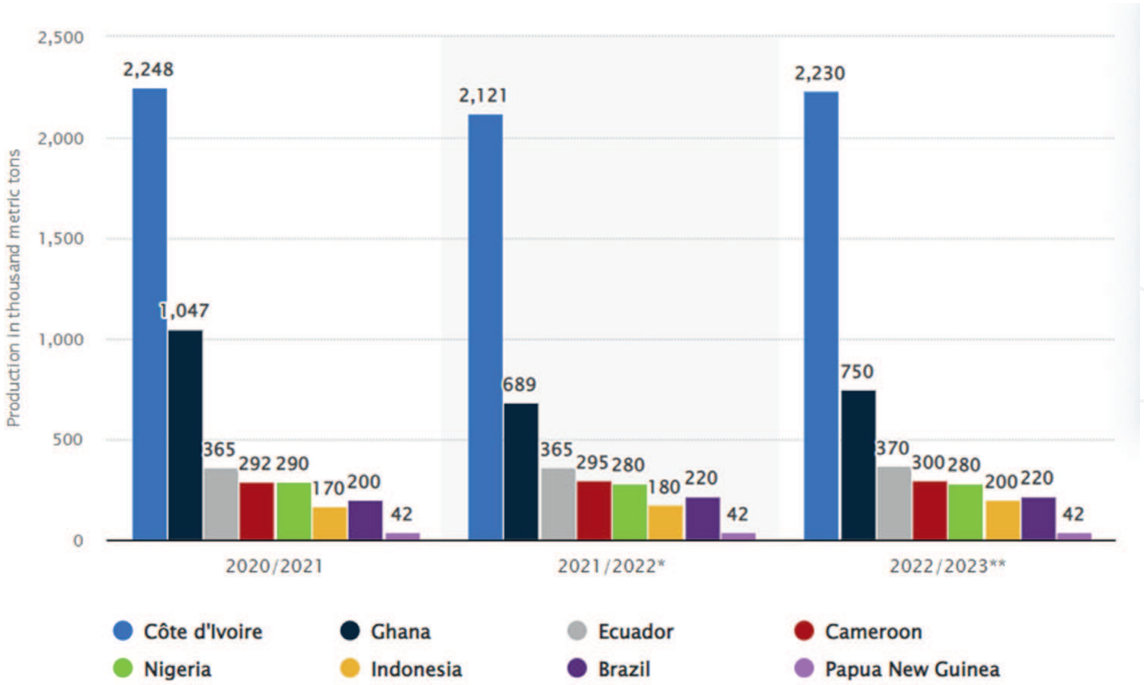
Cocoa production has rapidly increased over the past 40 years to a total of 4.9 million tons in the 2021/2022 cocoa season, with 75% coming from West Africa [9]. Côte d'Ivoire and Ghana alone account for 63% of the total global production (See **Figure 2** below).

It is evident from the graph that the sustainability of global cocoa production depends on how the West and Central African countries are able to deal with the existing and future threats, particularly regarding pests, diseases and climate change.

1.3 History of cocoa cultivation

Increased popularization of cocoa began in 1592, when the Spanish explorer, Hernan Cortés introduced cocoa drink in Spain. To reduce the bitter taste, he added sugar to the drink. It was here it became accepted as a beverage and was taken to

Figure 1.
Cocoa growing countries of the world (source: ICCO, 2023).



*** Estimate and ** Forecast as of February 2023.**

Figure 2.
Global cocoa bean production (in 1000 metric tons) by top eight countries from 2020/21 to 2022/23 (source: Statista, 2023).

other European countries, including Italy, France, Belgium and England [10]. The developed taste for chocolate beverages in Europe sparked cocoa trading. It opened the way for large-scale cultivation of cocoa by European slave merchants in plantations in the West Indies in the late seventeenth century; and Central and South America (e.g., Mexico, Venezuela, Ecuador and Surinam). Cocoa was planted in Brazil much later in the 1780s. The powerful economic gains from the production and export of cocoa beans into Europe to feed the appetites of royals, aristocrats and the growing middle class fuelled the expansion of cocoa cultivation in the fertile tropical climes.

However, the cultivation of cocoa in Africa began much later. In 1822, the Portuguese transported cocoa from Brazil and established plantations in Principe and Sao Tome in West Africa. Principe and Sao Tome became the fourth largest production region exporting over 34 million kilograms in 1901 ([3], p. 34). Later in the century, seeds were taken to Ghana, Nigeria and Côte d'Ivoire to form the basis for cocoa growing in West Africa [10].

Unfortunately, cocoa production in the plantations of Principe and Sao Tome by the Portuguese planters was largely achieved with the inhumane system of black slave labour, which was very different from the serviçal labour system laid by Royal decrees of the ruling Portuguese elites [11]. The slave labour policy on the cocoa plantations in Principe and Sao Tome followed the earlier transatlantic exportation of African slaves to the Portuguese Americas to plug in for the declining availability and use of Indians as slave labour on the sugar plantation, which prevailed in the sixteenth and seventeenth centuries [12]. The author contends that the deferential Portuguese slave labour policies amongst Indians and Africans on both sides of the Atlantic Ocean were influenced by the religious ideologies that considered labour as God's punishment for Adam's sin. Therefore, it was justified to use unfree slave labour as "the hands and feet of the noble sugar-mill masters" ([11], p. 284). When the Jesuits became mills and farm owners, they ideologically justified the enslavement of blacks but fought against the captivity of the Amerindians on the basis that they had souls just like the whites and could be used to control the black African slaves.

Contrary to the Portuguese colonizers approach in Sao Tome and Principe, where large plantations were established using captive African slave labour from Angola, cocoa cultivation in Ghana (the Gold Coast) and the rest of Africa followed a completely different model of small peasant farmer plantations ([3], p. 8). This was because earlier attempts by colonial Dutch missionaries, who planted cocoa in the coastal areas in 1815, and by the Basel missionaries at Aburi later in 1857 had both failed. It took a local Ghanaian blacksmith named Tetteh Quashie, who brought Amelonado cocoa beans from Fernando Po (Equatorial Guinea) and successfully planted a cocoa farm at Akwapim Mampong in the Eastern Region in 1879 [13]. He later sold seed pods to other local farmers, who showed interest in cultivating the crop, which spread cocoa in the region. In 1886, the colonial British Governor seeing the potential, imported cocoa pods from Sao Tome, raised seedlings at the Aburi Botanical Garden and distributed them to farmers [13]. Cocoa was cultivated in Nigeria in 1874, Cameroon in 1876, Côte d'Ivoire in 1919 [14].

1.4 Conditions for growing cocoa

Cultivated cocoa is largely divided into two subspecies Criollo and Forastero, with the latter divided into several varieties [10]. The Criollos, dominate Central America and are characterized by rounded beans, white in cross-section and a special weak flavor. On the other hand, the Forasteros have smaller and flatter beans with violet cotyledons. They have higher fat content and stronger flavor that provides the basis for plain and milk chocolate. Amelonado, a Forastero variety, was first grown in Brazil and Ecuador and later in Fernando Po in West Africa, from where it was spread to other countries in the subregion in the late nineteenth century ([10], p. 4).

Several factors influence cocoa health such as soil type and fertility, the amount of rainfall, humidity, wind and shading, crop management and pest and disease control. Wood and Lass [10] summarized the optimal growth conditions for cocoa as follows: rainfall of 1250–3000 mm per annum and preferably between 1500 and 2000 mm, a dry season of no more than 3 months; mean maximum temperature between 30 and 32°C; mean minimum of 18–21°C, and an absolute minimum of 10°C and no strong winds. Sale [15], using controlled-environment growth rooms, showed that cocoa functioned satisfactorily with high humidity (80–95% RH) at about 27°C.

Generalization about a good or suitable cocoa soil is very difficult, since soil types and conditions tend to vary significantly from one country to another. Likewise, different countries, for instance, Côte d'Ivoire and Nigeria emphasize on physical texture, based on analytical data, while in Ghana good cocoa soils are said to be deep, vary from loamy sands to friable clays, red or reddish-brown in color and should have a pH greater than 6.0 [16]. Contrarily, cocoa was successfully grown on heavy clay soil, yellow to red overlying a deposit of hydrated iron oxides in Democratic Republic of Congo [10]. Nevertheless, several cocoa soils analyzed from different countries tended to fall into the alfisols and ultisols classification [17].

2. Global economic and social impact of cocoa

Consumption of cocoa continues to grow and impacts the world economy, particularly in the emerging middle-income countries such as Brazil, China, India, Mexico and in Eastern Europe [18]. Revenue from the sales of cocoa beans significantly influences the GDP of many producing countries, particularly Côte d'Ivoire, Ghana, Cameroon, and Nigeria [8, 19]. Currently, cocoa accounts for 40% of Côte d'Ivoire, the world's largest producer's GDP. Both Ghana and Côte d'Ivoire have experienced significant deforestation of their primary forests, which is of great concern for sustainable production [20]. Likewise, there are serious issues of exploitation and use of child labour in the cocoa production processes [2].

Of the total annual cocoa production processed into cocoa mass, cocoa butter, cocoa powder, chocolate or other products, over 79% takes place outside the main producing centres in Africa [9]. Over one-third (36%) of the beans are processed in Europe, followed by Asia and Oceania (23%), then Africa (21%) and the Americas (20%). A comprehensive evaluation of global cocoa production states that the chocolate industry surpassed a retail value of USD 100 billion in 2021 and is expected to grow at a compound growth annual rate of 4.5–5.7% until 2027 [21].

These figures show the enormous contribution of the cocoa industry to the global economy. Unfortunately, trade liberalization reforms undertaken by the producing countries in the 1980s and 1990s have concentrated power in the hand of a few transnational companies at the expense of the small cocoa farmers, who are the pillars of the industry [22]. Farmers and their producing countries have suffered low farmgate and producer prices respectively, due to the unjustifiable imbalance of power at the hands of the controlling buyers and grinders, and the transnational chocolate companies and retailers, who enjoy 80–90% share of margins generated from cocoa products [21]. This immoral situation, where the hardworking farmers are just reduced to "price takers," with no bargaining power have left one in three (of the estimated 6 million cocoa farmers) in poverty, without adequate financial resources to take care of their families or invest in integrated crop management practices that could ensure their farms remain healthy and contribute to the sustainable future of the industry ([21], p. 17).

3. Impact of pest and diseases

Of the many challenges cocoa farmers face, diseases remain the most serious constraint to economic production. Available reports estimate that total global cocoa bean losses due to the major pest and diseases stands at 1 million tons, which is between 30 and 40% of the annual production [7]. For over a century, diseases have continued to pose a major threat to cocoa production due to lack of durable resistant cultivars. This is exacerbated by lack of well-funded technical infrastructure in terms of effective extension services support to farmers [7, 23]. According to Appiah [17], the ranking of cocoa diseases due to their severity, impact as limiting factor(s) to profitable production, and regional importance in the 12 leading producer countries are as follows:

3.1 *Phytophthora* pod rot (black pod disease)

Several *Phytophthora* species infect cocoa, causing leaf blight, bark canker and pod rot diseases [24]. Black pod disease is found in all the cocoa-growing regions of the world, and in particular, West Africa, where it is most severe. In 1985, worldwide losses were estimated at £1540 million [25]. Van der Vossen [6] reported that black pod disease causes an estimated 44% of the total global crop loss. More recently, Bowers *et al*. [26] stated that global black pod losses were $423 million. It is evident from these figures that black pod has become increasingly a major concern to global cocoa production.

Of the major species, *Phytophthora megakarya* (Brasier & Griffin) is indigenous to West Africa [14] and it is the most aggressive. *Phytophthora palmivora* (Butl.) Butl. is ubiquitous, *P. capsici* (Leonian) is found in South & Central America, West Indies and India and *P. citrophthora* (Smith & Smith) Brazil, Mexico and India [27]. The dynamics of *Phytophthora* infections in West Africa has changed dramatically over the years. For example, until the mid-1980s, only *P. palmivora* was known as the causal agent of the disease in Ghana. Crop losses attributed to this species were estimated at between 4.9 and 19%. However, in 1986, *P. megakarya*, was identified in the Ashanti Region of Ghana, which caused severe crop losses ranging between 60 and 100% [28]. Nationwide surveys showed that *P. megakarya* had spread rapidly across the country and threatened the livelihood of many cocoa farmers [29]. *P. megakarya* has become the dominant species and has spread west-wards to all West African cocoa-growing countries beginning from Cameroon, where it is predominant [30] through Nigeria, Togo, Ghana and Côte d'Ivoire, and southward to Gabon and Equatorial Guinea [24, 31].

3.2 Witches' broom disease

Witches' Broom disease caused by *Moniliophthora perniciosa*, is the most threatening cocoa disease in Central and South America. The disease begins when fungal spores germinate and infect meristematic tissues, developing into biotrophic hyphae that slowly occupy the intercellular spaces causing hypertrophic growth of buds, which gives the characteristic witches' broom from which the name is derived [32]. It also causes pod infection, which can lead to a high percentage of pod loss. The disease causes an estimated 29% of global crop loss [33]. Witches broom is restricted to the Western Hemisphere, including Central and South America and the Caribbean. It is currently a limiting factor to cocoa production in several Latin American countries [10]. The fungus is indigenous to the Amazon Basin. A significant spread occurred in 1984, when the disease was detected in the traditional cocoa-growing State of Bahia, Brazil, which then produced over 300,000 tonnes of cocoa per annum [10]. Currently, annual pod losses due to the disease reach between 50 and 90% in many parts of the Amazon region and production declined to 185,000 tonnes in 1997 [34].

3.3 Cocoa swollen shoot virus disease (CSSVD)

CSSVD is caused by a virus [35]. It has been and is still a major problem of all the cocoa-growing countries in West Africa [33], particularly in Ghana, where very virulent strains led to the removal of millions of Amelonado trees and were replaced with tolerant Upper Amazon hybrids [35]. The CSSVD outbreak was first reported in Ghana, then Liberia and Sierra Leone, followed by Nigeria, Côte d'Ivoire, and Togo [33]. CSSVD causes 11% of global crop loss [6]. There are many strains of the cocoa swollen shoot virus, which differ in the symptoms they produce, the vectors that transmit them and the range of their alternative hosts [10]. Virulent strains predominate and cause various types of leaf chlorosis, root necrosis, root and stem swellings and dieback in cocoa. It is quite unfortunate that after eight decades of CSSVD control and research, there are still no resistant cultivars available for farmers, the eradication and replanting policies have not been implemented properly, and new infections continue in the Western Region, which is the most concentrated cocoa growing area of Ghana [35].

3.4 Vascular-streak dieback (VSD)

VSD is caused by a basidiomycete originally named *Oncobasidium theobromae* but now *Ceratobasiduim theobromae* [36]. The pathogen causes streaking of the vascular tissue and yellowing of one or two leaves in the second or third flush from the growing tip with a characteristic pattern of green spots scattered over the yellow background. Infected leaves fall within a few days of yellowing, and the infection spreads to neighboring leaves. This leaves a distinctive situation where the youngest and oldest leaves are present, but all the middle ones are fallen. This distinguishes infection from physiological dieback due to environmental stress or insect attack [36]. VSD causes 9% of the total global loss and is important, particularly in Indonesia, Malaysia, and Papua New Guinea [6].

3.5 Moniliophthora pod rot

Moniliophthora pod rot, popularly known as frosty pod rot due to the frosty appearance of the white mycelial mat, is caused by *M. roreri* and infects only green pod tissues [37]. The pathogen grows between the parenchyma cells of the cortex, covering the pod with a white mycelial mat after the lesions have coalesced and produced conidia both within and on the surface of the host tissue [37]. It causes an estimated 5% of the total global cocoa losses and is an increasingly serious problem in Ecuador, Colombia and Central America. Frosty pod disease is said to be the most difficult to control because of the environmental resilience of its spores, ease of spread, profuse sporulation on affected pods and latent infection that can be transported great distances before conspicuous symptoms develop as well as great susceptibility of cocoa to the disease [27]. The threat posed by this disease to other continents, especially Africa, is becoming more apparent due to the vast numbers and persistence of its conidia, as well as its ability to be dispersed by wind.

It is evident from the above that diseases and pests pose a real threat to the sustainable production of cocoa. This is demonstrated by how Ghana lost the leading producer position to Côte d'Ivoire due to the CSSV epidemic that led to the destruction of a large population of cocoa trees. Similarly, disease and pests have drastically reduced cocoa production in Brazil and Malaysia [5] to the extent that Malaysia has become a net importer of cocoa.

4. Environmental and climate change impact

According to Cilas & Bastide [5] climate change is having a significant impact on land and water availability for cocoa production, changes in wind, increase in temperatures and carbon dioxide levels are contributing to higher mortality of young trees and the spread of disease vectors. Lahive *et al*. [38] predicted that atmospheric CO_2 concentration would rise to about 700 ppm by 2100. They show that such enhanced carbon dioxide level has a positive impact in stimulating photosynthesis in both cocoa seedlings and mature cocoa trees, and it appears to ameliorate some of the negative effects of water deficit through improvements in water use and quantum efficiencies.

However, the long-term effect of increased CO_2 occurred in pod biomass instead of bean dry weight per pod, which was not significantly affected. The authors suggested that an alteration in biomass allocation patterns occurs under enhanced CO_2 conditions. This could be a physiological response to adverse factors, such as water stress and temperature increases. Climate change would have an impact on cocoa's response to new pests and diseases and the spread of existing ones. These areas require further research.

According to Laderach *et al*. [39]'s climate modeling, although there would be a relatively drastic decrease in the climatic suitability of the current cocoa growing areas in Ghana and Côte d'Ivoire due to predicted increases in temperature up to 2.0°C, and decreases in monthly precipitation by 2050, there was no need for panic. Instead, we should focus on measures that would reduce the vulnerability of cocoa farmers. These include breeding more drought-resistant cocoa varieties, encouraging crop diversification, conduct research into management practices that would make farms more resilient to increasingly severe and frequent dry spells. We should adopt spatially differentiated communication and engagement strategies that would allow stakeholders evolve appropriate adaptation measures based on their geographical circumstances.

4.1 Integrated disease management strategies

In conjunction with other agronomic and soil factors, healthy cocoa production requires effective integrated pest and disease control measures [7, 40]. These should include determining the appropriate shade regimes, regular weeding, fertilization, pruning, sanitation (removal of diseased materials), timely application of environmentally friendly and target-specific pest and disease chemicals, use of locally identified biological control agents, and importantly, planting of improved disease tolerant or resistant cultivars. The effectiveness of the management and control of cocoa diseases in different countries vary in terms of techniques as well as in level of efficacy. This is due to several factors including the variation of disease-causing pathogens, availability of extension services support, phytosanitary practices and the climatic conditions involved [17].

4.2 Phytosanitary control

Cultural control strategies are environmentally friendly measures and are generally aimed at reducing humidity and the sources of inoculum for infection on the cocoa farm. A summary of cultural control practices employed in *Phytophthora* pod rot control is presented in **Table 1** [from [17]].

In general, management practices increase aeration, which help in black pod disease control. In Bahia, Brazil, shade reduction in commercial plantations lowered the incidence of *P. palmivora* black pod disease by around 40% [41]. In Ghana, a package of phytosanitary practices has been shown to adequately control black pod disease caused by *P. palmivora* [40]. These methods are less expensive and potentially affordable to small-scale farmers compared with the cost of chemical control but are time-consuming.

Activity	References [Cited from [17]]
Good aeration and exposure to sunlight	Muller [1974]
Regular weeding and judicious reduction of overhead shade	Newhall & Diaz [1967], Dakwa [1973]
Removal of mistletoes and basal chupons Ameliorative pruning of canopy	Dade [1927]
Planting at recommended spacing and draining of stagnant waters	
Regular and frequent harvesting	West [1936], Owen [1951], Hislop [1964]
Removal of diseased and mummified pods*	Thorold [1953]

**Considered unimportant by Dade [1927] and West [1936].*

Table 1.
Cultural practices used in black pod disease control.

4.3 Chemical control

The spraying of protective fungicides has been practiced for over 50 years to minimize black pod loss, but this has not always been economical [40]. Black pod disease control with chemicals primarily involves spraying protective fungicides with a pneumatic knapsack sprayer to coat healthy pods. Different copper-based protective fungicides have been tested and are used in black pod disease control. These include Bordeaux mixture (copper sulphate and calcium hydroxide, 25.43% Cu *a.i.*), Kocide 101 (77% cupric hydroxide *a.i.*) and Copper Nordox (50% cuprous oxide *a.i.*). Protective fungicides must be sprayed frequently for effectiveness due to their mode of operation and problems associated with pod growth and the cocoa environment. This requires technical training and involves high labour and input costs, which many subsistence farmers are unable to afford. There are situations where trees are so tall that fungicide sprays are not able to reach the canopy.

Copper has been shown to be redistributed in water [42]. Peirera [43] took advantage of this phenomenon in his single application technique developed against *P. palmivora* in Brazil. The method involved spraying higher doses of fungicide, which is later washed down the trunk to effect control. On the same basis, Sreenivasan *et al.* [44], tied materials impregnated with copper fungicide about two metres from the base of cocoa trees which was redistributed slowly down the tree by rain water.

These methods work against *P. palmivora* black pod but are not effective against *P. megakarya*, due to the vast differences in the sporulation abilities and their main sources of primary inoculum (tree canopy for *P. palmivora* and soil for *P. megakarya*). Opoku [45] compared the production of sporangia and zoospores by *P. megakarya* and *P. palmivora* on different media and established that *P. megakarya* produced 4–6 times more sporangia and zoospores than *P. palmivora* under all conditions.

A semi-systemic fungicide, Ridomil 72 Plus (60% cuprous oxide, 12% metalaxyl), and a single injection of Foli-R-Fos 400 (potassium phosphonate, 40% *a.i*), which is a systemic fungicide and a foliar fertilizer has shown to be more effective than contact copper fungicides in the control of both *P. megakarya* and *P. palmivora* [46]. Studies in Ghana have also shown that extended intervals of four-weekly applications using Nordox 75 and Ridomil 72 Plus effectively and economically control black pod disease caused by *P. megakarya* [47]. The four-weekly spraying significantly reduces the number of applications per cocoa season (May to October) from the current recommendation 8–9 to 5–6 and communicated to farmers could reduce production cost and increase adoption. Phosphonic acid is not subject to any patent, has lower toxicity compared to contact fungicides and the single injection provides lower economic cost, lower operator risk and no environmental contamination of the cocoa ecosystem.

In Central and South America, copper-based fungicides and azoles are used to control witches' broom and frosty pod diseases, albeit not very effective due to many constraints enumerated above [48]. Generally, the profitability of fungicide application depends on the level of farm management, the nature of land tenure and labour arrangements for farm operations [40]. However, due to increasing concerns about antifungal resistance and negative impacts on human health and the environment, alternative strategies are desperately needed [49].

4.4 Biological control

Peirera [50], in a review of prospects for effective control of cocoa diseases, mentioned that while the textbook advantages of biological control management strategy are not in doubt, in cocoa, the promise of actual field use has not been realized, and more research is required. Antagonism *in vitro* of *P. palmivora* by biocontrol agents has been demonstrated. Galindo [51], reported that *Pseudomonas fluorescens* isolated from the surface of a healthy cocoa pod was antagonistic to *P. palmivora in vitro* and was more effective than copper oxide and chlorothalonil in the field. More recent biocontrol efforts have shown mixed results. In Peru, Kraus and Soberanis [52] showed that *Trichoderma* spp. reduced moniliasis, witches' broom and black pod. However, in Costa Rica, field application isolates of the hyper parasitic fungi *Clonostachys byssicola* and *Trichoderma asperellum* made no significant improvement to healthy yields [53]. Ferraz *et al*. [48] touted the potential of yeast species as they are safe for humans, easy to manipulate, shown to enhance plant wellbeing and being environmentally friendly biocontrol agents against witches' broom disease in Brazil.

In Africa, Deberdt *et al*. [54] found that *Trichoderma asperellum* biocontrol agent (strain PR11) was promising in Cameroon but not as effective as the fungicide treatment under high disease pressure. Therefore, integrating biocontrol agents into an IPM strategy was recommended. In Nigeria, farmers have a favorable disposition towards the use of bioagents due to high cost and safety concerns of synthetic fungicides [55]. Similarly, biological control efforts have been made in Côte d'Ivoire, Kebe *et al.* [56] reported that isolates of *Trichoderma* sp. showed fungicidal effects; and two bacteria isolates of the *Bacillus* genus significantly reduced cocoa leaf susceptibility to *P. palmivora*. In Ghana, Akrofi *et al*. [57], in a study of cocoa microbiota obtained 17 isolates, mainly *Pseudomonas* species from three notable cocoa varieties in Ghana. These demonstrated significant inhibition of mycelia growth of *P. palmivora* on plates and prevented disease establishment on pods.

The above results show potential and receptivity to biocontrol as a better alternative to the prevailing copper-based fungicides, which have non-target, food chain contamination and environmental effects [50]. Therefore, serious research investments and greater efforts in the producing countries are needed to find effective biocontrol agents against the endemic pathogens causing cocoa diseases in the different geographic sub-regions. The search for biocontrol agents should focus on the areas identified as the centres of origin or diversity of each cocoa disease, since the potential to find co-evolved natural control agents are high in these areas. A fully integrated pest management approach that utilizes all the available methods including endophytes and mycoparasites, development of tissue culture and tolerant cultivars, should be pursued to minimize the application of fungicides, which the chocolate industry is tightening control of their use on health grounds, as residues contaminate the food chain and their unintended impact on the cocoa ecosystem.

4.5 Development of resistant varieties

Developing genetic resistance against the five major diseases of cocoa have a long history beginning from the Pound collections in 1938, aimed at selecting and accumulating desirable characteristics including high-yielding and disease resistance or tolerance varieties [58]. It is undeniable that genetically resistant varieties are the most cost-effective and reliable method of disease control [59]. Over the years, different breeding and screening techniques have been developed with significant success and challenges (for details see [58]).

In 1978, Lawrence [60] stated that no major genes for resistance to *P. palmivora* had been identified in *T. cacao*. Ten years later, Phillip-Mora and Galindo [61] reported 19 resistant cocoa cultivars to *P. palmivora* in Costa Rica. In Ghana, field evaluation of individual cocoa trees for resistance to *P. megakarya* began in 1990 in two endemic areas: Bechem and Akomadan in the Ashanti Region. From 25 trees that were selected as "resistant" parents, nine showed promise against *P. megakarya* after the challenge inoculation of attached pods. The high level of susceptibility obtained was attributed to the narrow genetic base of the parents [62]. However, in 1997, Van der Vossen [6] noted that no genotype had been found with complete resistance to black pod diseases caused by either *P. palmivora* or *P. megakarya*.

There are many challenges in cocoa breeding work. These include narrow genetic base of available germplasm, annual nature of cocoa production, differences in the diseases caused by the same species, the presence of multiple diseases in the same sub-region and the geographic separation in the areas of influence of each major disease. For example, each of the five *Phytophthora* species involved in black pod disease differs in structure, geographic distribution, ecology and pathogenicity. These challenges necessitate that prospective new cultivars have to be tested for resistance to each of the disease pathogens present. This had not been possible until recently, due to lack of international collaborative projects between producing countries and the danger of introducing new diseases due to poor and inadequate quarantine facilities.

The CFC/ICCO/IPGRI[1] project [63], which involved 10 major cocoa-growing countries and international centres for cocoa germplasm conservation and improvement, addressed these barriers. The objectives were to select better cocoa varieties, reinforce population breeding activities, characterize, evaluate, and enhance cocoa germplasms with emphasis on disease and pest resistance. Twenty-five locally selected clones were tested against local isolates of pathogen and "ring tests" involving isolates from participating countries against the selected germplasm in a non-cocoa growing country. According to Eskes [64], the follow-up project evaluated 1500 trees selected by farmers for yield or low disease or pest incidence that are high-yielding and pest- and disease-resistant candidates, which have been released to cocoa farmers. This demonstrates the power of global collaborative research and the practical results from large investments in research.

The challenges of standardized protocols in accessing levels of resistance expressed in different tissues used in screening work were addressed by the development of the leaf disc inoculation technique [65]. Subsequently, Iwaro *et al*. [66]

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[1] CFC/ICCO/IPGRI – Common Fund for Commodities/International Cocoa Organization/International Plant Genetic Resources Institute

demonstrated a strong correlation between detached and attached leaf lesions. They also assessed the resistance to *P. palmivora* in leaves and pods of different genotypes at the penetration and post-penetration stages of infection. A significant correlation between the resistance of leaves and pods at the post-penetration stage was established, showing that internal resistance is common between leaves and pods and that leaf resistance at this stage could be used to predict pod resistance. A high positive correlation between attached leaves and pods with their detached counterparts was confirmed. These screening techniques are now accepted standard tools for early screening. Different mechanisms may be involved in penetration and post-penetration resistance [17, 66]. Depth of inoculation and stages of pod maturity influenced the level of resistance; hence there is a need to standardize these factors in the screening of cocoa germplasm for resistance to *Phytophthora*.

Expression of defense gene response to *P. palmivora* in different genotypes of cocoa has been found to occur in blocks. These are constitutively expressed at different levels and are potential sources for the many quantitative trait loci (QTLs) contributing to resistance in cocoa [67]. Selecting host resistance is needed for all the major diseases of cocoa. However, the lack of resistance in the international cocoa germplasm collection (ICGC) is a major challenge [68]. It is also interesting to note that some clones in the ICGC have been designated as "resistant" and also susceptible to isolates of the same pathogen. This illustrates the variability in pathogens and the lack of durability, as a clone could be resistant to one isolate and susceptible to another. Both CSSVD and VSD are systemic diseases, and a better understanding of the mechanism of resistance is needed. According to Dzahini-Obiatey *et al*. [35], the ultimate strategy to overcome viral diseases will be to produce genetically engineered cocoa plants by introducing resistant genes using non-conventional biotechnological techniques.

4.6 Modern biotechnological tools: Hope or hoax?

Recent technological advances in biotechnology offer hope for achieving long-term durable resistance in cultivated crops. The increasing legislative constraints on the use of agrochemicals and climate change challenges [49] make biotechnological solutions more imperative for agricultural crops-dependent countries. This is particularly important in the tropics, where the challenges to crop production are most severe. Governments in these countries should consider investing heavily in modern biotechnological tools and the associated capacity building to accelerate improvements in yields and, in particular, resilience to biotic (pest and diseases) and abiotic (climate change) stresses.

Considerable achievements have been made in cocoa breeding and selection, including sequencing of two cocoa genomes [69], which has allowed the identification of genes and proteins that code for specific traits [70], gene discovery and marker-assisted breeding using single-nucleotide polymorphism identifications [71], QTLs mapping of resistance [71] and genome-wide characterization [72]. These developments show great prospects towards targeted gene transfer and guided selective breeding for durable resistance in cocoa against these challenging diseases.

Currently, there are many new powerful plant biotechnological techniques, for example, genome editing, which involves precise modification of specific DNA sequences using three protein-dependent DNA cleavage systems, namely the zinc-finger nucleases, transcription activator-like effector nucleases, and RNA-dependent DNA cleavage systems (i.e., CRISP-associated proteins) [73]; RNA interference, and cisgenesis - the single gene transfer from sexually compatible crosses [74]. Amongst these modern gene editing technologies, CRISPR/Cas9 is reported to be faster, cheaper, precise, and highly efficient in editing genomes, even at the multiplex level [75]. It has been successfully used in cocoa leaves and cotyledon cells to delete the *TcNPR3* gene, which suppresses the plant defense response using *Agrobacterium*-mediated transient transformation, elevated expression of downstream defense genes and increased resistance to infection caused by *Phytophthora tropicalis* [76].

Now we have valuable genome datasets and functional tools for rapid and target-specific genetic changes that could confer vigor, resistance to diseases, pests and resilience to abiotic stresses in cocoa. These new tools for characterization of cocoa genes and genetic manipulation of disease resistance in other important tropical crops overcome problems associated with traditional breeding techniques. However, whether these biotechnological improvements would be seen as genetically modified organisms, which are not widely accepted in the northern hemisphere, remains unclear [77]. Also, these cutting-edge approaches require specialist training and expensive equipment and supplies, which many producer countries are not equipped with.

5. Conclusions

The cocoa industry, particularly chocolate manufacturers, has enjoyed a steady supply of cocoa beans that have allowed uninterrupted manufacturing of consumable products and the holding of good buffer stocks. Conversely, cocoa producers continue to struggle due to low prices, diseases, pests and a rapidly changing climate. Cocoa has been described as a crop "produced in the south and consumed in the north" [9]. The story of cocoa production requires rebalancing the colonial power dynamics in the value chain to bring equitable benefit to all involved.

Currently, cocoa production faces significant but not existential challenges. These include threats posed by pests and diseases, low cocoa prices paid to farmers, as well as climate change and its potential adverse impacts on food production in cocoa growing areas. The economic benefits, enjoyment and health value of cocoa products to the masses, producing countries, the large transnational businesses and the small-scale farmer (who is at the heart of everything) should serve as strong incentives for all stakeholders to come together to address the critical issues ([21], p. 6). It behooves on the chocolate industry, the largest beneficiaries to keep the goose that is laying the golden eggs healthy and productive. There is a need for investment in critical research and development, adoption of fair and ethical trading policies. An introspective look and re-examination of the power imbalances in the existing cocoa value chain are urgently needed for a sustainable cocoa future.

5.1 Recommendations

The quest for sustainable cocoa production that adopts environmentally friendly farm management practices, avoids child labour and embraces the voluntary standards would happen if farmers are given their deserving living income from their work [21, 77]. To address the perennial threat of pest and diseases, increased efforts and heavy investments are required to develop cocoa varieties that are truly resistant. We propose several interrelated political and technical recommendations to key stakeholders. These are:

5.2 Governments of coca producing countries

The governments of producer countries should:

- Strengthen the Cocoa Producers Alliance to become a strong and united organization that could control production levels (like the Organization of Petroleum Exporting Countries), negotiate just a share of cocoa income in terms of producer prices, and adopts uniform trading policies.

- Engage in serious dialog with the powerful Western cocoa trading and chocolate manufacturing companies to address the existing trading imbalances.

- Develop good infrastructure including transportation systems in the rural cocoa farming areas for easy access to market.

- Provide fair pricing and government-backed financing with low-interest rate and flexible repayment terms.

1. **Scientists and Cocoa Boards**

- Producing countries and scientists backed by policymakers must develop integrated pest management strategies in partnership with farmers that allow them to utilize environmentally friendly phytosanitary practices, improved planting materials and biological control measures.

- The IPM strategy should allow limited and targeted use of approved fungicides at critical period of infection.

- Farmers should be trained in scientific agriculture and farming as a business including cocoa ecotourism.

2. **Chocolate Industry and Scientists**

- The chocolate industry should increase research funding and provide local scientists resources to conduct a non-conventional biotechnological cocoa improvement programme to hasten cocoa breeding and selection work.

- Research institutions should put greater emphasis on developing effective biological control of cocoa diseases and understanding the mechanisms responsible for the variability experienced in field trial.

- Regional collaborative biological control research groups and centres should be established with funding from the chocolate industry and Cocoa Producers Alliance.

3. **Farmers**

- It must be recognized that farmers hold the key to long-term, sustainable cocoa production; therefore, improving their conditions should be the primary concern of key stakeholders in the cocoa value chain. In this regard:

  - Farmers should be encouraged to form strong local cooperatives.
  - Farmers unions and associations must be empowered to collectively bargain for humane farmgate cocoa prices.
  - Train farmers on environmentally friendly practices [7].

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Conflict of interest

The author declares no conflict of interests.

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