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Global Importance of Coffee Leaf Rust */Hemileia vastatrix/* on Coffee Industry and Its Management Options

Kifle Belachew Bekele

Plant Protection Department, Jimma Agricultural Research Centre, Ethiopian Institute of Agricultural Research, Jimma, Ethiopia

Email address:
kiflekef@gmail.com

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Abstract: In Global coffee industry, coffee leaf rust, a fungal disease caused by Hemileia vastatrix Berk. et Br., was first recorded in 1861 near Lake Vitoria (East Africa) on wild Coffea species. It is thought to have originated at wild Arabica coffee in its center of diversity at south-western part of Ethiopia. Its damage was first observed in cultivated coffee in Sri Lanka (Cylon) in 1868 and reported from India in 1869. Today, the disease is highly devastating at all coffee arabica and Coffea canephora coffee-growing countries, and continues to threaten coffee production with losses that range from 30 to 50%. Global crop loss due to this disease is estimated $1-2 Billion. Disease risk is increased in arabica coffee compared to canifora, and lower production is expected in the year following an epidemic due to early defoliation and drying of branches. Its control is still very difficult; however, several varieties were developed in the country using sources of resistance from germplasm collections in Portugal. However, very few are completely resistant, instead exhibiting various levels of partial resistance. The disease is currently damaging and its epidemics total change the livelihood of millions in Latin America and Africa. The review indicated that coffee leaf rust is the most devastating coffee disease in the World. Different coffee leaf rust disease management opthions are helpful to reduce it damage. Among these, use of resistant variety, cultural control, use of effective chemicals, biological control and integrated disease management options. From cultural management options, the use of organic soil fertility management was the most attractive option for resource poor small holder coffee farmers under without supplementary irrigation condition given that it reduces on both costs of inorganic chemical fertilizers and support the tolerance of coffee plant for disease and help in high yield.

Keywords: Coffee, Coffee Leaf Rust, Epidemiology, Hemileia Vastatrix, Importance

1. Introduction

Coffee (*Coffea spps)* is one of the most traded and consumed commodities worldwide with an estimated 2.4 billion cups consumed per day and an estimated retail value of 70 billion USD per annum [1]. It is crucial for the economy of more than 60 countries and is the main source of income for more than one hundred million people [1]. Its consumption rate increased in average 2.4% annually for the last 10 years [1]. The increase in the use of coffee as one of the best stimulant beverages, has favoured the expansion of coffee cultivation and commerce. At present, the two economic species of coffee, *C. arabica* L. (Arabica coffee) and *C. canephora* Pierre ex Froehne (robusta coffee), are grown in 80 countries in tropical and subtropical regions of Africa, Asia and Latin America [2].

Ethiopia is the leading producer in Africa, and the 5th in the world, following Brazil, Vietnam, Colombia and Indonesia and produces premium quality coffee. If we consider Arabica coffee alone, Ethiopia is the 3rd largest producer after Brazil and Colombia [1]. The country has the longest tradition of coffee consumption in the world with a traditional way of cultivation and the performance of inimitable coffee ceremony [3]. The country is the primary center of origin and genetic diversity of *C. arabica* L. and coffee is well known being the pillar of Ethiopian economy. In Ethiopia, coffee stands first among the top three agricultural exports, then follows oil seeds and pulses [4]. Coffee is accounting for 5% of the gross domestic product (GDP), 10% of the total national income, 12% of the agricultural economy, 42% of government taxes from foreign trade [3]. Moreover, it contribut to more than 29% of the total export and 37% of agricultural export earnings of the nation; more than 5 million small-holders directly involved in producing coffee and about 25 million people directly or indirectly depends on coffee sector for their livelihoods [3, 4].

Because of diverse agro ecology in Ethiopia, the crop can grow in an altitudes ranging from 500 masl in Gambella to 2300 masl in Wello [5]. According to CSA (2019), the total productive coffee area in Ethiopia is estimated at 764,863 hectare with annual total production of 494,574.36 tons and productivity of 646 kg/ha. According to ICO statistics, the production of Ethiopian coffee has been constantly increasing since 2000/01 harvest season. The annual production has hit the highest level of 8.10 million bags (= 449 thousand tons) in 2012/13 against 3.11 million bags (= 186.6 thousand tons) in 2000/01 cropping season. The productivity has also reportedly reached 748 kg/ha in 2014 crop season as indicated earlier against 300 – 500 kg/ha before a decade [3], however, the productivity reduced to 646 kg/ha in 2018 [4]. It is believed that the surge in production is largely attributed to the increase in cultivated area from 400,000 ha in the early 2000s to roughly 764,863 ha currently [4]. Ethiopia also has the largest highland area suitable for Arabica production and, hence has the potential to be a leading producer of coffee in both quality and quantity [3]. Nearly all coffees produced in Ethiopia are shade grown, with 40-60% canopy cover, except few home garden systems in Eastern Ethiopia. The coffee plants are also mainly either local varieties/ land races or of wild origin [3].

Considering the economic and social importance of the crop and the environmental problems associated with inappropriate use of pesticides, developing an effective and safe way of CLR management such as a cultural method which involve soil fertility management and supplementary irrigation [2] is very important. Such an integrated disease management approach can significantly help for better quality and quantity coffee yield for national and international market. Among the key requirements to achieve such a level is the development and validation of effective integrated disease management options which involve management of soil factors (fertility and moisture).

2. How CLR Damage Coffee

The symptom of coffee leaf rust disease is well understood and has been described by several authors [5, 6]. The first observed symptom of coffee leaf rust disease is small discolored spots which develop on the underside of the leaves. The small patches of pale yellow color (1–3 mm of diameter) appear and expand (up to 20 mm of diameter) on the abaxial side of the leaves. Uredinia form in the chlorotic spots where powdery-like yellowish-orange urediniospores are produced. Chlorotic yellow spots appear on the abaxial side of the leaves, which becomes necrotic. Urediniospores produced in infected leaves are the main primary inoculum for coffee rust epidemics. These small spots increase in size and are powdered with spores of the pathogen ranging in color from yellowish orange to bright orange [7, 8]. On the upper surface of the leaves, the lesions are less conspicuous but on lower side of the leaves the lesions increase in size depending on the growth of the fungus inside the leaf [7]. The lesion eventually turns brown as the leaves cell exhausted [8]. The lesions may also occur on cotyledons and, occasionally, on young green stems and berries [9]. *H. vastatrix* produces group of sori which are strictly abaxial and usually expanding radially. The urediniospores are orange, reniform, ventrally smooth and dorsally coarsely echinulated with tightly clustered spines between echinulate and smooth area [10].

Coffee leaf rust affect plant growth by reducing the amount of leaf area available for photosynthesis, either by occupying leaf area or by inducing defoliation principally of the attacked leaves [7, 11]. It brings loss of physiological activities in the affected part of the leaves and cause leaves to fall [8]. Potent attack of the disease can cause branches to wither completely and this hinders the plant or even stops its development. If the leaves are unable to supply the needs of the developing coffee berries, which act as powerful sinks, then they draw on the carbohydrate reserves of the roots and stems [12]. Subsequently, badly diseased and weakened coffee plants do not survive then tend to death of the tree [8]. Depending on the severity of the CLR, not only fewer flowers are formed but also the flowers and fruits formed fall prematurely and the remaining fruits often do not reach the maximum size; hence, causing reduction in both weight and volume of the yield. The lower bean yield and poor bean quality in turn result from sever leaf fall and the general debilitating effect of CLR on the tree [13]. Moreover, not only the current product yield and quality reduced due to reduction of photosynthetic area, but also in the following year by reduction of fruiting branches [8].

3. Biology and Epidemiology of Coffee Leaf Rust

Taxonomic classification: *H. vastatrix* belongs to Pucciniaceae family in Order, Uredinales of the Class Basidiomycetes. Forty two species are so far known under the genus, *Hemileia*, occurring mainly on uncultivated plants with in the tropical to subtropical regions of Asia and Africa [10]. The genus has unknown pycnial and aecial stage [10] and characterized by suprastomatal sori, ovoid to reniform urediniospores with smooth side and irregularly lobed teliospores [10]. *H. vastatrix* is a type specimen of the genus *Hemileia* first described by Berkeley and Brooome, from samples of *C. arabica* leaves from SirLanka in 1869 [7, 10, 14]. As described by Berkeley and Broome (1869), *H. vastatrix* urediniospores are reniform, 28-36 × 18-28 μm; the urediniospore wall is hyaline, strongly warted on the convex face, smooth on the straight or concave face and 1 μm thick; teliospores are spherical, subglobose to napiform, 20-28 μm in diameter; the teliospore wall is hyaline, smooth and 1 μm thick [15]. *Hemileia vastatrix* can be distinguished from *H. coffeicola,* as the latter produces sori scattered throughout the leaf and presents urediniospores with fewer but larger spines.

Both rusts have *C. arabica* and other *Coffea* species as hosts, but *H. coffeicola* is of low economic importance and is geographically confined [10]. Only the dikaryotic urediniospores are responsible for the disease [2, 7, 16] and allow it to survive, reproduce and repeatedly infect its only host [10, 16]. The teliospores are rarely produced when conditions are favorable and it germinates and produces basidospores, which are apparently functionless, as it does not infect coffee leaves.

The pathogen primarily exists as different physiologic groups and so far over 50 different races have been identified all over the world [2] but the mechanism of race formation is incompletely understood. A recent study by Brazilian scientists involving cytometric imagery of DNA content revealed the presence of hidden sexual reproduction within asexual spores (urediniospores) of *H. vastatrix* [16]. According to the authors, this type of reproduction, called cryptosexuality, may explain the frequent and rapid emergence of new physiological races of *H. vastatrix*. The frequency of a specific virulence gene or combinations of virulence genes in the rust population will depend on mutation rates, dissemination of the genes in the population and selection pressure from the corresponding host resistance genes [16].

When germination and infection processes observed, the urediniospores land, germinate and form an appresorium on the abaxial side of the leaves. Urediniospores germinate only in the presence of free water and it does not germinate even at high relative humidity if the free water is absent. Moreover, an exponential equation was fitted to data describing the relationship between leaf wetness duration and rust severity [7]. The spores germinate in 2-4 hours under optimum conditions and complete penetration process within 24-48 hours at 100% RH. The presence of free water is very important until the penetration process is completed [7].

Latency period is strongly influenced by temperature and is significantly extended when temperatures are higher than 28°C or lower than 18°C [2]. The optimum temperature range for germination of uredioniospores was estimated to be 21–25 °C in the absence of light [5, 6]. The germination is more active at temperature between 20°C and 25°C showing its highest activity at 22°C [6] while a temperature between 18°C and 28°C is reported as favorable condition for the fungal development [10]. The maximum and minimum temperature that prevented germinations were estimated in 32.5 and 12.5°C, respectively [7, 17].

The urediniospores germinate and produce a germ tube, which grow on leaf surface until it encounters stoma. The germ tube produces an appresorium (penetration peg) from which infection hyphae develop and enter the leaf through the stomatal pore. The infection hyphae ramify intercellularly in the substomatal cavity and nearby tissues and penetrate cells by means of haustoria [17]. The external manifestation of this process is the presence of lesion on the leaf surface, which depends on the extent of hyphal ramification and on environmental conditions. The mycelium then produces protosori that generally emerge through the stomata. Successful infection develop within the host leaf, eventually reaching the lower leaf surface where the bulk of developing urediniospores come out through the stomatal opening and form a bright orange pustule covering the leaf. The duration of the latency period ranges from 20 to 55 days under field conditions, most commonly lasting 25 to 35 days [16, 17].

The urediniospores are dispersed by both wind and rain [5]. Urediniospores may spread over long distances by wind, reaching 1,000 m up in the atmosphere and potentially reaching coffee plantations located thousands of miles away from the source [18]. Wind is responsible for long distance dispersal while rainfall spreading the pathogen due to splashing of raindrops from one leaf to another and important for dissemination of the disease within the coffee canopy [7, 19]. It can also be introduced into distant areas by use of seedlings transported from infected plantation, or through bodies of insects and other animals [18].

The pathogen primarily survives as mycelium in the living tissue of the host, and since infected leaves drop prematurely; this effectively removes a huge amount of potential inoculum from the epidemics. Nevertheless, a few green leaves always persist throughout the dry season, linking some viable inoculum to infect the newly formed leaves at the start of the next rainy season [20].

Epidemiology: CLR infections seldom kill the host plant, although severe infections affect the yield in subsequent years because they hamper vegetative development and can generate polyetic epidemics over successive seasons. Climate (including the altitude effect), shade, soil fertility and canopy architecture influence disease severity. 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 [8]. Genetically susceptible coffee plants in rust conducive environments can be attacked at any growth stages [14]. 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 [8]. 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 [21].

Although water plays a great role in the disseminating rust, various authors also attributed the distribution of CLR to wind. The introduction and rapid spread of rust in Latin America [7, 14] and its possible introduction to Brazil from Angola [2] has been attributed to wind dispersal. Corroborative evidences indicated that wind is responsible for long distance transport, of plant pathogens. Contrarily, [6] could not trapped spore at wind speed up to 19 km/hour and they could wash off many spores from lesions by a jet of water but not by wind. Based on this, they concluded that wind might be responsible for disseminating insignificant amount of spore over a short and medium distance, which results in scattered lesions, but epidemics is induced by dispersal of spores by water splash alone or accompanied by wind. Similarly, [21] reported considerably lower amount of CLR spores in air to rain trapped using volumetric spore trap.

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. The shorter the latent period results in greater number of generations completed in a given time hastening rust epidemic generation. 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 [6, 21].

Altitude influence local climatic conditions, which in turn affect the development of the disease. CLR intensity was reported to decrease with altitude in Kenya [21], in southern American continents [7] in Pauna New Guinea [21] and in Ethiopia [22, 23]. High altitudes are associated with lower night temperature and a cooler day temperature that result in lowered disease severity [7, 23]. Coffee management practices also influence the epidemics of CLR development. Generally, its effect is manifested on either yield or modifying the environment. According to [2], 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. According to [2] studies showing 20% of variations in the rate of development of CLR epidemics explained by year to year variation in berry production. This may be partly explained by variation in leaf fall and new leaf formation, in low and high yielding years, and by higher susceptibility of leaves that feed developing berries and in high yielding years massive leaf fall reduce initial inoculums for the next low yielding year when disease is further diluted by renewal of the leaf canopy [16, 17].

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 [10]. In shaded plantations, however, shading generally allows for intermediate yields that are always sufficient to render coffee leaves susceptible enough to infection [16]. As opposed to this, more rusted trees were observed in orchard and garden plantation (relatively intensive) than dense forest coffee management systems in Ethiopia [22, 23]. In plantation without shade there is high radiation interception by the coffee canopy enabling coffee trees to achieve very high yield which is conducive to serious epidemic development. Similarly, fertilization induces greater leaf area which leads to increased yield that predispose the coffee plant to rust infection also favour spore interception. However, pruning reduces the amount of inoculum at which initial inoculums presents, and available for dispersal and the probability of spore interception [16].

4. Economic Importance of Coffee Leaf Rust

Coffee leaf rust is a major economically important disease of coffee in all coffee growing countries of the world [2, 24]. It is known that most of coffee producing and exporting countries are low income, the small reduction in coffee yield or modest increase in production costs caused by CLR has huge impact on coffee producers, support services, and even the banking system in those countries whose economics are heavily depend on coffee export. In spite of ravaging coffee plantation and its replacement by tea or rubber in Sir Lanka, termination of coffee export to United Kingdom compelled habituated consumers to adapted tea drinking [25]. Moreover, it was responsible for sharp decline of coffee yield from 1500 to 300 kg/ha and cessation of coffee cultivation with marginal yield in India [25]. Generally, rust incurs an estimated yield loss between 35 - 50% in different countries [2] and cost of control with fungicide is very high. In Brazil annual loss was estimated to about 30% [7] and the entailed expense for chemical control add up to equivalent 100-120 million USD [25]. Estimates of global crop losses due to coffee leaf rust were roughly estimated at 1-2 billion USD annually [19].

This epidemic of coffee leaf rust affecting the centeral America is the worst seen since the disease first appeared in the region in 1976 [24]. Since 2012 there have been more intense CLR outbreaks in Central and South America, particularly in Nicaragua, Ecuador, El Salvador, Panama and Honduras with losses of over 90% [24], and the total damage in the region was estimated to 2.7 million bags, costing the region around US$500 million [24]. Apart from economic loss, there has also been a significant social impact on the societies. It is estimated that 374,000 jobs were lost [2]; since the labour used to harvest the crop was not needed and leads to the issue of food security both for the farmers and other societies whose livelihood is depend on coffee.

In Ethiopa, CLR was widely distributed all over coffee growing regions of the country with varying intensities [22]. High disease incidence was observed in Kaffa (42.5%), Illuababor (41.9%), and Hararghe (39.6%). According to [22] the earlier national percent tree attack was 12.9% which latter raised to 36.3% after ten years in 1990 and increased with three fold. A mean incidence of 32.2% at Berhane-Kontir and 96% at Harenna forest coffee area was observed in 2005 in Ethiopia (Zeru et al., 2005). Moreover, the existence of coffee leaf rust infection on forest coffee reported at Yayo (31.1%), Berhane-Kontir (21.4%), and Bonga (7.9%) [22, 23]. Hararghe region where garden coffee production system is dominant, the severity of the disease was 27% [25]. According to [25, 26], in Ethiopia, coffee leaf rust occurs in all areas and under all growing systems like forest, semi-forest, garden and plantation coffee not following a certain altitude preference. Over time coffee leaf rust situation in Ethiopia changed and become an important in coffee production of the country [22, 23, 25, 26]. This situation may be due to climate change which favor the virulence of the pathogen and changes in the system of coffee management to improve production has increasing the importance of coffee leaf rust in Ethiopia [22, 23, 25, 26]. However, in Ethiopia much work has not been done on the economic impact of coffee leaf rust and information is lacking, although the disease is moving into many coffee producing areas where the symptom was not observed before.

5. Coffee Leaf Rust Disease Management

5.1. Use of Resistance Varieties

Breeding coffee plants for resistance to rust is considered the best disease management strategy both environmentally and economically [2]. The first effective effort to select resistant germplasm was conducted in India in 1911, giving rise to the release of the cultivar 'Kent's', which replaced the susceptible cultivar 'Coorg' [14]. Investigating CLR away from coffee-growing areas enabled CIFC (international coffee rust research institute in Portugal), to receive plant and fungal material from collaborating institutions around the world, which in turn allowed breeders in coffee-growing countries to have their genotypes characterised for resistance to races that are not present in such countries.

In Arabica coffee, vertical (complete), horizontal (race non-specific) and incomplete (partial) resistance to the leaf rust disease was reported [14]. Complete resistance inhibit the infection process and prevent production of inoculum while the partial resistance which may also called incomplete resistance does not inhibit the infection process completely but allow the production of certain inoculum [2] through increased latency period and reduced lesion density. Horizontal resistance to coffee leaf rust aim at reducing the intensity of the attack and lengthening of the latency period, thus reducing the sporulation of the pathogen [8]. Consequently, it delays the epidemic and reduces the disease level in a population.

The rapid plant cell death at the infection site (hypersensitive reaction) is the most common interaction of incompatibility of gene for gene interactions. Resistance mechanism with hypersensitive response appeared to be efficient particularly against biotrophic pathogens, such as rust fungi, which depend on living host cells for their reproduction [24, 25]. Cytological and biochemical studies have shown that coffee cultivars display a hypersensitive response to the leaf rust associated with callose deposition, haustoria incasement, deposition of phenolic like compounds and host cell wall lignifications [24, 25].

HDT (Hibrido de Timor) populations derived from a plant discovered on the island of Timor in 1927 exhibiting resistance to rust among 'Typica' coffee crops [24]. 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 [14]. In 1960, CIFC started a breeding programme aiming to transfer resistance from HDT to the main Arabica cultivars. Some selected F1 and F2 plants with resistance to all known races were supplied free of charge to all institutions in coffee-growing countries that requested these materials. With continued breeding efforts, the tetraploid genotypes known as Hibrido de Timor (HTD), derived from a spontaneous interspescific cross between *C. arabica* and *C. canephora* has been discovered and found resistant to CLR [8]. These materials showed high level of resistance to all races of rust existed in Kenya [9] and Brazil [16]. Some of these lines were also introduced to Ethiopia from Portugal in 1979 and tested across locations *viz.* Tepi, Bebeka and Metu and the best two lines (Catimor J19 and Catimor J21) were released for production in low land areas. At that time, these lines conferred complete resistance to rust at all locations [25, 26] although they were not stringently tested.

Rust resistance in HDT populations is conferred by Robusta-derived genes, such as S_H6, S_H7, S_H8, S_H9 and others not yet identified, in addition to Arabica resistance genes (S_H1, S_H2, S_H4 and S_H5). These genes, along with S_H3 (derived from *C. liberica*), condition coffee response to rust according to Flor's gene-to-gene theory [2], enabling the classification of genotypes into physiological groups, ranging from resistant to all known rust races to susceptible to almost all known races [2, 16]. The usefulness of HDT populations as resistance donors led to several studies seeking to identify markers linked to resistance genes [2], targeting downstream marker-assisted selection approaches.

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. For instance, the genotype HDT CIFC832/2 carries additional genome introgressions compared to other genotypes [27] and presents a pre-haustorial (non host-like) resistance [14, 27]. In fact, post-haustorial resistance response is typically found in most coffee - *H. vastatrix* interactions [16, 27]. The cytological and biochemical aspects of coffee resistance to CLR have been revised by [27] and addressed by [27]. In brief, both pre- and post-haustorial resistances are associated to the hypersensitive response and to the activation of several genes, including receptor-like kinases, WRKY transcription factors, glycosyltransferases, lipoxygenases and PRs [24, 27].

As the resistance in several HDT-derived genotypes is being lost [24], new sources of resistance are being investigated. Given the ample resistance found in *C. canephora*, along with the successful history of HDT, one tempting approach for the identification of new sources of resistance for Arabica coffee is to perform *C. arabica* ×*C. canephora* crosses. Such studies have promised new resistance sources [16, 24, 27]. To breed one of India's most popular Arabica genotypes (S.795), [16, 24, 27] developed two SCAR markers closely linked to the S_H3 gene. This is a highly effective rust resistance gene naturally introgressed into *C. arabica* from *C. liberica* [16, 24, 27]. Partial and non-specific polygenic resistance have been evidenced in *C. canephora*, in some *C. arabica* genotypes and in some interspecific hybrids [16, 24, 27]. This corroborates previous reports suggesting that, in addition to S_H genes, other major and minor genes might condition coffee-rust interactions [16, 24, 27]. Such studies, however, are hampered by the necessity of a laborious and time-consuming downstream breeding effort in order to introduce resistance factors into elite lines with adequate agronomic and quality traits.

Identifying resistance in wild *C. arabica* populations would be of interest as it avoids breeding to eliminate undesired traits from other *Coffea* species. However, the analysis of wild *C. arabica* germplasm has so far provided little support for the identification of resistance sources, as rust occurs frequently among plants in forests across the native range of *C. arabica* in Ethiopia [16, 24, 27]. Information regarding susceptibility of wild germplasm to the different rust races is scarce [14, 27], and the very low genetic diversity among wild populations suggests little promise of success in finding new sources of resistance [10, 14, 27].

According to [6, 7] incomplete polygenicaly inherited resistance might be more durable than resistance related to major genes. Resistance towards pathogens that do not show host specific pathogenecity is likely to be durable [6, 7, 8]. Highest resistance to pathogen has expected to exist in the center of origin of host species or varieties where both hosts and pathogen have evolved [7]. Testing different coffee collections taken from Ethiopia at various occasion for resistance to CLR using leaf disc inoculation indicated the importance of these materials as good source of horizontal resistance (race non specific resistance) [9, 27]. Many coffee plants with high levels of incomplete resistance were also identified from these collections in Brazil [7].

5.2. Cultural Control

Cultural management practices can indirectly control CLR. Shade control, providing wider spacing and ensuring that trees are pruned appropriately helps to prevent prolonged wetness and high relative humidity, to some extent, hinder the pathogen germination and subsequent infection cycle [9]. Pruning is an agricultural operation commonly practised in tree crops. It used to made tree architecture, renew the assimilating system and stimulate new reproductive organs. These practices are also beneficial to fungicide application, as they open up the coffee bush to allow effective penetration of sprayed fungicide. It is also recommended for controlling numerous diseases including CLR [20, 26]. Pruning opens up the coffee canopy and allows air circulation within the canopy thus resulting in reduced surface wetness and reduced relative humidity within the canopy [20, 25]. Removal of CLR infected leaves from the tree and from the ground reduce the major sources of primary inoculum in the succeeding cropping season [5, 6].

Based on some reports, coffee shade tree helps for CLR management. According to [22, 23, 26], shading modifies microclimatic conditions by reducing ambient temperature (2°C to 4°C) that helped to reduce over bearing and delay fruit ripening, which might have reduced the tree stress and exposure to CLR. In shaded plantations, shading allows for intermediate yields that are always sufficient to render coffee leaves susceptible enough to CLR infection [24, 27]. At the beginning of coffee cultivations, coffee bushes were planted under shade canopy to simulate their natural habitat [16-18]. Coffee grown without shade potentially out yielded shade coffee [12, 13, 18, 20]. In Ethiopia, decreasing shade to increase coffee production caused losses of plant species diversity and expose to CLR. Optimum shaded coffee tends to flower and produce balanced good crop each year, whereas under unshaded plantation conditions, heavy flowering and fruiting exist then coffee tree becomes committed to filling all the beans that are formed after the fruit expansion stage resulting in a large sink capacity in the seed endosperms [15, 18, 27]. Overbearing exhausts the tree's and predispose for heavy CLR infection [15, 24]. Although [7], using artificial inoculation of leaves found that increased shading was associated with increased *Coffea arabica* resistance to CLR.

Proper fertilization and soil nutrient management has direct and indirectly control over CLR. Rust on cultivated coffee may also be controlled using a mixture of nutrients which can help the plant to tolerate the disease and exhibit fungicidal effect. The formulation called Viçosa mixture, a colloidal suspension of partially neutralized salts with calcium hydroxide (750 g copper sulphate pentahydrate, 300 g zinc sulfate, 400 g magnesium sulfate, 100 g boric acid, 400 g potassium chloride, 350–550 g calcium hydroxide, pH 5.6–5.8) and prepared at the time of application [2]. Advantages of this mixture apart from CLR control are the control of other diseases such as brown eye spot and the supply of mineral elements to the plants such as copper, zinc and boron. Results obtained at UFV since 1985 have shown a 80% yield increased compared to untreated plants [2].

High altitude coffee cultivation helps for indirect management for CLR. Reports indicate that CLR intensity decreased when the elevation increases [18, 22, 23, 25, 26]. Altitude influence local climatic conditions, which in turn affect the development of the disease. The relationship between altitude and CLR severity is likely to be linked with temperature. The level of temperature determines the rate of germination and penetration processes of the pathogen, which likely decreased the latency period of the disease [24]. The negative relationship between altitude and level of CLR is also demonstrated by [21] in Kenya, [7] in southern American continents and [21] in Papuna New Guinea. High altitudes are associated with lower night temperature and a cooler day temperature that result in lowered disease severity [7, 22-25, 27].

5.3. Chemical Control

In perennial plants like coffee where replacement of susceptible with resistant varieties would take many years, chemical control is most realistic measure. Chemical control of CLR is the last option in the absence of other effective disease management methods. It is based on the spray of protectant and/or systemic fungicides on the foliage [2, 8]. Preventive treatments are typically carried out with copper-based fungicides, while curative treatments are conducted with systemic fungicides (e.g., epoxiconazole, pyraclostrobin). Among protectant fungicides, copper-based ones such as Bordeaux mixture, copper oxychloride, copper oxides and hydroxides are the most effective [2, 8]. Among systemic fungicides, triazoles are applied alone or in mixtures with QoI (strobilurin) fungicides, and are applied either on the leaves or in the soil (in this case, together with systemic insecticides for control of leaf miner). The combined use of copper-based fungicides with systemic fungicides has the additional advantage of providing copper to the plants, besides reducing the risk of selecting fungicide resistant rust populations [2].

Various rules can be used to aid the decision of when to start fungicide applications. These include calendar, weather, phenology and disease monitoring based criteria. In years of high load of fruit berries, four to five sprays of protectant fungicides are usually performed or two sprays of systemic fungicides (including a QoI) [2]. In any case, disease incidence and weather should be taken into account in the decision making process. In years of low load of fruit berries, the number of applications is reduced by half. The use of systemic fungicides combined with insecticide application via soil should be performed in the beginning of the rainy season (November in Brazil or May in Ethiopia) [25-27]. The fungicide-plus-insecticide formulation should be applied in the soil around and beneath the branches of the plants [2]. These applications should be made whenever there is sufficient moisture in soil, so that the active ingredients can be more effectively released and absorbed by the plant roots. In coffee-producing regions where leaf miner does not cause damage, the systemic fungicide can be applied to the soil alone [2].

In Brazil spraying decisions are based on disease monitoring, 10 leaves are randomly collected per plant, totalling 100 leaves per plot, which are taken from the lower third of the plants and the middle of the branches (third or fourth pair of leaves). If rust incidence (percentage of symptomatic leaves) reaches 5%, a systemic mixture including a QoI fungicide is highly recommended, otherwise cupric fungicides should be sprayed [2, 28]. One of the advantages of systemic over protectant fungicides is their ability to act curatively (after the infection is established). However, their curative efficacy is greatly reduced if rust incidence is greater than 10% in years of high fruit load [2, 28]. In this case, systemic fungicides should be used alternated with cupric fungicides to avoid the selection of fungicide-resistant strains. Triazol fungicides applied alone or in combination with insecticide to the soil are efficient to control the disease in conilon coffee [2, 28]. The option to spray a triazol + strobilurin fungicide alone instead of applying triazol to the soil with insecticides (usually after the first rains in the beginning of the season) should be based on the disease incidence (5% threshold) [2, 28].

Chemical control represents an environmental hazard and a social concern as organic coffee is increasingly valued [2, 28], as well as an economic burden. For instance, in Tanzania, 50% of the coffee cultivation production costs refer to the chemical control of the two main fungal diseases, CLR and coffee berry disease [2, 28]. Even if chemical control is practical, the cost is very high and application is not easy due to the steep terrain where the coffee is grown. Moreover, pesticides have been reported to reduce the population of indigenous natural enemies of some insect pests as well as population of microflora which may serve as antagonists in the biocontrol of coffee diseases like CLR [2, 28].

5.4. Biological Control

Biological control is an environmentally benign and potentially attractive alternative for CLR management, although relatively underexplored. Biological control of rust is desirable as an alternative to chemicals that may disturb the balance between natural enemies and coffee insects and diseases. Several studies demonstrated experimentally an existing effect of antagonistic microbes against *H. vastatrix* [23, 27, 29]. The most common and noticeable evidence of mycoparasitism of *H. vastatrix* is seen as a complex of "white colony forming-taxa" usually promptly recognized under the generic names *Verticillium* sp. or *Lecanicillium* sp. The report from Ethiopia explain the occurring of hyperparasites, *Verticillium lecanii* and considered to be the most important in suppressing the epidemics as biocontrol of CLR on *Coffea arabica* production in Ethiopia [27, 29].

Nevertheless, examples of systematic surveys of mycoparasitic fungi on *H. vastatrix* are limited to a single study performed outside the center of origin of coffee and *H. vastatrix* in Mexico [29, 30]. These authors have collected and described the following fungi in association with CLR pustules: *Acremonium byssoides, Calcarisporium arbuscula, C. ovalisporum, Sporothrix guttuliformis, Fusarium pallidoroserum* and *Verticillium lecanii.* Identifications were based solely on morphology and cultural. Recently, fungal communities associated with CLR were investigated in Mexico and Puerto Rico using single-molecule DNA sequencing (PacBio) of fungal rRNA [30]. The unexpected presence of ahyper-diverse fungal community associated with *H. vastatrix* emerged from this study [30]. Interestingly only two species of *Akanthomyces* were recorded in that study, but none of them belonging to *A. lecanii*.

Bacterial and some fungal strains present in the coffee ecosystem have been investigated for their use as potential biocontrol agents against *H. vastatrix*. Specific strains of the bacteria *Pseudomonas putida*, *Bacillus megaterium* and *B. thuringiensis*, along with two *Fusarium* sp. isolates, provide promising levels of antagonism [27, 30]. There are yet no known practical examples of application of biological control of CLR, despite the publication of some promising research results. For example, *Bacillus subtilis* and *Pseudomonas putida* applications reduced fungal infection by 70% [29]. Similar results were obtained with *Bacillus thuringiensis* and *B. subtilis* sprays [30]. Little has been published on the use of antagonistic fungi against CLR. There are also few reports of surveys for mycoparasites of *H. vastatrix*, the sole exceptions being [27, 29, 30].

5.5. Integrated Coffee Leaf Rust Management

Integrated disease management is a broad ecological approach to control disease in a compatible manner. It advocates control of the diseases through the combination of several control practice without depending heavily on one control practice like chemicals. The main goals of an integrated plant disease management are elimination or reduction of the initial inoculum, reduction of the effectiveness of the initial inoculum, increasing the resistance of the host, delay the onset of the disease, and slow the secondary cycles [2, 24]. The integration of a number of practices with the aim of reducing or eliminating the impact of the disease is the most realistic option for solving the problem [16].

Integrated disease management is the preferred strategy because of the limitation of a single alternative management option to achieve the same level of control and reliability as that of single chemicals control. Thus all alternative management tactics like cultural, host resistance, biological and safe chemicals could be the best options in managing coffee leaf rust. The effects of potassium silicate and essential oils were recently tested with some success on management of CLR [2]. Moreover, promising results have been obtained with a resistance inducer of the benzothiadiazole (BTH) group, such as acibenzolar-S-methyl [2, 24]. BTH-treated coffee leaves over express genes involved in pathogenesis-related protein synthesis, oxidative burst, and cell wall strengthening, suggesting a general shift in metabolism from housekeeping to defence [2, 24]. The effect of phosphites and plant formulations based on the by-products of coffee and citrus industries for the control of CLR have been evaluated in the greenhouse and field. Some of the formulations have shown an intermediate to good efficiency compared to standard fungicides, proving to be effective alternatives for the management of coffee rust and other diseases [2, 24, 28]. This also enables better penetration and coverage of fungicides if these are used. The capping of the taller stems of multiple-stemmed coffee can also decrease the incidence of CLR, as these provide a major source of inoculum for the crop [9, 24]. In spite of these facts, there is limited report in integration of tactics for CLR managements in Ethiopia. Thus, future research should address this issue and work to incorporate all individual tactics and practices into strategies to develop integrated disease management (IDM) program for coffee.

6. Conclusion

The review indicated that coffee leaf rust is the most devastating coffee disease in the World. Different coffee leaf rust disease management opthions are helpful to reduce it damage. Among these, use of resistant variety, cultural control, use of effective chemicals, biological control and integrated disease management options. From cultural management options, the use of organic soil fertility management was the most attractive option for resource poor small holder coffee farmers under without supplementary irrigation condition given that it reduces on both costs of inorganic chemical fertilizers and support the tolerance of coffee plant for disease and help in high yield. Supplementary irrigation was highly required when inorganic fertilizers are used for coffee plant, since without moisture inorganic fertilizer adversely affect the physico-chemical properly of soil. The use of organic fertilizer highly improves the physico-chemical properly of soil and consequently help for the better growth performance of coffee plant and reduce the disease intensity under supplementary irrigation. However, application of inorganic fertilizers without supplementary irrigation during drought season negatively affects the crop performance by yield and disease tolerance.

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