World Journal of Agricultural Sciences 17 (5): 418-429, 2021
ISSN 1817-3047

DOI: 10.5829/idosi.wjas.2021.418.429

Coffee Leaf Rust Disease and Climate Change

Yitagesu Tadesse, Dereje Amare and Asela Kesho

Ethiopian Institute of Agricultural Research,
Holetta Agricultural Research Center, Addis Ababa, Ethiopia

Abstract: Coffee is the most important agricultural commodity and second most valuable commodity exported by developing countries. Despite the largest share in production and economic contribution, *C. arabicais* prone to several diseases among them coffee leaf rust (CLR) is the most destructive coffee disease in the world. It causes losses of 1-2 billion USD annually and is one of the main limiting factors of Arabica coffee production worldwide. Climate change threatens crop yields, both directly through changes in plant growth and production and indirectly through impacts on crop diseases. It has been estimated that changes in climate have already been reducing global agricultural production by 1-5% per decade over the last 30 years. CLR was not problematic above 1000 m.a.s.l until the post-2011 epidemic, when CLR infestations of equal intensity were observed from 400 to 1400 m.a.s.l due to climate change. The primary weather-related variables that affect CLR include temperature, moisture and wind. As average minimum temperatures increase, the incidence and severity of CLR epidemics also increases, more areas at higher elevations likely will become favorable to CLR. Moisture plays a key role in the progress of CLR, affecting the germination, infection and spread of spores and the overall health of the coffee plants. Understanding the climate and weather connections to CLR outbreaks may allow farmers to prepare for and manage the disease more effectively and ultimately reduce crop losses. In future, further research will be focused on discovering climate change adaptation strategies feasible for smallholder producers for practically implement.

Key words: *Coffee arabica* · Coffee Leaf Rust · *Hemileia vastatrix* · Climate change · Temperature

INTRODUCTION

Coffee is the most important agricultural commodity; worth an estimated retail value 70 billion USD, crucial for the economy of more than 70 countries. Coffee is the second most valuable commodity exported by developing countries [1, 2]. There are more than 100 coffee species but only two, *Coffea arabica* (Arabica) and *Coffea canephora* (Robusta), are commercially used for the production of coffee as a beverage.

Despite the largest share in production and economic contribution, *C. arabica* is prone to several diseases among which coffee berry disease (CBD), coffee wilt disease (CWD) and coffee leaf rust (CLR) caused by C*olletotrichum kahawae* Waller and Bridge, *Gibberella xylarioides* (Steyaert) Heim and Saccas and *Hemileia vastatrix* Berk. and Br., respectively, are the major fungal diseases [3, 4].

Coffee leaf rust (CLR) is the most destructive coffee disease in the world and has negatively impacted coffee production since the late 1800s [5]. CLR causes losses of 1-2 billion USD annually and is one of the main limiting factors of Arabica coffee (*Coffea arabica*) production worldwide [5]. CLR was first recorded by an English explorer in 1861 near Lake Vitoria (East Africa) on wild *Coffea* species. Soon after its first report, the disease wiped out coffee cultivation from Ceylon (Sri Lanka), with devastating social and economic consequences [6]. The pathogen affects living leaves and causes chlorotic lesions on the underside of the leaves. This reduces the photosynthetic area and in severe attacks, defoliation of leaves leading to die-back of branches with heavy losses for farmers. CLR damages coffee plants and decreases yields, which in turn reduces labor, influences wages, affects market prices and inhibits farmers' ability to manage their farms. The cumulative effects reduce farmer

Corresponding Author: Dereje Amare, Ethiopian Institute of Agricultural Research,
Holleta Agricultural Research Center, Addis Ababa, Ethiopia.

income, affecting livelihoods and food security and force some to abandon their farms or switch to different crops altogether [7].

Nine major dominant resistance factors to *H. vastatrix* have been so far inferred on the basis of the gene-for-gene concept. The resistance to leaf rust of coffee plants therefore appears to be conditioned by at least nine resistance genes designated as SH1–SH9, either singly or in combination, while the corresponding virulence have been indicated as V1–V9 [8]. This allows coffee genotypes to be classified in resistant groups according to the physiological races of the rust pathogen [9]. Of the 9 resistance factors, SH1, SH2, SH4 and SH5 have been found in *C. arabica*. The other genes, SH6, SH7, SH8 and SH9, have been introgressed from the diploid species *C. canephora*, while SH3 probably originates from another diploid species, *C. liberica*.

In the second half of the 20th century, the identification and characterization of “Híbrido de Timor” (HDT) populations provided the basis for a breeding program that enabled the release of rust-resistant cultivars in different coffee growing countries, including the Americas [10, 11]. CLR epidemics have been particularly damaging in Latin American and the Caribbean [12]. In 2012–2013, CLR epidemics cost farmers in these regions an estimated $500 million in lost production alone and led to reduced production for at least two years [12, 13].

Climate change threatens crop yields, both directly through changes in plant growth and production and indirectly through impacts on crop diseases. It has been estimated that changes in climate have already been reducing global agricultural production by 1-5% per decade over the last 30 years [14]. Climate change affects pathogen biology not only directly but also indirectly through effects on host development and phenology. Climate change will influence the occurrence and development of crop diseases and alter the geographical distribution of pathogenic species [15, 16]. Milder winters could favor the cold-season survival of fungal foliar pathogens and higher minimum temperatures could generate early spring infections. However, an increase in the variability of rainfall patterns will affect the pathogens differently, depending on whether they require free water or saturated humidity to initiate the infection process [17, 18]. Many pathogens are likely to shift their geographic distribution through bioclimatic niche expansion or higher latitudes spread [19].

Recently CLR regained notoriety as the result of a severe and widespread epidemic throughout Central America, Colombia, Peru and Ecuador, due to the convergence of several agronomic, climatic and economic factors [12, 20, 21]. Yield losses were up to 35%, with a direct impact on the income and livelihood of hundreds of thousands of farmers and laborers. The pathogen can cause foliage loss up to 50% and berries up to 70% [22].

Plant pathogens, including fungi, bacteria and viruses are significant biotic limitations to production in managed agricultural and forest systems. Temperature, relative humidity and precipitation are major factors contributing to the incidence and severity of plant diseases. Many plant pathogens co-evolved with their hosts, developing optimal growth conditions in concurrence, so that outbreaks may occur under otherwise optimal agronomic conditions [23]. Plant pathogens can thrive in high moisture environments, which favor establishment, growth and infection of susceptible hosts. Moderate rain events can increase disease in susceptible crops, as fungal spores are splash-dispersed onto wet plant surfaces [24].

The production of coffee declined by around 40% due to a severe CLR outbreak that occurred across Colombia and neighboring Latin American countries from 2008 to 2013 [12]. Several hypotheses have been proposed to explain the recent CLR outbreak, including the evolution of a new, virulent race of the pathogen, changes in plantation management regimes promoting disease development and favorable weather conditions due to climate change [12]. Presently, coffee farmers from Colombia to Mexico are experiencing massive infestation and as a result, big losses in yield. Recorded yield losses from the Latin American region alone were 25% in the year 2013 [25]. From Mexico to Peru farmers were experienced 40-50% reduction yield [25, 26]. Thus, the objective of this review was to integrate climate variability and its effect on CLR diseases and to express the need for research in this area.

Taxonomy and Phylogeny of CLR: The genus *Hemileia* is a member of the phylum Basidiomycota, class Pucciniomycetes, order Pucciniales (rust fungi). Currently, more than 50 rust physiological races and 23 coffee differentials have been identified [10, 27]. Races are attributed to isolates with distinct and unique combinations of virulence genes as inferred by Flor’s gene-to-gene theory and described as sequential roman numerals in order of detection [28]. Thus, as no further genetic confirmation has been possible so far, inferred rust race genotypes comprise virulence genes ranging from v1 to v9 in isolates derived from *C. arabica* and tetraploid interspecific hybrids, while those of the races that attack diploid coffee species are not known. Within the scale of coffee differentials, race II (v5) presents the most restricted infection spectrum and is considered the most common and widespread rust race in the world, acquiring a generalized occurrence probably as a consequence of the uniform genetic background of most *C. arabica* cultivars worldwide [29].

Epidemiology: The perennial nature of *C. arabica* and its distribution around the equator ensures the presence of CLR throughout the year without a closed season unlike other rusts which undergo a period of survival [30]. Genetically susceptible coffee plants in rust conducive environments can be attacked at any growth stages [10]. However, since the spores of the pathogen germinate only in the presence of free water, epidemics are prevalent during the wet season.

Rainy spells show an increase in the spread of the disease and period of intense infection corresponds to those of high rainfall [31]. Generally, the pattern of rainfall determines the pattern of CLR development. In Kenya, to the east of Rift Valley, where there are two periods of rainy seasons, the rust progress curve also had two peaks as against one peak to the west of Rift Valley where there was only one season or rain was continuous [32]. In Ethiopia, onset of rust in monomodial rainfall at high altitude is October to January with peak period in November to December while in lower altitudes rust increase from August to November with peak in September [33]. Other researchers reported the occurrence of maximum rust incidence in November to December [34].

When free water is present, the level of temperature determines the rate of germination and penetration processes. The seasonal and daily fluctuation in temperature affects the rate of disease development. Within minimum and maximum limit, the lower and higher temperatures extend and reduce the latent periods, respectively. At very low temperature (< 10°C) and very high temperature (> 35°C) lesion enlargement is inhibited and often ends up as chlorotic lesion and perhaps completely inhibit infection [30, 35, 36].

Altitude influence local climatic conditions, which in turn affect the development of the disease. CLR intensity was reported to decrease with altitude in Kenya [32], in southern American continents [35] in Pauna New Guinea [36] and in Ethiopia [33, 37]. Coffee management practices also influence the epidemics of CLR development. According to Avelino *et al.* [38], the effect of coffee management practices on infection is through variation in fruit load of coffee trees and high yielding years are generally conducive to rust infection. On the other hand, the humidity generated by the presence of shade trees generally favor propagation of leaf rust disease with a ratio of intensity that increases with the density of canopy [31].

CLR Life Cycle: The fungus begins its life cycle as a microscopic spore. Spores deposited on the underside of a coffee leaf during favorable weather conditions will germinate and infect the leaf, penetrating it through the stomata and growing, or colonizing the leaf, to extract nutrients [39, 40]. Once the spores begin germinating, the infection process usually is completed within 24 to 48 hours, provided there is a continuous presence of moisture and the temperature ranges between 15 and 30°C. After infection, the fungus will grow and produce new spores in about three to four weeks [41]. The time needed for germination, infection and the production of new spores and the extent of the infection are largely determined by weather conditions, particularly temperature and moisture [38]. As other biotrophic fungus, the infection process of *H. vastatrix* on coffee leaves involves specific events including appressorium formation over stomata, penetration into the leaf and colonization of living host cells by intracellular specialized fungal structures (haustoria) that penetrate the plant cell wall and allow nutrient uptake.

Symptom and Damage of Coffee Leaf Rust: The first symptom of coffee leaf rust disease is small discolored spots which develop on the underside of the leaves. These small spots increase in size and are powdered with spores of the pathogen ranging in color from yellowish orange to bright orange [31]. Observable symptoms are small, pale yellow spots on the upper surfaces of the leaves. As these spots gradually increase in diameter, masses of orange urediniospores (= uredospores) appear on the under surfaces. The powdery lesions on the undersides of the leaves can be orange-yellow to red-orange in color and there is considerable variation from one region to another. While the lesions can develop anywhere on the leaf, they tend to be concentrated around the margins, where dew and rain droplets collect. The centers of the spots eventually dry and turn brown, while the margins of the lesions continue to expand and produce urediniospores.

Early in the season, the first lesions usually appear on the lowermost leaves and the infection slowly progresses upward in the tree. The infected leaves drop prematurely, leaving long expanses of twigs devoid of leaves. When a coffee plant does not have the optimal amount of leaf area, it does not have the ability to accumulate adequate energy via photosynthesis and store up the appropriate resources for fruit production.

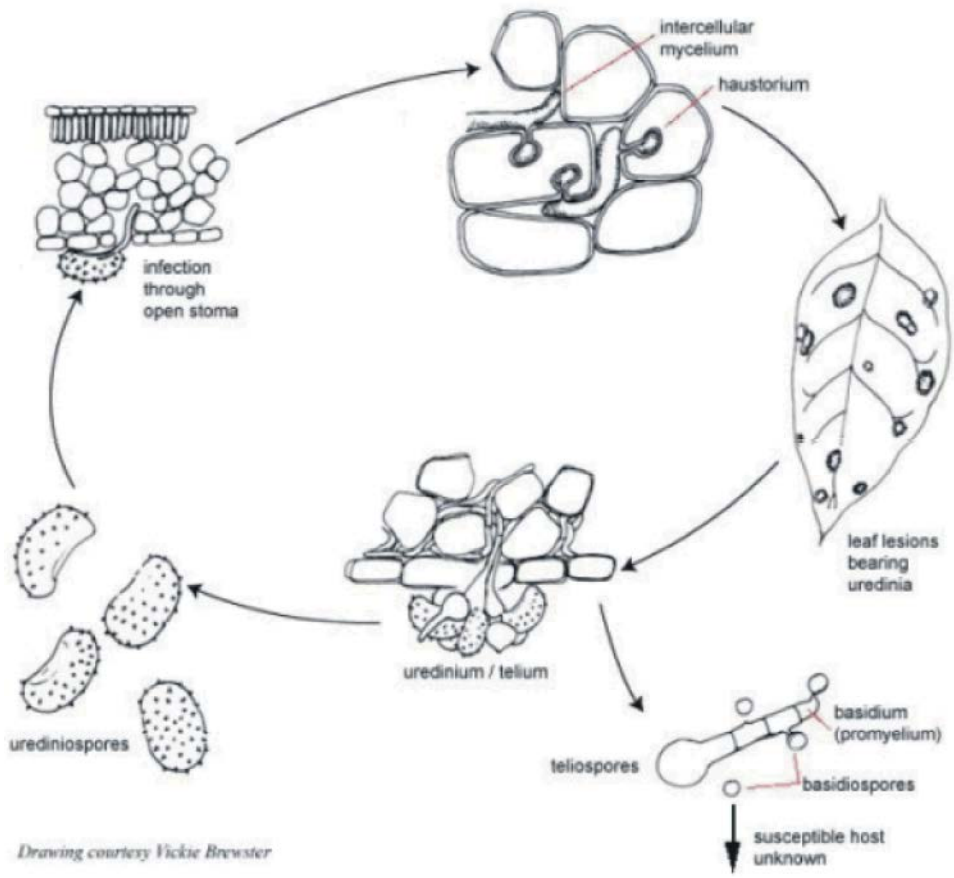

Fig. 1: Life cycle of *Hemileia vastatrix*. Drawing from: (www.apsnet.org/online/feature/edcenter)

In severe cases the fungus can present on young leaf buds or fruits. This is why there is generally a loss of yield even the year after rust outbreaks [38].

Climate, Weather and Coffee Leaf Rust: Climate change will influence the occurrence and development of crop diseases and alter the geographical distribution of pathogenic species [15, 16]. Milder winters could favor the cold-season survival of fungal foliar pathogens and higher minimum temperatures could generate early spring infections. However, an increase in the variability of rainfall patterns will affect these pathogens differently, depending on whether they require free water or saturated humidity to initiate the infection process [17, 18].

Many pathogens are likely to shift their geographic distribution through bioclimatic niche expansion or higher latitudes spread [19, 42]. Various factors could be put forward to explain the pace of pathogen emergence and spread such as domestication of ecosystems and human activities through trade and travel [43, 44]. Moreover, complex changes in crops and agricultural practices may result in future changes in both pathogen diversity and pathogen threats. However, climate change and increased climate variability are already available to assess the direct impacts of climate change on the distribution and importance of certain pathogens [19, 45].

Climate influences the incidence as well as temporal and spatial distribution of plant diseases. The main factors that control growth and development of diseases are temperature, light and water; similarly these factors affect type and condition of host crop [46, 47]. The environment may affect plant pathogen, therefore, survival, vigor, rate of multiplication, sporulation, direction, distance of dispersal of inoculums , rate of spore germination and penetration can be affected [48, 49].

Climate change will affect temperature, precipitation, CO_2 levels and frequency of extreme weather events, so these will have a significant effect on agricultural production and the temporal and spatial distribution of pests and diseases [50]. Climate change will also affect crop yields by altering rainfall and temperatures, but also by enhancing the growth of plant pathogens. Prior to the post-2011 CLR epidemic farmers considered small losses

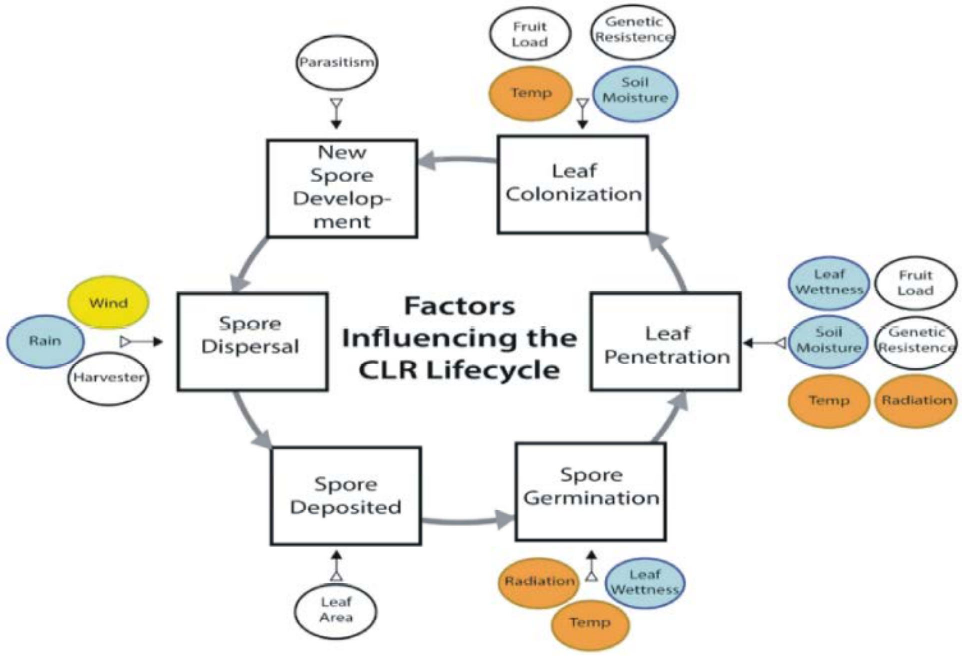

Fig. 2: Influence of climate and weather variables on different CLR life cycle stages
Sources: Avelino *et al*. 2014

to CLR normal and expected. CLR was not problematic above 1000 m. a. s. l until the post-2011 epidemic, when CLR infestations of equal intensity were observed from 400 to 1400 m a s l [12].

For example, rising temperatures threaten coffee tree plantations by boosting the fungal pathogen *Hemileia vastatrix*, infiltrates the leaves of coffee trees, defoliating them and often killing the tree. However, because the fungus cannot survive below 10°C, trees planted at higher elevations have historically been safe from this blight. “Until recently, rust only appeared below 1, 300 m altitude; cooler temperatures protected higher altitude plantings from the disease [51].

The primary weather-related variables that affect CLR include temperature, moisture and wind. These variables influence CLR at difference stages in its life cycle: temperature affects germination, infection and the time required for the fungus to produce new spores; moisture (in the form of soil moisture, leaf wetness, or rainfall) affects germination, infection and spore dispersal; and wind primarily affects dispersal, though it can influence temperature and moisture as well.

Temperature: Temperatures in tropical highlands are increasing and this terrain is experiencing earlier and heavier rainfall, allowing *H. vastatrix* to grow at higher altitudes than ever before. Since 2012, Central America has been struck with an epidemic of coffee rust that is badly damaging trees and undercutting local coffee-dependent economies. Rust has been in the Americas for over 40 years, but never affected more than 5% of the crop. In 2013 the incidence was 53% [51].

Temperature plays a significant role in several lifecycle states, in addition to affecting pathogen survival and the plant’s ability to respond to the infection [52, 53]. Temperature most strongly influences germination and infection (i.e. penetration and colonization). Specifically, during germination, CLR is most affected by daily minimum and maximum temperatures, diurnal temperature variation (the difference between the high and low temperatures that occur during the same day) and the frequency of cold nights and warm days. Optimal temperatures for spore germination and infection are between about 21 and 25°C [54, 55]. Temperatures below 18°C and above 28°C delay the production of new spores [41], while temperatures below 15°C and above 30°C more severely suppress germination and infection [30, 54, 55]. As average minimum temperatures (typically experienced at night) increase, the incidence and severity of CLR epidemics also increases. Conversely, the more frequently temperatures fall below the minimum threshold of 15°C, the lower the infection rate and severity of CLR. With the expectation that temperatures will continue to rise in the future, more areas at higher elevations likely will become favorable to CLR [53].

Since the last century, scientists have predicted that global temperature would rise due to an increase in the concentration of greenhouse gases in the atmosphere from natural and anthropogenic sources [14]. In the past 150 years, the average surface temperature has increased by 0.76°C and could increase from 2.4 to 6.4°C in the period of 2090-2099 relative to 1980 to 1999 [14]. High atmospheric CO_2 concentrations, temperatures and changes in precipitation patterns as well as the frequency of extreme weather phenomena will significantly affect crop grow and production and therefore the presence of diseases will be altered under these conditions [56]. This change highlights the role climate has played in the CLR outbreak and will play in the future. Warmer temperatures are expanding the range of CLR to higher altitudes. Ghini *et al*. [57] observe that warmer minimum temperatures contribute to a reduction in diurnal range, thus reducing the latency period for CLR and increases epidemic intensity. Reduction in diurnal range is a key and consistent factor proceeding CLR epidemics [12]. Average global surface temperatures have increased by nearly 0.98°C in the century to 2015 GISTEMP [58], accompanied by significant changes in the dynamics of the oceans and atmosphere IPCC. Wild populations of plants and animals have shifted their geographical ranges and phenologies in response [59] and changes in crop–pathogen interactions mediated by altered climates are thus a reasonable expectation [60, 61].

Increase in temperatures with sufficient soil moisture may increase evapo-transpiration resulting in humid microclimate in crop and may lead to incidence of diseases favored under these conditions [62]. As the temperature increases, the duration of winter and the rate of growth and reproduction of pathogens may be modified [63]. Drought and temperature stress have been shown to negatively affect a plant's ability to respond to biotic stresses via changes in endogenous abscisic acid levels that affect defense responses involving salicylic acid, jasmonic acid, or ethylene [64].

CLR outbreaks in Colombia in 2012–2013 have been attributed in part to above-normal minimum temperatures and below-normal maximum temperatures [65]. This period was associated with La Niña conditions; for Colombia, other parts of northern South America, Central America and the Caribbean, that meant increased cloud cover and precipitation and thus decreased solar radiation and a narrower range between daily maximum and minimum temperatures [65]. These conditions led to more days with optimal conditions for CLR proliferation and potentially to shorter periods between plant infection and the development of new spores that could infect plants [66].

Moisture: Moisture plays a key role in the progress of CLR, affecting the germination, infection and spread of spores and the overall health of the coffee plants [67]. Although high humidity (greater than 80 percent) for 24 hours or longer increases spore germination and rust infection [68], humidity by itself in the absence of free water is not enough [54, 67]. Free water on the leaves for at least six hours is necessary for spore germination and infection, although germination alone can occur in as little as three hours if spores are fresh and conditions are optimal and continuous leaf wetness for 20 hours is optimal for high infection rates greater than 80 percent [54]. Additionally, the longer leaves remain wet, the greater the severity of the disease and thus damage to the plant [41]. Water also plays a critical role in the local dispersal of CLR spores. When it rains, rust spores are dislodged from leaves and carried in water droplets to other leaves on the same plant or sometimes to other plants. This mechanism is known as "rain splash" and is responsible for CLR spore dispersal over short distances [69].

Changes in the onset of rainy seasons may also affect CLR and plant health, where early onset of rains may extend the growing season for CLR and late onset may stress plants, making them more vulnerable to diseases [66]. CLR outbreaks in Latin America in recent years have been associated with an earlier onset of the rainy season and also may have allowed CLR to proliferate more than in previous years [66].

Wind: Wind plays an important role in spore dispersal and may also affect leaf wetness and overall plant health. Wind needs to be sufficiently strong (greater than about 7mph) to dislodge spores from leaves and transport them to other plants and higher speed winds tend to transport larger quantities of spores than slower winds [70]. Wind can also affect plant health. Storms and hurricanes often severely damage coffee trees and reduce coffee yields [71]. Plants that are stressed by storm damage may be more susceptible to CLR and other disease.

In general, high moisture and temperature must be favorable and act together in the initiation, development of plant diseases, as well as germination and proliferation of fungal spores of the vast majority of pathogens [47]. Due to changes in temperature and precipitation regimes, climate change may alter the growth stage, development rate and pathogenicity of infectious agents and the physiology and resistance of the host plant [72]. A change in temperature may favor the development of different inactive pathogens, which could induce an epidemic.

Other Factors Influencing CLR: In addition to climate and weather, a number of other factors related to agricultural practices and other environmental stressors influence incidence and severity of CLR in any given place or time. These include coffee plant exposure to shade or sun, the density of coffee plants, the amount of viable CLR spores remaining from the previous year, soil quality and human dispersal of spores. Additionally, some varieties of coffee particularly Arabica are more susceptible to infection than others. Shade can create optimal temperature and moisture conditions for CLR, with the exception of dew, which tends to be less prevalent in shade [38], but has differing effects on spore dispersal depending on moisture conditions. Shade suppresses CLR by decreasing stomatal density [38], which creates optimal conditions for another fungus, *Lecanicillium lacanii*, a natural parasite of the CLR fungus [73] and by reducing coffee crop yield [67, 74]. Higher yield, or "fruit load, " is associated with higher incidence of CLR and because fruit loads tend to be lower under shade, shade can reduce the incidence of CLR [67, 74]. When berries are removed before they ripen, the severity of the infection decreases, possibly because the plants can contribute more toward resistance instead of fruiting [35].

Leaves in full sun are more susceptible to CLR than leaves in the shade [75]. Conversely, shade can increase the incidence and/or severity of CLR by reducing solar radiation reaching the coffee plants and increasing leaf size, which increases the surface area of leafs onto which CLR spores can land [38].

Farms with high coffee plant density tend to experience more frequent and severe disease outbreaks [35], possibly because the rust spores are easily transmitted from one plant to another, making control difficult [76].Although wind and rain splash are important dispersal mechanisms of CLR spores, humans have also played an important role in spore dispersal over both short and long distances.

CLR Disease Management: Several factors may strongly influence coffee rust epidemics such as: shade status, coffee tree density, fertilization and pruning since they produce effects on microclimate and plant physiology which, in turn, influence the life cycle of the fungus. These factors should be considered in crop management depending if coffee is cultivated in intensive or extensive plantation [38].

Disease Resistance Breeding: Breeding coffee plants for resistance to rust is considered the best disease management strategy both environmentally and economically [11]. The first effective effort to select resistant germ plasm was conducted in India in 1911, giving rise to the release of the cultivar 'Kent's', which replaced the susceptible cultivar 'Coorg' [10]. Several missions to Ethiopia were subsequently conducted, but no effective resistance sources were identified [10]. In the 1950s, concern for the potential introduction of rust into the American continent led F. Wellman and W. Cow gill to conduct field missions in the Eastern Hemisphere, collecting more than 100 coffee types new to the Americas. In collaboration with Branquinhod' Oliveira, the work of these researchers led the USA and Portuguese governments to provide financial support for the creation of the Coffee Rusts Research Center (CIFC, Centro de Investigação das Ferrugens do Cafeeiro) in Portugal, located far from coffee-growing regions and thus centralizing research on CLR at the international level. Since 1955, CIFC has received and characterized coffee and rust germplasm and supplied breeding programmes at coffee research institutions with characterized resistance sources, along with scientific and technical information and training. HDT (Híbrido de Timor) populations derived from a plant discovered on the island of Timor in 1927 exhibiting resistance to rust among 'Typica' coffee crops [29]. In the 1950s, these populations were shown to be natural hybrids between C. *arabica* and C. *canephora*, most of them offering resistance to all rust races known at that time [10]. The importance of HDT populations as resistance sources relies on the long durability of some of these resistance factors, which in some cases resistances have been in use for more than 30 years. In Ethiopia 8136, 7516 and 1579 coffee cultivars showed resistant reaction for CLR [77].

Biological Control: With coffee rust insects, mites and various fungal species have been reported. Insects and mites may reduce rust spore load through direct feeding of the urediniospores but could also be important disseminators of urediniospores [78]. Among fungal species reported as hyperparasites, *Verticillium lecanii* is the most common ones occurring in many countries. *H. vastatrix* spores are hyperparasitised by the Ascomycete fungus *Lecanicillium lecanii*. Although unable to effectively control CLR, this hyperparasite is capable of reducing spore viability and disease severity [25]. *Lecanicillium lecanii* is primarily an entomopathogen of the green coffee scale *Coccus viridis*, which in turn has a mutualistic association with the arboreal nesting ant *Azteca instabilis*. The relationships between these organisms suggest that complex ecological interactions may play an important role in disease incidence and severity, potentially explaining why CLR is sometimes a severe epidemic and other times a troublesome but not devastating problem [25]. A significant reduction in leaf rust severity by the presence of *Verticillium psalliotae*, especially when was applied 24 hours before the inoculation of *H. vastatrix*, demonstrated an evidence parasitism *in vivo* [79]. It has been showed that the hyperparasitic fungus *Verticillium hemileia* is able to colonize the coffee rust lesions and reduces the viability of the urediniospores, but it has very little impact on overall rust development [80]. *Pseudomonas* and mainly *Bacillus s*pp. were efficient in reducing the intensity of leaf rust under field conditions as effectively as copper hydroxide but many studies, including toxicological ones, are still required to prove the effectiveness and the safety to use these agents in biological control of CLR [81]. However, there was no complete report in the field experiment regarding its mass production, application and efficacy [78].

Chemical Control: Chemical control of CLR is the obvious choice in the absence of a resistance genotype and of other effective disease management strategies. Copper-containing fungicides are very effective in controlling coffee rust. In *Coffea arabica*, the recommended number of fungicide applications to control coffee leaf rust is four to five with copper fungicides or one to three applications of systemic fungicides from triazol group or triazo-formulated with estrobilurins. Preventive treatments are typically carried out with copper-based fungicides, while curative treatments are conducted with systemic fungicides (e.g., epoxiconazole, pyraclostrobin). The combined or alternate use of copper-based and systemic fungicides is advised to avoid the risk of selecting fungicide-resistant rust populations [41].

CONCLUSIONS

In spite of its destructiveness, worldwide distribution and economic impact on the production of such an important cash crop as coffee, *Hemileia vastatrix* has not been as widely studied as other rust fungi. The ability of farmers to manage CLR requires identifying early signs of the disease and being able to respond accordingly. Understanding the climate and weather connections to CLR outbreaks may allow farmers to prepare for and manage the disease more effectively and ultimately reduce crop losses. Understanding the climate CLR connection is especially important given that global climate change is likely to affect the incidence and severity of the disease in the near future. Generally, further research will be focused on discovering climate change adaptation strategies feasible for smallholder producers for practically implement.

REFERENCES

1. Hoffmann, J., 2014. The World Atlas of Coffee: From beans to brewing-coffees explored, explained and enjoyed. Hachette UK.
2. International Coffee Organization (ICO), 2016. World Coffee Production. International Coffee Organization. <http://www.ico.org /prices/po-production.pdf>.
3. Hindorf, H., 1998. Current diseases of *Coffea arabica* and *C. canephora* in East Africa causing crop losses. Meded FacL and Bouwwet Univ. Gent, 63: 861-5.
4. Abdi, M. and J. Abu, 2015. Importance and Characterization of Coffee Berry Disease (*Colletotrichum kahawae*) in Borena and Guji Zones, Southern Ethiopia. Journal of Plant Pathology and Microbiology, 6: 1-6.
5. McCook, S., 2006. Global rust belt: *Hemileia vastatrix* and the ecological integration of world coffee production since 1850. Journal of Global History, 1(2): 177-195.
6. Morris, D., 1880. Note on the Structure and Habit of *Hemileia vastatrix*, the Coffee leaf rust Disease of Ceylon and Southern India. Botanical Journal of the Linnean Society, 17(104-105): 512-517.

7. World Coffee Research (WCR), 2014. Revitalizing the Central American Coffee Sectors after the Rust Crisis of 2012. Brief update and industry response through research and development.
8. Bettencourt, A.J., C.J. Clarke and R.R.J. Macrae, 1988. Principles and practice of coffee breeding for resistance to rust and other diseases Coffee, 4: Agronomy.
9. Herrera, J.C., G.A. Alvarado, G.H.A. Cortina, M.C. Combes, G.G. Romero and P. Lashermes, 2009. Genetic analysis of partial resistance to coffee leaf rust (*Hemileia vastatrix* Berk & Br.) introgressed into the cultivated *Coffea arabica* L. from the diploid *C. canephora* species. Euphytica, 167: 57-67.
10. Rodrigues Jr, C.J., A.J. Bettencourt and L. Rijo, 1975. Races of the pathogen and resistance to coffee rust. Annual Review of Phytopathology, 13(1): 49-70.
11. Silva, M.D.C., V. Várzea, L. Guerra-Guimarães, H.G. Azinheira, D.Fernandez, A.S. Petitot, B. Bertrand, P. Lashermes and M.Nicole, 2006. Coffee resistance to the main diseases: leaf rust and coffee berry disease. Brazilian Journal of Plant Physiology, 18(1): 119-147.
12. Avelino, J., M. Cristancho, S. Georgiou, P. Imbach, L. Aguilar, G. Bornemann, P. Läderach, F. Anzueto, A.J. Hruska and C. Morales, 2015. The coffee rust crises in Colombia and Central America (2008 2013): impacts, plausible causes and proposed solutions. Food Security, 7(2): 303-321.
13. International Coffee Organization (ICO), 2013. Report on the outbreak of coffee leaf rust in Central America and Action Plan to combat the pest. International Coffee Organization, Report 2157/13. May 13.
14. Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell and M.I. Travasso, 2014. Food security and food production systems. In Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Edited by Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC.et al.: Cambridge University Press, pp: 485-533.
15. Chakraborty, S. and A.C. Newton, 2011. Climate change plant diseases and food security: an overview. Plant Pathol., 60: 2-14.
16. Pautasso, M., T.F. Döring, M. Garbelotto, L. Pellis and M.J. Jeger, 2012. Impacts of climate change on plant diseases opinions and trends. European Journal of Plant Pathology, 133(1): 295-313.
17. Juroszek, P. and A. Von Tiedemann, 2011. Potential strategies and future requirements for plant disease management under a changing climate. Plant Pathology, 60(1): 100-112.
18. Pangga, I.B., J. Hanan and S. Chakraborty, 2011. Pathogen dynamics in a crop canopy and their evolution under changing climate. Plant Pathology, 60(1): 70-81.
19. Bebber, D.P., M.A. Ramotowski and S.J. Gurr, 2013. Crop pests and pathogens move polewards in a warming world. Nature Climate Change, 3(11): 985-988.
20. Rozo, Y., C. Escobar, Á. Gaitán and M. Cristancho, 2012. Aggressiveness and genetic diversity of *Hemileia vastatrix* during an epidemic in Colombia. Journal of Phytopathology, 160(11-12): 732-740.
21. Cressey, D., 2013. Coffee rust regains foothold. Nature, 494(7435).
22. Bhat, S.S., R. Naidu, S. Daivasikamani and Nirmala Kannan, 2000. Integrated disease management in coffee. In: IPM system in Agriculture Cash crops. Volume 6, edited by Upadhyay RK, Mukerji KG and Dubey OP, Aditya Books Private Limited (New Delhi, India), pp: 65-82.
23. Calonnec, A., J.B. Burie, M. Langlais, S. Guyader, S. Saint-Jean, I. Sache and B. Tivoli, 2013. Impacts of plant growth and architecture on pathogen processes and their consequences for epidemic behaviour. Eur. J. Plant Pathol., 135: 479-497.
24. Ziska, L.H. and G.B. Runion, 2007. Future weed, pest and disease problems for plants. In Agroeco-systems in a Changing Climate; Newton, P.C.D., Carran, R.A., Edwards, G.R., Niklaus, P.A., Eds.; CRC (Chemical Rubber Company) Press: Boca Raton, FL, USA, pp: 261-287.
25. Vandermeer, J., D. Jackson and I. Perfecto, 2014. Qualitative dynamics of the coffee rust epidemic: educating intuition with theoretical ecology. BioScience, 64(3): 210-218.
26. Martinati, J.C., R. Harakava, S.D. Guzzo and S.M. Tsai, 2008. The potential use of a silicon source as a component of an ecological management of coffee plants. Journal of Phytopathology, 156(7-8): 458 463.

27. Várzea, V.M.P., V.D. Marques, A.P. Pereira and M.C. Silva, 2009. The use of Sarchimor derivatives in coffee breeding resistance to leaf rust. In Proceedings of the 22nd International Conference on Coffee Science, Campinas, Brazil, 14-19 September 2008. ASIC, pp: 1424-1429.
28. Noronha-Wagner, M. and A.J. Bettencourt, 1967. Genetic Study of the Resistance of *Coffea* Spp. to Leaf Rust: I. Identification and Behavior of Four Factors Conditioning Disease Reaction in *Coffea arabica* to twelve Physiologic races of *Hemileia vastatrix*. Canadian Journal of Botany, 45(11): 2021-2031.
29. Bettencourt, A.J., 1981. Melhoramentogenético do cafeeiro; transferencia de factores de resistencia a *Hemileia vastatrix* Berk. & Br. para as principais cultivares deCoffea arabica L. Centro de Investigaçao das Ferrugens do Cafeeiro, Oeiras (Portugal).
30. Nutman, F.J., F.M. Roberts and R.T. Clarke, 1963. Studies on the biology of *Hemileia vastatrix* Berk. & Br. Transactions of the British Mycological Society, 46(1): 27-44.
31. Muller, R.A., D. Berry, J. Avelino and D. Biesse, 2004. Coffee disease. In: J. Wintgens (ed.). Coffee growing, processing, sustainable production: A guidebook for growers, processors and producers). WILEY-VcHVerlag GmbH & Co. kGaA. Weinheim.
32. Bock, K.R., 1962. Seasonal periodicity of coffee leaf rust and factors affecting the severity of outbreaks in Kenya Colony. Transactions of the British Mycological Society, 45(3): 289-300.
33. Meseret, W., 1991. Epidemiology and resistance of coffee leaf rust in Ethiopia. Ministry of Coffee and Tea Development. Addis Ababa, Ethiopia.
34. Eshetu, D., G. Teame and A. Girma, 2000. Significance of minor coffee diseases of *Coffea arabica* L. in Ethiopia; a review. pp: 58-64. Proceedings of the workshop on control of coffee berry disease in Ethiopia, 13-15 August 1999, Addis Ababa, Ethiopia.
35. Kushalappa, A.C. and A.B. Eskes, 1989. Advances in coffee rust research. Annual Review of Phytopathology, 27(1): 503-531.
36. Brown, J.S., M.K. Kenny, J.H. Whan and P.R. Merriman, 1995. The effect of temperature on the development of epidemics of coffee leaf rust in Papua New Guinea. Crop Protection, 14(8): 671-676.
37. Meseret, W., 1996. Coffee leaf rust epidemiology and management in Ethiopia. PhD dissertation, Imperial College of Science and Technology, London, pp: 304.
38. Avelino, J., L. Willocquet and S. Savary, 2004. Effects of crop management patterns on coffee rust epidemics. Plant pathology, 53(5): 541-547.
39. Nutman, F.J. and F.M. Roberts, 1970. Coffee leaf rust. PANS Pest Articles & News Summaries, 16(4): 606-624.
40. Kolmer, James A., Maria E. Ordonez and James V. Groth, 2009. "The rust fungi."eLS.
41. Zambolim, L., 2016. Current status and management of coffee leaf rust in Brazil. Tropical Plant Pathology, 41(1): 1-8.
42. Chakraborty, S., 2013. Migrate or evolve: options for plant pathogens under climate change. Global Change Biology, 19(7): 1985-2000.
43. Ali, S., P. Gladieux, M. Leconte, A. Gautier, A.F. Justesen, M.S. Hovmøller, J. Enjalbert and C. de Vallavieille-Pope, 2014. Origin, migration routes and worldwide population genetic structure of the wheat yellow rust pathogen *Puccinia striiformis* f. sp. tritici. PLoS Pathogens, 10(1): e1003903.
44. Bebber, D.P., T. Holmes, D. Smith and S.J. Gurr, 2014. Economic and physical determinants of the global distributions of crop pests and pathogens. New Phytologist, 202(3): 901-910.
45. Barbetti, M.J., S.S. Banga and P.A. Salisbury, 2012. Challenges for crop production and management from pathogen biodiversity and diseases under current and future climate scenarios-case study with oilseed Brassicas. Field Crops Research, 127: 225-240.
46. Rosenzweig, C., A. Iglesias, X.B. Yang, P.R. Epstein and E. Chivian, 2001. Climate change and extreme weather events; implications for food production, plant diseases and pests. Global Change & Human Health, 2(2): 90-104.
47. Agrios, G.N., 2005. Plant Pathology. 5th Ed. Elsevier, USA, pp: 922.
48. De Wolf, E.D. and S.A. Isard, 2007. Disease cycle approach to plant disease prediction. Annu. Rev. Phytopathol., 45: 203-220.
49. Kang, W.S., S.C. Yun and E.W. Park, 2010. Nonlinear regression analysis to determine infection models of *Colletotrichum acutatum* causing anthracnose of chili pepper using logistic equation. The Plant Pathology Journal, 26(1): 17-24.
50. Ghini, R., E. Hamada, P. Júnior, M. José, J.A. Marengo and R.R.D.V. Gonçalves, 2008. Risk analysis of climate change on coffee nematodes and leaf miner in Brazil. Pesquisa Agropecuária Brasileira, 43(2): 187-194.

51. Alvarado, G., M.C. Combes, G. Romero and P. Lashermes, 2009. Genetic analysis of partial resistance to coffee leaf rust (*Hemileia vastatrix* Berk& Br.) introgressed into the cultivated *Coffea arabica* L. from the diploid C. canephora species. Euphytica, 167(1): 57-67.
52. Sutton, J.C., T.J. Gillespie and P.D. Hildebrand, 1984. Monitoring weather factors in relation to plant disease. Plant Disease, 68(1): 78-84.
53. Alves, M.D.C., L.G. De Carvalho, E.A. Pozza, L. Sanches and J.D.S. Maia, 2011. Ecological zoning of soybean rust, coffee rust and banana black sigatoka based on Brazilian climate changes. Procedia Environmental Sciences, 6, 35-49.
54. Kushalappa, A.C., M. Akutsu and A. Ludwig, 1983. Application of survival ratio for monocyclic process of *Hemileia vastatrix* in predicting coffee rust infection rates. Phytopathology, 73(1): 96-103.
55. De Jong, E.J., A.B. Eskes, J.G.J. Hoogstraten and J.C. Zadoks, 1987. Temperature requirements for germination, germ tube growth and appressorium formation of urediospores of *Hemileia vastatrix*. Netherlands Journal of Plant Pathology, 93(2): 61-71.
56. Rosenzweig, C. and F.N. Tubiello , 2007. Adaptation and mitigation strategies in agriculture: an analysis of potential synergies. Mitig. Adapt. Strat. Glob. Change., 12: 855-873
57. Ghini, R., E. Hamada, P. Júnior, M. José and R.R.D.V. Gonçalves, 2011. Incubation period of *Hemileia vastatrix* in coffee plants in Brazil simulated under climate change. Summa Phytopathologica, 37(2): 85-93.
58. NASA Goddard Institute for Space Studies GISTEMP Team, GISS surface temperature analysis (GISTEMP). http://data.giss.nasa.gov/gistemp/ (accessed 15 July 2016).
59. Chen, I.C., J.K. Hill, R. Ohlemüller, D.B. Roy and C.D. Thomas, 2011. Rapid range shifts of species associated with high levels of climate warming. Science, 333(6045): 1024-1026.
60. Garrett, K.A., S.P. Dendy, E.E. Frank, M.N. Rouse and S.E. Travers, 2006. Climate change effects on plant disease: genomes to ecosystems. Annu. Rev. Phytopathol., 44: 489-509.
61. Bebber, D.P., 2015. Range-expanding pests and pathogens in a warming world. Annu. Rev. Phytopathol., 53: 335-356.
62. Mina, U. and P. Sinha, 2008. Effects of climate change on plant pathogens. Environ. News, 14(4): 6-10.
63. Ladányi, M. and L. Horváth, 2010. A Review of the Potential Climate Change Impact on Insect Populations- General and Agricultural Aspects. Applied Ecology and Environmental Research, 8(2): 143-152.
64. Asselbergh, B., D. De Vleesschauwer and M. Höfte, 2008. Global switches and fine-tuning-ABA modulates plant pathogen defense. Molecular Plant-Microbe Interactions, 21(6): 709-719.
65. Cristancho, M.A., Y. Rozo, C. Escobar, C.A. Rivillas and A.L. Gaitán, 2012. Outbreak of coffee leaf rust (*Hemileia vastatrix*) in Colombia. New Disease Reports, 25(19): 2044-0588.
66. Georgiou, S., P. Imbach, F. Anzueto, G. del Carmen Calderón and J. Avelino, 2014, December. Weather and climate indicators for coffee rust disease. In AGU Fall Meeting Abstracts.
67. Avelino, J., H. Zelaya, A.Merlo, A. Pineda, M. Ordoñez and S. Savary, 2006. The intensity of a coffee rust epidemic is dependent on production situations. Ecological Modelling, 197(3): 431-447.
68. Capucho, A.S., L. Zambolim, P.G.C. Cabral, E. Maciel-Zambolim and E.T. Caixeta, 2013. Climate favourability to leaf rust in Conilon coffee. Australasian Plant Pathology, 42(5): 511-514.
69. Boudrot, A., J. Pico, I. Merle, E. Granados, S. Vílchez, P. Tixier, E.D.M.V. Filho, F. Casanoves, A. Tapia, C. Allinne and R.A. Rice, 2016. Shade effects on the dispersal of airborne *Hemileiav astatrix* uredospores. Phytopathology, 106(6): 572-580.
70. Martinez, J.A., D.A. Palazzo and M. Karazawa, 1977. Importance of the wind in the release and dissemination of spores of *Hemileia vastatrix* Berk& Br. Fitopatologia Brasileira, 2(1): 35-42.
71. Eakin, H., K. Benessaiah, J.F. Barrera, G.M. Cruz-Bello and H. Morales, 2012. Livelihoods and landscapes at the threshold of change: disaster and resilience in a Chiapas coffee community. Regional Environmental Change, 12(3): 475-488.
72. Chakraborty, S. and S. Datta, 2003. How will plant pathogens adapt to host plant resistance at elevated CO_2 under a changing climate? New Phytol., 159: 733-742.
73. Jackson, D., J. Skillman and J. Vandermeer, 2012. Indirect biological control of the coffee leaf rust, *Hemileia vastatrix*, by the entomogenous fungus *Lecanicillium lecanii* in a complex coffee agroecosystem. Biological Control, 61(1): 89-97

74. Lopez-Bravo, D.F., E.D.M. Virginio-Filho and J. Avelino, 2012. Shade is conducive to coffee rust as compared to full sun exposure under standardized fruit load conditions. Crop Protection, 38: 21-29.
75. Eskes, A.B., 1982. The effect of light intensity on incomplete resistance of coffee to *Hemileia vastatrix*. Netherlands Journal of Plant Pathology, 88(5): 191-202.
76. Paiva, B.R.T.L., P.E.D. Souza, M.S. Scalco and L.A. Santos, 2011. Progress of rust in coffee plants in various densities of cultivation in irrigated planting after pruning. Ciência e Agrotecnologia, 35(1): 137-143.
77. Adugna, G., C. Jefuka, D. Teferi and A. Zeru, 2009. Multiple resistances to coffee berry disease, coffee wilt and leaf rust in *Coffea arabica* populations. In 22nd International Conference on Coffee Science, ASIC 2008, Campinas, SP, Brazil, 14-19 September, 2008 (pp: 1454-1462). Association Scientifique Internationale du Café (ASIC).
78. Eskes, A.B., 1989b. Natural enemies and biological control. pp: 161-169. In: A.C. Kushalappa and A.B. Eskes, (eds.). Coffee rust: Epidemiology, Resistance and Management; CRC Press Inc., Florida.
79. Mahfud, M.C., Z.A. Mior Ahmad, S. Meon and J. Kadir, 2006. *In vitro* and *in vivo* tests for parasitism of *Verticillium psalliotaeon Hemileia vastatrix* Berk. and Br. Malaysian Journal of Microbiology, 2(1): 46-50.
80. Eskes, A.B., M.D.L. Mendes and C.F. Robbs, 1991. Laboratory and field studies on parasitism of *Hemileia vastatrix* with *Verticillium lecanii* and *V. leptobactrum*. Café Cacao Tea XXXV, 4: 275-282.
81. Haddad, F., L. Maffia, E. Mizubuti and H. Teixeira, 2009. Biological control of coffee rust by antagonistic acteria under field conditions in Brazil. Biological Control, pp: 114-119.