Review

Coffee Leaf Rust *(Hemileia vastatrix)* in Kenya—A Review

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Abstract: Coffee is one of the most important cash crops and beverages in the world. Production of coffee is limited by many factors, which include insect pests and diseases, among others. One of the most devastating coffee diseases in many coffee-producing countries is Coffee Leaf Rust caused by the fungus *Hemileia vastatrix*. Kenya is a coffee-producing country and has conducted studies to understand and manage the disease. Management strategies for the disease include the development and use of fungicide spray programs, cultural control practices, breeding resistant coffee varieties, and biological control agents. This paper reviews the status of the disease and management options applied in Kenya.

Keywords: coffee; Kenya; Coffee Leaf Rust; races

1. Introduction

Coffee is an important crop and beverage in the world, creating incomes for over 125 million people. In terms of commerce, it is the second most traded commodity after oil [1]. Coffee is a tropical crop mainly grown in Southern America, Africa, Asia, and parts of Oceania primarily by smallholder farmers. In Africa, coffee is produced in Eastern, Central, and West Africa, with Ethiopia being the largest producer. It is also the origin of Arabica coffee (*Coffea arabica*) which is the main species produced in the world. Kenya produces Arabica coffee and is currently the fifth largest producer in Africa, down from being the second-largest producer in the 1980s [2–4]. Coffee in Kenya is produced in 32 counties by 800,000 smallholder farms and 6000 estates [2,5].

On the global scale, coffee production has been on a decline over the last two decades as compared to consumption which has been on a steady increase over the same period [1,6,7]. The recent decline has mainly been attributed to the Coffee Leaf Rust, *Hemilleia vastatrix* Berk. and Br. (CLR) outbreak that hit most coffee-producing countries in 2008–2011 [8–11]. Other challenges facing coffee production include climate change, insect pests, other coffee diseases, volatile prices, soil fertility management, competition from other enterprises, aging farmers, and high costs of production [4].

Coffee Leaf Rust is a major disease of Arabica coffee, causing significant economic losses and has been reported in over fifty (50) coffee-growing countries [12]. The disease can cause yield losses in excess of 75% where outbreaks are severe [13] due to loss of foliage by up to 100% and loss of berries by up to 70% [14]. The disease cause losses of one to two billion US dollars annually [15]. Since 1976 when the disease was observed in Central America, the worst was the recent epidemic affecting all countries in the region, during which a 53% incidence was experienced. The first case of CLR in Kenya was reported in 1912, though records indicate that it was noticed in 1861 near Lake Victoria (western Kenya) on wild coffee [16]. This indicated that the pathogen was infecting other *Coffea* species before the introduction of Arabica coffee in Kenya.

Coffee in Kenya is mainly grown in two regions, the East of Rift Valley (areas around Mount Kenya, the Aberdare ranges, and Machakos) and West of Rift Valley (Kisii highlands,

area around Mt Elgon and the North of the Rift valley) [17,18]. In the East of the Rift valley, the distribution of rainfall is bimodal with two distinct rainy seasons, where the peak of the first one is in April and the second peak in November [19] while the converse is true for the eastern part of the country. The West of the Rift Valley experiences a bimodal rainfall distribution with the peak of the long rains occurring in the months of March–May and the short rains in September–December while some areas have a third minor peak during the months of June–July–August [20]. These weather patterns affect the epidemics of CLR with the peak of the disease coming soon after the rainy seasons when it fully sporulates from latent infections that occur during the rainy season, but they sporulate when temperatures rise after the rains [21,22].

Understanding and managing CLR has been a focus of research internationally for a long and the recent devastating effects of the disease, coffee-growing countries have enhanced efforts to initiate more research aimed at alleviating the threat of leaf rust through their national research institutions, partners, and international research centers [23]. This review paper provides an insight into research efforts made into understanding the biology of the pathogen, efforts done in Kenya in breeding for CLR resistant coffee varieties, and other management practices adopted.

2. History and Spread of CLR

Coffee Leaf Rust (CLR) was reported in 1869 in Ceylon (now Sri Lanka) and by the 1920s, it had spread to most parts of Africa and Asia [24,25]. Towards the end of the nineteenth century, CLR caused severe damage to the coffee plantations of Sri Lanka, the Philippines, Java (an island in Indonesia), and Malaya (now part of Malaysia), which led to the collapse of the coffee industry in the region [26]. The disease was detected in the Americas in 1960, and until recently, it caused losses of 20–25% per annum in some regions [27]. In late 2012, it emerged in Mesoamerica, the Northern part of South America, and the Caribbean as a significant threat to coffee production with yield losses predicted to reach 50% for the 2013 harvest season [28].

In Kenya, CLR was first reported in 1912 [11] but it was not serious until 1954 [11]. However, there are chronicles that it was observed in 1861 in Western Kenya near Lake Victoria on uncultivated coffee [29], an indication that this disease probably existed earlier in Eastern Africa without causing epidemics or considerable loss on certain coffee varieties or species. Possibly, the co-existence between coffee and rust for a long period might have kept the rust infection at low levels [9]. The disease has been a major threat to the production of coffee in the lower coffee-growing areas of Kenya but is increasingly being observed in higher altitudes due to climate change [30].

3. Taxonomy and Biology of CLR Pathogen

Coffee Leaf Rust is caused by the fungus *Hemileia vastatrix* which was first described by Berkeley and Broome in 1869 [9] and is classified as follows: Phylum: Basidiomycota, Sub-phylum: Pucciniomycotina, Class: Pucciniomycetes, Order: Pucciniales, Family: Incertae sedis, Genus: *Hemileia*. *Hemileia vastatrix* (Berkeley and Broome) is an obligate-host-specific pathogen characterized by a powdery coating of yellow urediniospores on the underside of the coffee leaves [31].

Through international collaborations coordinated by the Coffee Rusts Research Centre (CIFC, (Centro de Investigacao das Ferrugens do Cafeeiro) in Portugal, detailed studies on CLR have been undertaken with several genes for resistance and compatibility described in detail in the host and the pathogen respectively [29]. Studies have shown that at least nine resistance genes (S_H1–S_H9), confer resistance of coffee plants to CLR either singly or in combination [32]. In *C. arabica* S_H1, S_H2, S_H4, and S_H5 have been found while S_H6, S_H7, S_H8, and S_H9, were introgressed from the diploid species *C. canephora*. The S_H3 which provides durable resistance originated probably from *C. liberica*. Intense studies have also been done on the pathogen diversity to identify its races. Only six races of the pathogen (I, II, VII, XV, XX, and XXIV) had been reported in Kenya up to the year 2012 when six

additional races (III, XVII, XXIII, XXXVI, XLI, and XLII) were reported [29]. The new races confirmed the presence of three new virulence genes (v1, v7, v8) and a possible fourth one, (the v9) but these races are not widespread [29]. Currently, more diversity studies are ongoing at Coffee Research Institute, Ruiru Kenya as part of international collaborative efforts to understand the pathogen. The continuous increase in the number of races of the pathogen is a major threat to coffee production and could cause a drawback to the progress made in breeding for resistance in Kenya and worldwide.

4. Epidemiology

Hemileia vastatrix requires temperatures of 10 °C to 35 °C and water to develop [33,34]. Rust development is affected by temperatures with temperatures below 15 °C hampering spore germination and slowing down growth while temperatures above 35 °C slow down fungal growth. Uredinial germination and infection require about 24 to 48 h of continuous free moisture. The most optimal temperature for the growth and proliferation of the rust is between 21–25 °C with 100 percent Relative Humidity [35]. Weather patterns affect the epidemics of CLR with the peak of the disease coming soon after the rainy seasons when it fully sporulates from latent infections that occur during the rainy season but sporulate when temperatures rise after the rains [21]. The peaks of rainfall pattern therefore always correlate to CLR infection peaks with the peaks of the disease occurring immediately after the peak of the rains.

In Kenya, coffee-growing regions are broadly classified into West of Rift and East of Rift regions and the seasonal variability of the disease in the regions has been established. In areas West of Rift, the long rains start in March through August while the short rains start in September through November and this corresponds to two CLR peaks in June to July and October to December. In areas East of Rift, the long rains start in March through May and short rains start in October through December resulting in two CLR peaks in May to June and January to March [20,21,36]. Rainfall distribution is more influential in the progression of the disease whereby light and broken rain is more favorable than continuous rain [8,34,37]. The spread of the disease within a farm is mainly by rain splash and reduction of the infectivity of the spores at the start of rains can greatly reduce the development of an epidemic [33]. Wind and human activity may play a higher role in introducing the disease in new areas but insects may also play a role [38]. Unseasonal rainfall resulted in a longer period of disease progression that produced more disease later and the peaks of the disease could be traced to individual rainfall periods [39].

Further, [21] identified the three factors that affect the course of the disease when rainfall is not limiting as (i) the intensity and distribution of the rainfall (ii) residual inoculum at the troughs, and (iii) the leafiness of the tree with heavily foliated trees having more rust particularly at low inoculum levels.

Young lesions may appear as small chlorotic spots before sporulation occurs (Figure 1). Yellow to orange powdery blotches appear on the underside of leaves, with corresponding chlorotic patches on the upper side. Initially, these are only 2–3 mm diameter, but steadily expand, coalesce, the centers of older lesions become necrotic and the sporulating zone is restricted to the outermost zone (Figure 2). On older leaves, several lesions may merge to produce irregular diseased areas covering much of the leaf. Occasionally, rust lesions occur on young green stems and berries [25,40]. The major effect of CLR is defoliation (Figure 3) which reduces the photosynthetic area [41]. Photosynthesis provides the most essential carbohydrates for the proper metabolic functioning of plants and any disease adversely affecting the leaves affects production negatively [15,25]. A heavy CLR infestation of leaves not only reduces the assimilation area but can also result in complete defoliation [42] leading to dieback and a loss in both yield and quality. Defoliation, by reducing the growth potential of the plant, restricts the growth of new stems on which the following season's crop would be produced [43].

Figure 1. Young orange to yellow lesions of Coffee Leaf Rust on the underside of a coffee leaf.

Figure 2. An active fully expanded CLR Lesion (**left**) and advanced stages of Coffee Leaf Rust infection showing coalesced lesions and necrotic centers (**right**).

Figure 3. Coffee trees defoliated due to Coffee Leaf Rust infection.

5. Management of CLR in Kenya

Effective management of CLR is of utmost importance in sustained production and productivity of coffee [44] and the use of fungicides was the earliest adopted in Kenya [45]. Currently, the use of cultural practices, planting resistant varieties, and application of contact and systemic fungicides are the most adopted practices among farmers [14,46–48]. Efforts continue to be made to reduce the reliance on chemical control and only consider it as the last resort because it is expensive and injurious to humans and the environment. The status of the management options practiced by coffee producers in Kenya is discussed below.

5.1. Resistant Varieties

The growing of resistant coffee varieties has always been considered the most sustainable and affordable management of CLR [49]. In Kenya, the development of CLR-resistant coffee varieties can be traced as far back as the 1920s when selection for disease resistance/tolerance, high yields, and quality was started [32]. This led to the release of the first Kenyan coffee varieties (SL28, SL34, and K7) in the 1930s which had high yields and good cup quality but were susceptible to coffee berry disease, leaf rust, and bacterial halo blight of coffee (*Pseudomonas syringae* pv. *garcae*). Further studies indicated that K7 had tolerance to some races of CLR as well as partial resistance to CBD [50].

After a severe outbreak of CBD and CLR in the late 1960s, a breeding program for disease resistance was started in 1971. The program aimed at developing varieties that combine resistance to CBD and CLR coupled with high yields and beverage quality culminating in the release of the variety Ruiru 11 in 1985 [49] and later Batian in 2010 [9]. The cultivar Ruiru 11 is a composite of 66 F1 hybrid sibs each derived from crosses between specific female and male populations [9]. The male parents are tall statured selections from multiple crossbreeding programs involving the Coffee Berry Disease (CBD) resistant donor parents Rume Sudan (R gene), Hibrido de Timor (T gene), K7 (k gene), and the susceptible high yielding good quality cultivars N39, SL28, SL34, Bourbon, and SL4 [49]. The female parents are short compact advanced generations (F3, F4, and F5) of the Colombian cultivar Catimor (a hybrid between Caturra rojo and Hibrido de Timor clone 1343/269 [49]. Batian is true to type variety selected from three breeding lines of the male parents of Ruiru 11 after a series of selfing to fix the CBD resistant genes. The development of durable resistance is hampered by the high variability of the CLR pathogen [50], but the development of resistant coffee varieties continues to be a priority in Kenya [51]. Ruiru 11 has remained highly resistant to CLR since its release while Batian exhibits intermediate resistance to CLR.

5.2. Cultural Practices

Cultural control is the deliberate modification of crop-production systems, to reduce pest populations or avoid pest injury to crops. Cultural practices that have been adopted by farmers in Kenya to manage CLR include but are not limited to mixed-cropping with fruit trees, shade trees, and maintenance pruning of the coffee trees [52,53]. Studies have shown that CLR incidences and severity were lower on intensively grown coffee trees than on those grown traditionally [54]. Pruning plays a major role in the management of CLR as it reduces the tree foliage increasing air circulation between branches thus modifying the within tree microclimate. This causes rapid evaporation resulting in reduced periods of leaf wetness, a key factor in spore germination. Further, management of the tree architecture increases nutrient and water use efficiency resulting in healthier plants, as well as increasing the efficiency of chemical sprays by enhancing spray penetration. Canopies of shade trees can also lower CLR levels by intercepting and reducing the energy of raindrops, diverting others from their trajectory as they approach the coffee trees. Therefore the raindrops that fall onto coffee trees via foliage of shade plants might not be energetic enough to dislodge and disperse conidia [55].

Studies in Kenya showed that coffee bushes under shade retained the infected leaves for significantly longer periods than coffee in the open sun while the disease severity was significantly higher in the trees in shade than in open sun [56]. The pattern is affected by distance from the shade tree hence the intensity of shade and the amount of rain since light rains do not wet coffee in shade as much as that in the open [57]. These findings underscore the complexity of the progression of CLR in coffee agro-systems as discussed by [58].

Proper and timely pruning is adopted by most coffee farmers in Kenya as a strategy to manage CLR. Coffee Research Institute has developed an elaborate coffee canopy management guideline that is accessible to all farmers [36]. This guideline emphasizes that pruning and shading is a critical integral cultural practice for the control of CLR. Other research work has reported that shade could alter the microclimate and soil properties within coffee plantations, which directly or indirectly affects pest incidences and development [23,58].

Though shade has been linked to positive gains in the management of various pests, it is essential to consider its contribution to an increase or decrease in coffee diseases which can be region dependent. Proper shading is critical, as the resulting microclimate alterations may favor one species or stage of development or could be unfavorable to another species or developmental stage [59]. The use of shade to manage coffee pests and diseases is thus done by considering all pests present, to find the shading balance point where desired ecological control mechanisms are promoted, adverse effects are minimized, and farmer's preference is incorporated.

5.3. Biological Control

Biological control involves the use of whole or parts of living organisms to lower the population of pests [60]. Studies on biological control of CLR have been ongoing for several decades [31,61,62]. Despite numerous studies on the biological control of CLR, there are very limited classical applications of biocontrol agents in Kenya. Commercial production of biologically based products for the management of CLR in Kenya has also been very insignificant. There is currently only one product that has been tested, approved, and is commercially available for use by farmers, Serande ASO® consisting of *Bacillus subtilis* strain QST 713 1.34% *w/w*. Despite the slow uptake of biological control at the farm level, successful laboratory studies have isolated and identified potential biocontrol agents that can be used to manage CLR. Studies in this area are ongoing at Coffee Research Institute, Kenya.

5.4. Chemical Control

Coffee Leaf Rust is effectively managed by timely application of fungicides and their use in Kenya started in 1960 [44]. The fungicides that are currently registered for use to manage the disease in Kenya are listed on the Pest Control Products Board (PCPB) website and the list is frequently updated (https://www.pcpb.or.ke, accessed on 25 November 2021).Timely application of chemical control is critical in its success as it largely depends on the disease-pathogenesis stage at the moment when the fungicide is applied [63]. Copper-based fungicides such as Bordeaux and Burgundy mixtures were established to manage CLR by the last decade of the 19th century [45,64]. Cuprous oxide is still being used in many formulations such as Nordox 50WP, Nordox Super 75WP, and Nordox 75WG [36]. Copper hydroxide (commonly known as blue copper) and Copper oxychloride (Green copper) were later introduced to manage CLR [64,65] while more recently, copper sulfate has been introduced. The main chemical families are coppers, Iprodione, Vinclozolin, and Chlorothalonil Benzimidazoles (Thiabendazole), sterol inhibitors (Triadimefon, Cyproconazole, Hexaconazole, and Propiconazole), and the most recently introduced Strobilurin (Trifoxystrobin, Pyraclostrobin, and Azoxystrobin) [63]. The use of these compounds needs to be alternated to avoid the development of tolerant strains of the pathogen as was found early in the management of Coffee Berry Disease (CBD) using benzimidazole in Kenya [66]. Furthermore, there is a wave of banning various pesticides as more information on their effects on humans, ecosystems, and the environment is being reported and countries adopt different assessment methods [67].

Before a fungicide is introduced into the Kenyan market for use in coffee, Coffee Research Institute (CRI) undertakes field efficacy trials for the management of CLR on behalf of the Pest Control Products Board (PCPB). After evaluation, PCPB uses the CRI report to register the fungicide and provides farmers with a list of registered products, indicating the recommended rates as well as the proper timing of application. Following the rainfall patterns in the main coffee growing regions, fungicide sprays for CLR control in Kenya starts in mid-October, just before the start of short rains followed by a second spray, three weeks after the first spray [35,44]. These two sprays reduce the production of new spores leading to low inoculum potential at the beginning of the long rains [67]. For the long rain period, the first spray is applied in late February or early March followed by one or two sprays at three weeks intervals for copper formulations and four-week intervals for

other formulations. Systemic formulations are applied only twice in a season to reduce the risk of the development of resistance. However, the spray program needs to be monitored and varied in response to weather patterns [67] because climate change is affecting the rainfall amounts and distribution.

6. Conclusions

Coffee Leaf Rust is a major threat to profitable and sustainable coffee production all over the world. Research work at national and international levels continues to provide options for managing the disease but new challenges do arise. These include global warming that makes hitherto unsuitable areas to be suitable for the disease, breaking of host resistance, customer, and environmentalists' demand for reduced use of fungicides, and potential tolerance of the pathogen to some fungicides. More work is required to keep abreast with the dynamics of the disease and develop more options such as biological control to manage the disease. It remains a constant concern that the pathogen may break the resistance of the two resistant varieties released for commercial production in Kenya. Integrated disease management combining resistant varieties, biological control agents, cultural practices, and judicious chemical control will offer an effective and sustainable CLR management strategy. Future research focus needs to address the above issues to sustain the productivity and profitability of coffee farming. This is best achieved in an integrated approach in managing the disease with an international exchange of knowledge and biological materials.

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