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Review

Integrated Disease Management for the Sustainable Production of Colombian Coffee

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Abstract: Coffee stands as a vital pillar of Colombia's economic prosperity, constituting approximately 7% of the nation's agricultural GDP. Moreover, it serves as a significant contributor to national agricultural employment, with direct jobs stemming from coffee cultivation comprising 26% of the total agricultural workforce. This underscores the pivotal role coffee plays in shaping Colombia's social and economic landscape, solidifying its position as the primary origin of mildly washed coffees for global consumers. However, Colombia's coffee production grapples with the challenge of operating amidst persistently rainy conditions, fostering an environment conducive to fungal diseases. This, compounded by environmental, economic, commercial, and safety constraints for disease control, creates a multifaceted scenario that continuously tests disease management strategies. Addressing this complex dynamic demands a crop protection framework that seamlessly integrates efficient and sustainable methodologies. Such methodologies should prioritize outbreak prevention, cost-effectiveness, adherence to national and international regulations, and the preservation of environmental and human health. Integrated disease management emerges as a solution capable of optimizing productivity tailored to the unique conditions of each plot. By mitigating the impact of pathogens while responsibly utilizing and conserving natural resources, this approach safeguards the well-being of both producers and consumers alike.

Keywords: economic impact; fungal diseases; production constraints; coffee safety

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1. Introduction

Coffee production in Colombia represents 9.8% of the global exports for this commodity, being the largest source of mildly washed coffees, and for the country, this activity results in 8.8% of the foreign currency income, which is distributed among half a million families across the countryside [1]. Coffee cultivation dates back to the late 18th century, when the first plants of *Coffea arabica* var. Typica (Gentianales and Rubiaceae) arrived in the country and were dispersed in an environment free from specific limiting diseases of the crop. Today, coffee serves as a significant source of income through its exports to over 30 countries worldwide, representing approximately 7% of the country's agricultural GDP [2,3]. As of 2023, Colombia boasted approximately 845,000 hectares dedicated to coffee cultivation, sustaining around 546,000 producing families across 23 out of 31 departments in the country [3]. The direct employment opportunities generated by coffee cultivation constitute 26% of the total national agricultural workforce [1], underscoring the pivotal role of its cultivation and commercialization within the country's social and economic framework.

The first reports of coffee plants in Colombia date back to 1730, with initial exports beginning in 1835 from the northeastern region. As the crop expanded to other areas, coffee became the country's main source of foreign exchange by 1875, maintaining this status for several decades until oil took over in the 1980s. Today, coffee plantations thrive in the highlands at altitudes between 1200 and 2000 m above sea level, with average temperatures

ranging from 17 to 23 °C [4]. Due to Colombia's diverse climatic conditions, particularly the rain patterns influenced by the Intertropical Convergence Zone, three large agro-ecological regions can be distinguished. These regions experience harvests concentrated in one semester (north and south zones) or distributed in both (central zone) [4]. Additionally, factors such as radiation intensity and duration determine the necessity of implementing shade through agroforestry systems [5]. The primary cultivated species is *C. arabica*, with varieties including Typica, Bourbon, Maragogype, Caturra, Colombia, Castillo, and Cenicafé 1 [6].

With the establishment of the first coffee plantations in Colombia, local and opportunistic phytosanitary issues emerged (Figure 1, Table 1). Among these, the American leaf spot, now named gotera or ojo de gallo (*Mycena citricolor*), was recognized as the first disease for coffee that emerged in the Americas with the diagnosis of the causal agent in 1910 [7]. Subsequently, other coffee diseases surfaced, including root rot (*Rosellina* spp.), originally associated with dead shade trees; others were exacerbated by pruning, like canker stain (*Ceratocystis* spp.), or thrived in environments of high humidity, as occurs with pink disease (*Corticium salmonicolor*), black rot (*Corticium koleroga*), and anthracnose (*Colletotrichum* spp.). Additionally, the country faced the emergence of diseases such as iron spot (*Cercospora coffeicola*), linked to poor nutrition in coffee plantations, and dieback (*Phoma* spp.), favored by exposure to low temperatures [7]. Furthermore, the introduction of practices such as constructing germination beds and nurturing plants under six months old in nurseries revealed additional issues, including damping off (*Rhizoctonia solani*) and root nematodes (*Meloidogyne* spp.) [7]. These diseases remained transient and localized, implying that, for nearly two centuries, coffee cultivation in Colombia did not necessitate regional or nationwide disease management strategies in the field, nor did it prompt the undertaking of epidemiological or economic impact studies on phytosanitary problems [8].

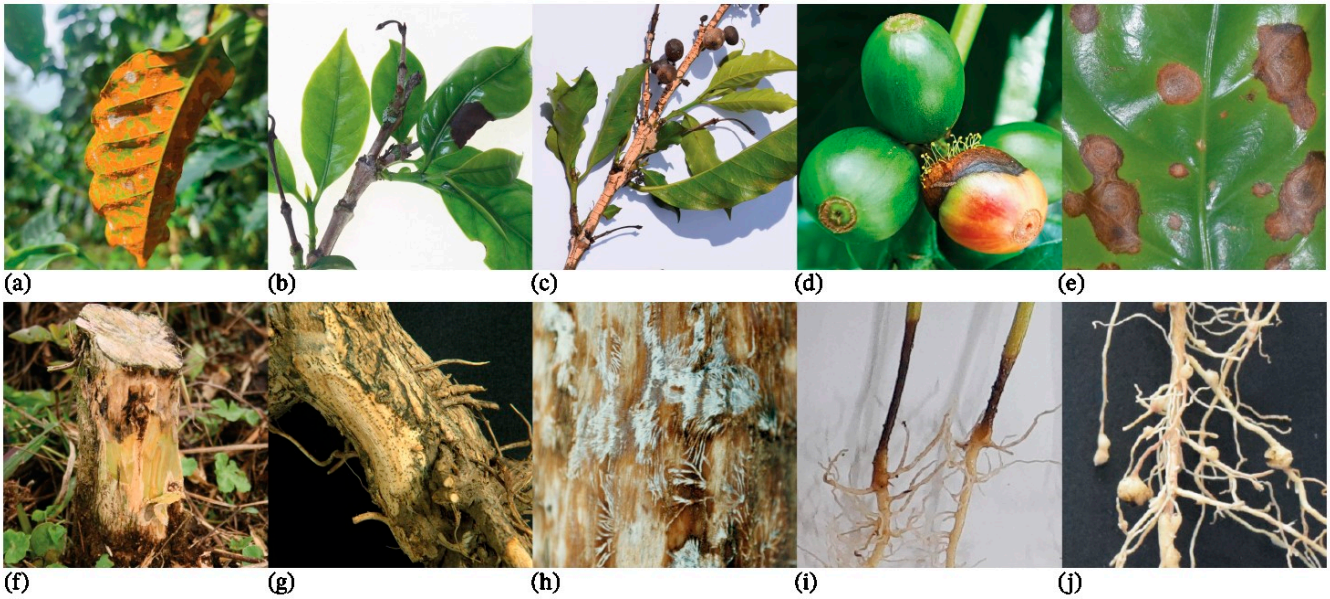

Figure 1. Symptoms of main diseases in coffee plantations in Colombia across different tissues and plant organs. (**a**) Coffee leaf rust (*Hemileia vastatrix*). (**b**) Plant tips showing dieback (*Phoma* sp.). (**c**) Coffee branch with pink disease (*Corticium salmonicolor*). (**d**) American leaf spot (*Mycena citricolor*) on fruits. (**e**) Close view of iron spot (*Cercospora coffeicola*) on leaves. (**f**) Ceratocystis canker stain (*Ceratocystis fimbriata*) on stumping plant, (**g**,**h**) Rosellinia root rot (*Dematophora pepo* and *Dematophora bunodes*) on plant roots. (**i**) Damping off (*Rhizoctonia solani*) in coffee nursery plants. (**j**) Root knot (*Meloidogyne* spp.) in coffee nursery plants. Images from Cenicafé´s archive.

Table 1. Pathogens associated with coffee diseases in Colombia.

Common Name	Scientific Name *	Classification *	Plant Organ Affected	Reference
Coffee leaf rust (CLR)	*Hemileia vastatrix* Berk. & Br.	Fungi Basidiomycota Pucciniales	Leaves	[9]
American leaf spot, Gotera or ojo de gallo	*Mycena citricolor* (Berk. & M.A. Curtis) Sacc (=Omphalia flavida Maubl, & Rang. Anamorph)	Fungi Basidiomycota Agaricales	Leaves, fruit, and stems.	[7]
Canker stain and wilt	*Ceratocystis fimbriata* Ellis & Halst. *sensu lato* (s.l.).	Fungi Ascomycota Microascales	Stems	[10]
Black root rot	*Dematophora pepo* (Pat.) C. Lambert, Wittstein & M. Stadler. Basionym: *Rosellinia pepo* Pat.	Fungi Ascomycota Xylariales	Roots	[11]
Black root rot	*Dematophora bunodes* (Berk. & Broome) C. Lambert, K. Wittstein & M. Stadler. Basionym: *Rosellinia bunodes* (Berk. & Broome) Sacc.	Fungi Ascomycota Xylariales	Roots	[11]
Damping off	*Rhizoctonia solani* J.G. Kühn	Fungi Basidiomycota Cantharellales	Seedling damping off	[7]
Anthracnose	*Colletotrichum* spp. Corda	Fungi Ascomycota Glomerellales	Flowers, fruits, leaves, and stems	[7]
Iron spot, brown eye spot, berry blotch	*Cercospora coffeicola* Berk. & Br.	Fungi Ascomycota Mycosphaerellales	Leaves and fruits	[7]
Pink disease	*Necator salmonicolor* (Berk. & Broome) K.H. Larss., Redhead & T.W. May. Basionym: *Corticium salmonicolor* Berk. & Broome	Fungi Basidiomycota Corticiales	Stems and fruits	[12]
Die back	*Phoma* Sacc.	Fungi Ascomycota Pleosporales	Sprouts and young leaves	[7]
Thread blight	*Corticium koleroga* (Cooke) Höhn. Basionym: *Pellicularia koleroga* Cooke	Fungi Basidiomycota Corticiales	Leaves	[9]
Oil spot	*Colletotrichum* Corda	Fungi Ascomycota Glomerellales	Leaves and fruits	[7]
Root knot	*Meloidogyne* Goeldi spp.	Nematoda Tylenchida	Roots	[7]
Coffee crispiness disease	Group 16SrIII-Related Phytoplasma		Systemic	[13]

* According to: www.mycobank.org, https://www.bacterio.net/ and http://nemaplex.ucdavis.edu/ (accessed on 19 May 2024).

This landscape underwent a significant transformation with the onset of coffee leaf rust (CLR, *Hemileia vastatrix*) in 1983. In the absence of resistant varieties, this necessitated the systematic introduction of chemical control methods and the incorporation of other disease management measures [14]. These measures were based on an understanding of the life cycle of causal agents, the variable climatic conditions across the country, and the idiosyncrasies of Colombian growers. The majority of these growers are family producers with an average of 1.3 hectares planted in coffee, often residing in the same areas where their

plots are located [1]. As studies delved deeper into disease, pest, and weed management, as well as sun and shade production systems, it became increasingly apparent that coffee cultivation occurs within a complex biotic interaction. This interaction now includes over 265 weed species, of which only 33% significantly interfere with coffee plants [15]. Additionally, there are 500 species of floral-visiting insects, including numerous wasps [16], and fungi [17] that serve as natural enemies to coffee health problems. All of this is compounded by the presence of 20 species of shade trees that play a role in regulating temperature and humidity in many coffee plantations [5].

Currently, economic, commercial, and safety conditions have become increasingly vital components of disease management strategies, particularly in industries like coffee, which ranks as the second most important commodity globally [1]. Constant fluctuations in international coffee prices compel producers to maintain low production costs to ensure adequate profitability, thus necessitating efficiency in minimizing the impact of phytosanitary issues on production. Markets continually raise quality standards, not only concerning the organoleptic characteristics of the cup but also regarding environmentally friendly and sustainable production practices for the future [2]. Consumers, situated at the end of the supply chain, have grown more demanding regarding the healthfulness of their coffee, prompting the adoption of more sensitive laboratory analysis methodologies. This trend consistently drives down levels of agrochemical and mycotoxin residues, leading to a reduction in the use of fungicides and other chemical control products [1]. Lastly, the pronounced effects of climate variability, both in intensifying existing diseases and facilitating the emergence of new challenges, coupled with the ease of global plant material movement and the accompanying risk of quarantine pathogens, have imposed new hurdles on coffee's phytosanitary control measures.

For these reasons, the current landscape of crop protection demands the integration of efficient and sustainable methods that prioritize outbreak prevention, economic feasibility, and the absence of negative impacts on the environment or health. The goal of integrated disease management is to enhance productivity tailored to the specific conditions of each plot, practicing precision agriculture while conserving natural resources such as air, water, soil, and biodiversity. This approach safeguards the health of both producers and consumers while ensuring profit margins that sustain the attractiveness of coffee cultivation. Confronting these challenges necessitates effective recommendations for producers, a guarantee achievable only through evidence-based knowledge and a comprehensive understanding of all agronomic aspects of coffee cultivation. Such a purpose demands collaborative efforts from all stakeholders in the value chain, coordinated with phytosanitary control entities in each country.

This review will present control tools that enable the design of integrated management for each disease, ensuring a consistent supply of high-quality and safe coffee. This approach will enable millions of people to continue enjoying a delicious and healthy cup of coffee every morning.

2. Legal Control

Legal control serves as the primary barrier in preventing the entry of pathogens into crops, involving the issuance and enforcement of legal measures by national authorities or through international agreements (Table 2). Generally, these measures encompass three main actions: exclusion, eradication, and coexistence [18].

Exclusion strategies aim to prevent the entry of pathogens into disease-free areas. Colombia initiated an exclusion plan following the emergence of CLR in Brazil in 1970 [19]. Through coordinated efforts with government institutions, Colombia successfully delayed the pathogen's arrival into national plantations until September 1983, positioning itself as one of the last countries in the region to confront the disease [8]. Exclusion may involve one or a combination of the following actions [18,20–22]:

a. Prohibition: This entails legally established quarantines and embargoes, prohibiting or restricting the importation of potential carriers of pathogens. The objective of

plant quarantine is to prevent the introduction and spread of potentially harmful diseases. Prevention proves more cost-effective than managing introduced pests and necessitates investment in designing, evaluating, and implementing containment, eradication measures, or long-term control.

b. Interception: This aims to detect pathogens by inspecting plants and their products both in the country of origin and at points of entry into the destination country. The entry of plant material subject to importation must be supported by a phytosanitary certificate issued by the official authority of the country of origin, guaranteeing freedom from quarantine pests. The sampling strategy and laboratory detection techniques must consider the biology and behavior of suspected pathogens to maximize detection opportunities and reduce the risk of false negatives.

c. Elimination: this involves treatments, either physical or chemical, applied either at the point of origin or entry to ensure the destruction or removal of pathogens.

Eradication measures are enacted once a disease is detected, swiftly implementing actions to destroy pathogen inoculum in field outbreaks. However, there are controversies surrounding the effectiveness of these measures, with some arguing that eradication policies and procedures for a pest merely delay its spread rather than prevent it outright [22].

Coexistence ensues when a disease has already established itself in a region, necessitating the formalization of control needs through resolutions. These resolutions outline obligations to report new outbreaks promptly, implement efficient control measures, and prevent dispersion to new sites, thereby mitigating economic and environmental impacts. Coexistence measures encompass activities such as seed production certification, the registration of nursery seedling sales, and restrictions on the movement of coffee seedlings across the country [23].

Given the current dynamics of legal and illegal migrations, there exists a risk of pathogens escaping inspections or entering through illicit channels. Therefore, the continuous surveillance of coffee crops within Colombian territory is essential to detecting outbreaks of any pathogen, complemented by the proper diagnosis of the causal agent. Recommendations are specific depending on the geographical area. In Colombia's case, legal control applies to quarantine diseases defined by the Colombian Agricultural Institute (ICA), which periodically compiles a list of pathogens posing the greatest risk to coffee cultivation that may either be absent from the country (A1 pests) or have a restricted distribution, requiring control and surveillance to limit their dissemination (A2 pests) [24]. The significance of each pathogen is determined through literature reviews identifying disease-causing agents, genetics, possible routes of entry into the country, risk assessments indicating conditions promoting disease development upon entry, and economic and environmental effects. While the primary concern relates to quarantine pests affecting food security and the regional impact of diseases on *Coffea arabica* crops, the economic and social ramifications also demand attention.

In Africa, the original site of coffee cultivation, the most significant diseases affecting coffee are coffee berry disease (CBD) caused by *Colletotrichum kahawae*, coffee wilt disease (CWD) caused by *Gibberella xylarioides*, and CLR (*Hemileia vastatrix*) [25]. Among these, the only non-quarantine disease for Colombia is CLR. However, from the wide diversity of microorganisms reported in coffee as plant pathogens, the list of those categorized as absent quarantine pests in Colombia include *Pseudomonas syringae* pv. *garcae*, *Xylella fastidiosa*, and *Ganoderma philippii* [24].

C. kahawae, the causal agent of CBD, induces anthracnose in young fruits during their expansion stage (weeks 4–14) [26]. Under favorable conditions, the fruits become mummified, resulting in direct losses in production [27]. *C. kahawae* naturally inhabits all organs of the coffee plant, coexisting with other non-CBD-causing *Colletotrichum* species [28]. In Africa, the disease occurs during the rainy season, typically coinciding with the fruit development stage. Conidial germination takes place at temperatures between 15 and 25 °C, with an optimal temperature of 15 °C for lesion development [29]. In Colombia, favorable climatic conditions for the disease align with the susceptibility states of coffee fruits to

C. kahawae, suggesting that the disease could result in significant losses in susceptible varieties. Recorded losses due to this disease can reach up to 100% in regions conducive to its development [30]. The cost of chemically controlling the disease constitutes approximately 30% of the annual production cost in endemic areas [31]. Therefore, its presence on the American continent can lead to losses and increased production costs.

Coffee wilt disease (CWD), caused by *Gibberella xylarioides*, has primarily been reported in *Coffea canephora* plantations in Congo and Uganda, with occasional attacks on *C. arabica* species in Ethiopia. Managing this disease poses challenges, as is typical with most soil-borne pathogen diseases. The immediate management of symptomatic plants involves removing and on-site destroying affected trees, along with preventing the movement of infected plant material and soil. Affected fields must remain unused for coffee cultivation for several years, with non-host plants used as replacements to reduce inoculum density [32].

Additionally, the bacterium *Pseudomonas syringae* pv. *garcae*, emerging outside the coffee's center of origin, poses a serious threat as the causative agent of Bacterial Halo Blight. Although other bacterial species associated with coffee crops have been found in Brazil, *P. syringae* pv. *garcae* is the most prevalent. This disease, affecting leaves and branch tips, hampers production in high-altitude, cold-weather crops with strong winds and heavy rainfall. Young tissues are most susceptible, thus exacerbating its severity during regrowth after pruning and in nurseries [33].

The three described quarantine diseases can pose significant challenges for coffee cultivation in Colombia. Therefore, legal control and disseminating knowledge of their existence and consequences among coffee growers are crucial management tools to prevent their entry into the country.

Within Colombian territory, the ICA has issued resolutions that complement the technical recommendations of the National Coffee Research Center—Cenicafé—for the management of both quarantine and present diseases. These include periodic evaluations of monitoring lots, the use of certified seed with official registration, restrictions on the circulation of propagation material, and intervention in lots if the producer does not implement control measures. The globalization of markets and the rapid increase in trade, travel, and tourism favor the spread of exotic species [34]. The increase in international coffee trade, along with the interest in innovation in production, generates risks of the dissemination of quarantine pests. For these reasons, coffee-producing countries that are free from potentially harmful diseases such as CBD, CWD, and bacterial blight must strengthen their quarantine management strategies to minimize the risk of introduction. They should include the following instructions within their legal regulations:

a. Strictly regulate the importation of coffee seeds and seedlings.
b. Strengthen sampling plans for imports and implement rapid diagnostic methods according to the biology of the pathogens.
c. Conduct continuous field surveillance for the early detection of outbreaks.
d. Promote the development of capacities and collaboration on quarantine pests at the regional level through agreements with neighboring countries.
e. Enhance quarantine surveillance at high-risk entry points, particularly land ports.
f. Strengthen early warning and rapid response capacity.

Legal control represents the fundamental and primary method of upholding a country or region's freedom from diseases, thereby averting the need for additional control measures.

3. Cultural Control

Cultural control relies on practices aimed at preventing contact between the host and the pathogen, creating environmental conditions unfavorable to the pathogen, or reducing the amount of pathogen inoculum (Table 2). A significant aspect of disease management in coffee in Colombia is preventive measures, relying on the implementation of sound and timely agronomical practices. The first step in establishing a coffee plot is to produce

healthy and vigorous plants to sow in the field. Seed germinators should be elevated above the ground and utilize a sterile substrate to prevent damping-off caused by "*R. solani*" [35] (Figure 2a). Renovations through stumping must be executed at the appropriate time of the year, typically during months with reduced precipitation, to prevent the onset of diseases such as ceratocystis canker [36]. Keeping coffee plantations young promotes better production and prevents diseases with long infection cycles, such as crispiness caused by phytoplasms [13]. Since older plans diminish productivity and are prone to diseases, the recommended crop cycle starts with new plantings, followed by stumpings every five to six years. Implementing temporary shade plants or intercropping beans or maize in young coffee plantations, as well as setting up rows of trees acting as barriers to reduce the effects of winds, cold currents, and abrupt temperature changes causing injuries to plant tissues, not only helps to reduce the presence of dieback but also contributes to the food security of coffee farmers [37].

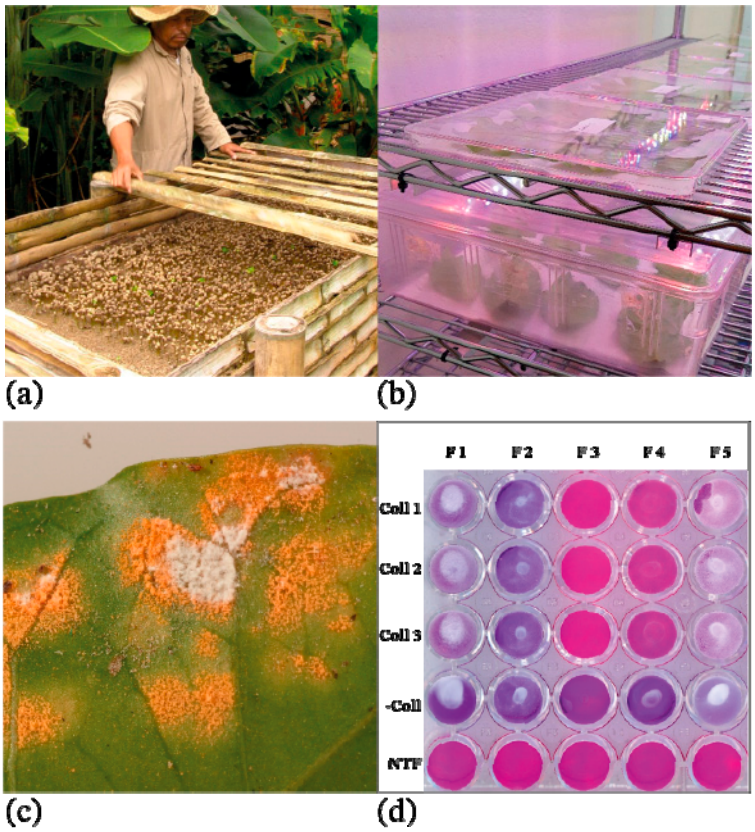

Figure 2. Technical components of the integrated disease management used in the sustainable production of Colombian coffee: (**a**) Cultural and physical control of seedling damping off caused by *Rhizoctonia solani*: utilization of germination beds filled with washed river sand to mitigate seedling attacks. (**b**) Genetic control of CLR: screening coffee genotypes under controlled conditions through detached leaf inoculation tests to identify resistant varieties against the fungus. (**c**) Biological control of CLR (orange uredospores) by *Lecanicillium lecanii* (white mycelium) in field infections. (**d**) *Colletotrichum* spp.'s response to fungicides in vitro: assessment of three strains of *Colletotrichum* spp. (rows Coll 1, Coll 2 and Coll 3) with five fungicides (columns F1, F2, F3, F4 and F5) utilizing resazurin sodium salt [38] to indicate fungicidal effectiveness, measured by the absence of metabolic activity in mycelium disks (initial purple color), compared with not treated wells (NTF). Images from Cenicafé´s archive.

Ensuring nematode-free roots can be carried out in the nursery by sampling a small percentage of plantlets, verifying the absence of knots in the roots or malformations in the taproot, such as pigtails, and discarding plants with any of the described problems

before planting the rest in the field [39]. Proper plant nutrition is another crucial practice for preserving plant health. In addition to promoting adequate root development, adjusting soil acidity is necessary to facilitate nutrient absorption by the plant. Apart from obvious deficiencies in specific minerals, diseases such as iron spot or CLR are favored by nutritional stress, especially during high yields [14,40].

Managing coffee plant densities, controlling weed presence, and regulating the amount of shade are also agronomic practices that not only affect productivity but can also lead to excessive humidity, diminished UV exposure, and reduced thermal amplitude (the difference between the maximum and minimum temperature during the day), thus favoring the onset of pink disease, anthracnose, American leaf spot disease, or CLR [41]. During renewal by stumping, the selection of suckers is necessary to maintain no more than 10,000 main stems per hectare. The pruning of shade trees, and preferably planting trees according to technical specifications, ensures adequate luminosity and humidity [41]. However, the death or removal of shade trees can lead to root rot spots due to the movement of *Rosellinia* spp. towards surrounding coffee trees [41]. Similarly, timely weed control reduces competition for nutrients and dissipates humidity and heat around the coffee trees [42].

In conclusion, the cultural control of coffee diseases is an effective and sustainable strategy for mitigating the negative effects of diseases on a crop and ensuring its long-term production. Therefore, it is crucial to implement good agronomic practices that not only benefit the farmer by increasing productivity but also minimize the effects of diseases, ensuring the long-term sustainability of cultivation.

4. Genetic Control

Among all disease control measures, the use of genetic resistance in a crop is the most easily adopted by the producer, in addition to being the environmentally friendliest alternative by reducing dependence on agrochemicals and thus lowering input costs, spray equipment, and labor. Coffee varieties with disease resistance have become an important tool in ensuring the sustainability of coffee production in Colombia [6,41]. This is because the climatic conditions of high and constant humidity and stable average temperatures throughout the year create a highly favorable environment for the dispersion and infection of phytopathogenic fungi, primarily *H. vastatrix*, which is an obligate parasite of the coffee plant and does not require alternate hosts to complete its life cycle [40]. However, other opportunistic diseases widely distributed in other plant species also pose a threat.

The recognized global importance of CLR, with devastating epidemics in Africa, Asia, and America and production losses ranging from 10% to 90% when efficient control measures are not implemented, or management costs amounting to approximately USD 350 per hectare annually, considering the cost of labor, equipment, and fungicides in the country [40,41], has promoted the improvement of disease-resistant varieties as one of the main alternatives for many coffee-producing countries. In Colombia, CLR has been a constant concern for coffee producers, particularly since the 1990s, with massive outbreaks of the disease being recorded in the country [40]. Since eco-evolutionary approaches, such as the use of mixtures of genotypes within the same species, can reduce both short-term plant disease epidemics and long-term pathogen evolution [43], this use of genetic diversity has become an important tool for CLR control in coffee production systems [6].

Through the crossing of commercial parents with resistant genotypes, mainly derived from a spontaneous inter-specific hybrid between *C. arabica* and *C. canephora* that occurred on the island of Timor (Timor Hybrid, HdT), various breeding programs have been successful in obtaining commercial varieties resistant to CLR such as Cauvery in India, the multilinear 'Colombia' variety in Colombia, and the F1 hybrid Ruiru II in Kenya [44]. The use of resistant varieties has been accompanied by the emergence of new races of the pathogen that can overcome this resistance, with the currently reported characterization of 30 physiological races [45]. On the one hand, this high mutation capacity of CLR has evidenced the presence of an incomplete or horizontal resistance background in

advanced progenies of Caturra/HdT hybrids in Colombia (Figure 2b), exhibiting typical characteristics of non-specific partial resistance to the disease [46]. On the other hand, new pathotypes have made it necessary to develop strategies that allow for field operation with durable resistance. This includes pyramiding multiple resistance genes along with those present in the Timor Hybrid, including some identified in the species *C. liberica* and *C. canephora* [46,47]. To date, 85% of the coffee cultivation area in Colombia is planted with CLR-resistant varieties [1], mainly Colombia and Castillo varieties and, more recently, Cenicafé 1 [6,41] (Table 2).

Efforts to develop resistance to other diseases, such as coffee berry disease (CBD), have been noteworthy. The selection of progenies for CBD resistance involves utilizing molecular markers associated with genes from the Rume Sudan accession (R gene) and the Timor Hybrid (T gene), which are already incorporated into commercial varieties in Kenya and Colombia [48,49]. Field trials have also been conducted to assess resistance to ceratocystis canker (*Ceratocystis fimbriata* and *C. colombiana*) using a Bourbon variety accession [50]. This research is significant due to the stem renewal process carried out every 5 or 6 years [51]. Prospecting coffee germplasm collections is essential to identifying resistance sources for many other coffee diseases that currently lack genetic control options.

Genetic control using resistant varieties should consider not only incorporating disease resistance but also preserving agronomic characteristics of interest to the producer, such as productivity, plant height, architecture, and adaptation to prevailing environmental conditions. In this way, since 2013, coffee production has increased by 23% when CLR-resistant varieties started to be widely used in Colombian territory, with a significant reduction in the use of fungicides across the country [1]. Additionally, bred varieties present an opportunity to improve the physical and sensory quality aspects of the coffee bean, resulting in increased profitability for the farm and beneficial effects on the environment [41]. For genetic control to be effective, it is necessary to have the support of a seed production system that guarantees the genetic identity and stability of the plant material to be delivered to the farmer [6,41].

5. Physical Control

Physical methods for disease control are widely utilized to manage soil-borne pathogens and those transmitted through seeds. Soil-borne pathogens can affect their hosts at any stage of the life cycle and specialize in underground organs, particularly the stem base and roots, thereby significantly impacting plant health and survival. Normal management practices involve the removal of affected individuals. In coffee cultivation, the progressive loss of plants in a plot results in reduced production; therefore, to ensure the economic viability of the crop, reseeding should be carried out once a threshold of 10% is exceeded [52].

The most important soil pathogens in coffee fields in Colombia are *Rosellinia* spp., *Ceratocystis sensu lato*, and *Meloidogyne* spp. [7]. In all cases, control is preventive, establishing the crop in plots with no history of these pathogens' presence. However, since they are natural inhabitants of the soil and have a wide range of hosts, their occurrence is common in coffee-producing areas. To ensure the economic sustainability of coffee cultivation in the presence of symptoms caused by *R. pepo* and *R. bunodes*, the recovery of lost sites is fundamental. This is achieved through a combination of physical and biological management tactics. Once diseased plants are identified, they must be removed along with neighboring plants suspected of being infected. Subsequently, the soil from each site is excavated, and all roots are removed, taken out of the plot, and burned. Infested sites are then subjected to solarization for three months [53].

Solarization is a hydrothermal process in which the infested soil is covered with transparent plastic to absorb radiation. This treatment has effects on pathogens, the microbial community, and the host. The soil intercepts solar energy, increasing its temperature to levels that are harmful to most soil-borne phytopathogenic microorganisms. The effect on the host is indirect, improving soil texture and nutrient availability, which are essential for its growth and development. In Colombia, there are regions with coffee cultivation

under open sun exposure where optimal conditions for implementing the technique occur during the dry season (Table 2). The effects of solarization on soil microbiota diversity are varied. While there is a decrease in populations of microorganisms sensitive to the temperatures reached by the treatment and toxic substances derived from organic material decomposition, the repopulation by some antagonists of phytopathogenic organisms is rapid due to increased soil nutrients [54].

In coffee, the highest concentration of roots is found within the first 25 cm of the soil profile [55], making solarization effective for controlling soil pathogens. After removing the infected plants and residues, the management of *R. pepo* and *R. bunodes* proceeds with solarization for three months, with flipping and homogenization performed monthly [53]. Before new planting, integrated management must include the application of fungicides like Methyl Thiophanate to the soil and *Trichoderma koningii* to the planting sites, in addition to inoculating the replacement plants with mycorrhizae (*Glomus fistulosum*, *G. manihotis*, and *Entrophospora colombiana*) during the seedling stage [56,57].

6. Biological Control

Biological control employs living organisms to minimize the impact of pathogens, offering a safer and more effective alternative to chemical pesticides without adverse effects on the environment and human health. Various coffee diseases can be managed through biological control, which proves particularly effective under regulated conditions such as germination beds and nurseries, as well as in stable environments like specific soil types. However, for diseases affecting the aerial parts of the plant, the results of applying biological control agents have been less consistent, especially in regions like Colombia where high and frequent precipitation is common and stable temperatures throughout the year provide ideal conditions for pathogen proliferation.

The most prevalent method for utilizing antagonists involves adding *Trichoderma harzianum* to the sand used in coffee germination beds to control the presence of *Rhizoctonia solani*, the causal agent of damping off [56,58]. This treatment must be administered preventatively, at least 6 days prior to seed sowing, allowing sufficient time for the biocontrol fungus to proliferate and colonize the substrate (Table 2). Additionally, maintaining appropriate humidity levels is essential [35]. In the case of nematodes belonging to the genus *Meloidogyne*, a combination of the fungi *Paecilomyces lilacinus*, *Metarhizium anisopliae*, and *Beauveria bassiana* has proven effective [59]. These can be applied either prior to filling the bags with the mixture of soil and decomposed pulp or within one week after the seedlings are transferred from the germination bed to the nursery bags [38]. This approach can be complemented with the addition of mycorrhizae, which forms a physical barrier around the roots, impeding nematode infestation [60].

The application of *Trichoderma harzianum* has also emerged as an option for controlling the attack of *Ceratocystis* spp. [61], which causes ceratocystis canker in wounds resulting from routine stumping or pruning [52,62]. These activities are integral to the renewal of coffee plantations, ensuring the vitality and productivity of the crops. Similarly, in soils treated against root rot diseases caused by *R. pepo* or *R. bunodes*, Trichoderma infestations have shown efficacy after physical controls such as solarization or chemical treatments have been applied to reduce the inoculum present in the organic matter. This approach, when combined with prior inoculations of mycorrhizae in replacement coffee plants sourced from nurseries, enhances overall disease management strategies [60].

Reports exist regarding strategies for the biological control of CLR using antagonistic fungi like *Trichoderma* spp. [63] and bacteria such as *Bacillus subtilis* or *Pseudomonas* spp. [64,65], as well as for the management of iron spot [66] and anthracnose [67], all including mechanisms involving the production of antagonistic metabolites, competition for nutrients, space on coffee leaves (Figure 2c), or the induction of plant resistance. However, evaluations of commercial products under experimental field conditions have yet to yield viable alternatives recommended for coffee crop protection against diseases.

Stringent regulations are imperative to ensuring the quality of commercial biological control products. Factors such as the genetic identity of the biological agent, its germination capacity, and the quantity of inoculum play pivotal roles in determining the success of their application. For producers, understanding that biological control operates differently from traditional chemical methods is crucial. This entails adopting preventive measures and optimizing conditions for the application of biocontrol agents, including product preparation, timing, humidity levels, UV exposure, and equipment selection. Such awareness is essential for seamlessly integrating this form of control into farm routines.

7. Chemical Control

Chemical control stands as one of the most frequently employed components in integrated disease management strategies. Agrochemicals have gained widespread use for their ability to promptly mitigate pathogen effects, either by exterminating them or curbing their growth and reproduction. The efficacy of this approach hinges on precise crop management practices from an agronomic standpoint, coupled with the accurate selection of application technology (including calibration, volume, and preparation). This ensures the fungicide's optimal biological effectiveness, thereby achieving the objective of minimizing pathogens' impact on the plant. More than with any other aspect of integrated disease management, careful considerations must be made regarding the costs-effectiveness and prerequisites for chemical control's use, encompassing factors such as product availability, procurement costs, necessary equipment for application, personnel training and protective gear, legal regulations, the effect on non-target organisms, resistance development on pathogens, market concerns on residues, and disposal procedures for leftover chemicals and containers. Nonetheless, integrated disease control demands the sustainable use of these products to extend their effectiveness over time, ensuring their availability when required by the farmer [68,69].

In Colombian coffee production systems, fungal diseases exert the most significant impact, leading to the common utilization of fungicides based on their mode of action, whether as protectants or curatives, and for local or systemic purposes. Protectants are administered before infection occurs to establish a barrier against the fungus, whereas curative fungicides are applied post-infection, aiming to halt the pathogen's spread. Contact fungicides act locally, remaining on the plant's surface for direct contact with the pathogen and providing external protection. In contrast, systemic fungicides are absorbed and dispersed throughout the plant, delivering internal defense against fungal pathogens. Notably, they can even appear in newly developed tissues following their application [14].

Rainy periods define stages crucial for fruit formation and abundant foliage, conditions that foster the development of epidemics, particularly CLR, the predominant disease in Colombia, capable of impacting nationwide yields. CLR stands as the sole ailment necessitating continuous epidemiological monitoring, prompting various fungicide spraying programs throughout the year [70] (Table 2). The fungus's growth rate significantly hinges on the volume of residual inoculum (CLR-infected leaves) during periods of extensive foliage and fruit formation. Moreover, research has revealed coffee plants' heightened susceptibility to CLR when experiencing high and concentrated production [71,72]. In the absence of disease control and favorable climatic conditions for epidemic expansion, the ailment progresses daily at a rate nearing 0.19% [14], necessitating swift preventive measures like fungicide applications during susceptibility peaks.

Given that CLR primarily affects foliage, preserving leaves becomes paramount, as they play a pivotal role in producing and supplying assimilates to developing fruits. Studies have highlighted the critical nature of maintaining healthy foliage from 60 days after flowering until 30 days before the peak harvest level [73]. Furthermore, ensuring foliage health not only secures the quantity and quality of ripe coffee during the production cycle but also fosters optimal plant development and sustains productivity in subsequent years. Effective fungicide control measures should commence during the initial phase of disease development, characterized by a low percentage of affected leaves [14].

Whether combating CLR or addressing any other disease, achieving biological effectiveness entails meeting specific requirements [14]:

a. Selecting appropriate fungicides based on the disease and its stage of development (preventive or curative) and implementing a proper rotation of products with different modes of action to prevent fungal resistance. For CLR control, a combination of triazoles (like cyproconazole) and strobilurins (such as azoxystrobin) has been demonstrated to be efficient [14]. Fungal sensitivity to fungicides is tested in vitro [38] (Figure 2d)., and formulation efficacy is tested in field assays
b. Timely application based on crop phenology and disease levels measured as incidence or severity. Considering the distribution of rainy periods throughout the country, the control of fungal diseases is determined mostly by flowering events, which, in the case of CLR, normally involves two sprays 60 and 120 days after floral anthesis [14].
c. Utilizing appropriate application technology and dosification.

Finally, chemical control in coffee plantations in Colombia must be used judiciously within the framework of integrated disease management, considering its potential effects on the environment and human health if excessively applied. The aim is to continuously enhance sustainable agricultural practices on farms. However, the current constraints regarding Maximum Residue Levels (MRL) and the banning of active ingredients at the international level pose significant challenges for producers in balancing productivity, production costs, and market availability. This occurs against a backdrop of increasingly stringent regulations by governments and farmers' expectations for long-term viability in the industry [74].

Table 2. Main measures implemented in the integrated management strategy of coffee diseases in Colombia and their effect on epidemics.

Common Name	Management Measure	Description	Effect	Reference
Quarantine diseases	Legal	Field surveillance, interception in ports, and exclusion by legal regulation of the movement of plants and their parts among countries.	Avoids the introduction of pathogens to disease-free areas.	[21,22]
Coffee leaf rust (CLR) *Hemileia vastatrix*	Genetic	Resistant varieties: Colombia, Tabi, Castillo, Castillo® Regionales (North, Center and South), and Cenicafé 1	Lowers infection rates Slows down epidemics. Long incubation period Low uredospore production	[44,48,75]
	Chemical	Fungicides applied based on any of the following criteria: 1. Fixed calendar 2. Main flowering time 3. Incidence of the disease	Reduction in disease progress: Inoculum eradication Lowers infection rate by preventing fungal infection, colonization, and reproduction	[14]
American leaf spot, gotera or ojo de gallo *Mycena citricolor*	Fungicides	Applied based on any of the following criteria: 1. Main flowering time 2. First symptom detection	Reduction in disease progress: Inoculum eradication Lowers infection rate by preventing fungal infection, colonization, and reproduction	[76,77]
	Cultural	Soil drainage to remove excess humidity. Shade regulation and proper light availability. Lowers plant density to favor aeration and diminishes humidity presence on leaves. Pruning of symptomatic organs.	Avoids proper environmental conditions for disease development.	[76,77]

Table 2. *Cont.*

Common Name	Management Measure	Description	Effect	Reference
Canker stain and wilt *Ceratocystis fimbriata*	Cultural combined with chemical control	Planting, pruning, and stumping during dry season.	Avoids climate conditions that benefit fungal infection.	[36,62]
		Disinfection of injuries	Chemical disinfection to protect the host	[36]
Black root rot *Dematophora pepo* and *Dematophora bunodes*	Physical	Eradication of infected plants and site solarization	Inoculum eradication	[53]
Damping off *Rhizoctonia solani*	Cultural	Elevating germination beds and clean substrate.	Avoids infection	[35]
	Biological	*Trichoderma harzianum*	Avoids infection, controlling primary inoculum by mycoparasitism, competition for resources, and antibiosis	[56]
Iron spot, berry blotch *Cercospora coffeicola*	Cultural	Proper plant nutrition. Shades plants	Avoids environmental conditions that favor disease development	[78]
Pink disease *Necator salmonicolor*	Cultural	Improves aeration in the field Pruning of symptomatic branches during the dry season. Includes alternate hosts in close proximity	Avoids proper environmental conditions for disease development Elimination of inoculum reservoirs	[79]
Dieback *Phoma* sp.	Cultural	Protects young plants from wind, planting beans or corn as physical barriers.	Protects plants from injuries caused by cold winds.	[80]
Root knot *Meloidogyne* spp.	Cultural	Use of clean substrates in nurseries, followed by monitoring. Brings healthy plants to the field. Crop rotation in the field with non-host species	Avoids infection by controlling primary inoculum.	[38]
	Biological	Mix of *Metarhizium anisopliae*, *Paecilomyces lilacinus*, and *Beauveria bassiana*	Avoids infection by controlling primary inoculum by parasitism, competition for resources, and antibiosis	[59]

8. Conclusions

Coffee producers worldwide face the challenge of managing diseases each season, ranging from local and opportunistic to global and persistent ones. The variability in weather conditions, the investment capacity for farming practices, the availability of technical advice, and farmers' knowledge determine whether diseases become production-limiting factors or remain manageable. Minimizing the impact of these diseases on the coffee supply and growers' income is crucial. While science has developed various methods to control pathogens, it is their integration that can allow for economic, labor, and ecological efficiency to be achieved. Colombian coffee growers have chosen to develop their own disease management recommendations based on scientific research conducted at their National Research Center, Cenicafé.

This approach has facilitated the alignment of disease control measures with technical advancements in agronomic plantation management to enhance productivity. However, it also entails significant effort in monitoring and implementing preventive measures. These efforts trigger early alerts at the local or nationwide level, allowing for a more efficient allocation of resources. Disease surveillance has been carried out for the last decade using

a standard methodology carried out by the Extension Service of the National Federation of Coffee Growers: randomly selecting 3000 coffee plots across the country, evaluating the main diseases and pests, as well as nutritional disorders, and publishing a quarterly bulletin that outlines specific actions to maintain healthy and productive plantations [81]. Besides recording the durability of genetic resistance to CLR and the onset of new rust pathotypes, this monitoring indicates the occurrence of warning thresholds (5% incidence) or spraying warnings (15%) [14].

In addition to agronomical enhancements, coffee production must advance together with cherry processing improvements, thereby elevating the quality of the beverage while ensuring market acceptance in terms of safety standards.

Nevertheless, further research is imperative to anticipate variations in pathogenicity, adapt to climate changes, and meet evolving market and consumer expectations. The industry's support is crucial for fostering innovation in products, equipment, and higher environmental and safety standards. These advancements will enable continued progress in integrated disease management, ultimately ensuring the supply of even better coffee to the world.

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