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Review

Strategies for Coffee Leaf Rust Management in Organic Crop Systems

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Abstract: Coffee is a crop of great economic importance in many countries. The organic coffee crop stands out from other production systems by aiming to eliminate the use of synthetic fertilizers and pesticides. One of the most important limitations in the organic system is the management of diseases, especially coffee rust, which is considered the main disease of this crop. Coffee rust causes a production slump of up to 50%, significantly affecting the profitability of coffee growers. This work aims to review the integrated rust management in organic coffee crop in different producing countries. Regarding the disease management strategies, this review addresses the use of rust-resistant cultivars, cultural management, biological control, use of plant extracts, and chemical rust control by cupric fungicides. Considering the importance of the organic system, the increase in world coffee consumption, and the potential market for this kind of coffee, this review may help researchers and producers looking for alternative strategies to control rust in an organic coffee cultivation system.

Keywords: organic agriculture; alternative control; plant disease; *Hemileia vastatrix*; *Coffea* sp.

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1. Introduction

Organic agriculture is a holistic production management system that aims to eliminate the use of synthetic fertilizers and agrochemicals by promoting environmental agroecosystem sustainability, in addition to the social and economic sustainability of the rural producer [1,2]. Among all the main products from the organic farming system, coffee stands out as one of the most consumed beverages worldwide. In recent years, there has been an approximate increase of 2% in the world coffee consumption, with 167,592 60 kg bags consumed only in the period 2019/2020 [3].

Organic coffee is grown on over 700 thousand hectares in the world and represents 6.7% of the global area planted with coffee [4]. There are several organic coffee-producing countries, including Brazil [5], Bolivia [6], Colombia [7], Costa Rica [8], Ethiopia [9], Honduras [10], Mexico [11], Nicaragua [12], and Uganda [13].

The coffee produced in this system has the potential for good cup quality [14], known as specialty coffees, which have attracted the attention of demanding consumers. Various products from the organic system of production are available in markets around the world. In addition to the pure roasted coffees and their blends; the decaf, the flavored one, the instant one, and the coffee capsules also stand out. Organic coffee has also been used to prepare desserts, soft drinks (ice cream and soft drinks), and candies, among others [15].

Although organic products have higher prices than conventional ones [16], sustainability is the main characteristic that positively influences consumer behavior for organic products, increasingly concerned with their health and the environment [17]. By restricting or eliminating the use of agrochemicals in the organic system, the threat of pests and diseases can increase [18]. Therefore, one of the greatest challenges in organic production is the management of plant diseases [19]. In the case of the organic coffee production system, the management of rust stands out since it is considered the main disease of the crop.

Coffee rust, a disease whose etiologic agent is the biotrophic fungus *Hemileia vastatrix* Berkeley & Broome causes losses from 30% to 50% in coffee production, depending on the level of resistance of the genotype, favorable climatic conditions for the disease, and management measures [20–23]. To aggravate the scenario, the impacts caused by coffee rust tend to increase due to global climate changes [24].

Considering the importance of this production system and the potential market for organic coffee in the world, a better understanding of how to manage its main disease, rust, is fundamental. In this regard, this paper discusses strategies for the integrated management of rust in the organic coffee cultivation system in different producing countries. In this review, the use of rust-resistant cultivars, cultural management, biological control, plant extracts, and chemical rust control is addressed.

2. Organic Agriculture

In the 1930s and 1940s, a movement in favor of organic agriculture was set in motion, aiming to reduce dependence on synthetic fertilizers and prioritize a sustainable production system with food security [2]. Organic food production started to gain popularity in the countries of Europe and North America, as well as Japan, approximately 30 years ago [25]. At that time, the organic food production system was recognized by some governments due to its economic growth, raising consumer awareness and preference [26]. Today, the term "organic" is considered an attribute of credibility due to several benefits related to the consumption of organic foods [27].

The main attributes favoring the consumption of these foods are the concern with environmental preservation, the beneficial effects on human health, and the nutritional quality of organic foods [28,29]. According to Popa et al. [30], the specific reasons related to these attributes include the following:

- Activation of the plant's defense system with the use of natural pesticides,
- Minimal loss of the nutritional value of fresh fruits and vegetables,
- Certification of organic production,
- Environmentally friendly agricultural system.

Organic Coffee Production

Organic coffee production is based on a sustainable cultivation system that eliminates the use of synthetic agrochemicals [31], reducing the dependence on fertilizers and pesticides, which are mostly imported from non-coffee-producing regions, in addition to guaranteeing better prices in specialized markets [32]. The main organic practices in coffee, according to Consonni et al. [33], are the following:

- The nonuse of chemical fertilizers, pesticides, herbicides, fungicides, hormones, antibiotics, or growth regulators,
- The use of compost, agricultural manure, green manure, and crop rotation to maintain and/or increase soil fertility,
- Soil management and crop diversification,
- Weed control by mechanical methods,
- Use of chemical-free and uncontaminated composting materials.

The producer's choice for organic management is influenced by several factors, such as (i) the availability of technology and community organizations, (ii) educational training, (iii) knowledge of agricultural practices, (iv) design of the coffee plantation, (v) coffee grower productivity and income, (vi) production costs and profitability, and (vii) interactions among these factors [34]. Another factor of great importance in choosing organic management is certification, to inform consumers that the product to be purchased has the characteristics of organic coffee, especially concerning the production chain [16].

Organic certification imposes some requirements on producers, such as the interruption of the use of synthetic fertilizers and agrochemicals, the adoption of conservation and pollution prevention practices during a transition period of 2–3 years, and the establishment of an internal control system to guarantee compliance with organic farming standards [7,8]. Despite these requirements, the organic coffee production system has advantages over the conventional one, such as (a) low dependence on external inputs, (b) competitive productivity regarding the average production in the conventional system, (c) added value to the product, (d) diversification of production, (e) alternative strategies for market access, and (f) improvement in soil fertility in terms of physical, chemical, and biological diversity [35,36].

3. Coffee Rust

Coffee rust, a disease caused by the biotrophic fungus *Hemileia vastatrix*, was described in 1869 by Berkeley on *C. arabica* leaves from Sri Lanka [22]. The symptoms include large orange spore masses on the abaxial leaf surface (Figure 1), which reduce the photosynthetic area of the leaf and lead to its premature fall [21], along with, in more severe cases, the death of branches, resulting in a significant decline in coffee production [37].

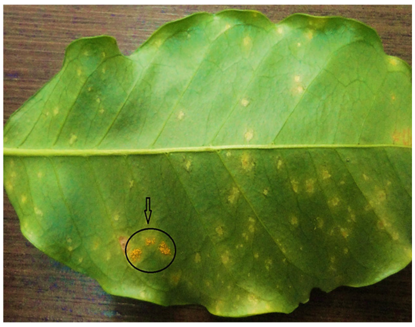

Figure 1. Leaf symptoms of coffee leaf rust on abaxial surface.

Due to the intensification of the coffee rust epidemics in Central and South America, there has been an estimated 30% to 90% of losses since 2012 [37]. In addition to the limitation of coffee production, the current rust epidemic in Latin America represents a socioecological crisis, as seen in Mexico, the largest producer of organic coffee [38].

The integrated rust management in an organic coffee growing system is a disease control strategy with environmental, economic, and social benefits [39]. In this review, the aspects of breeding coffee are addressed, aiming at rust resistance, cultural management, biological control, use of plant extracts, and chemical control allowed in organic crops.

3.1. Genetic Resistance

The use of rust-resistant coffee cultivars is considered the best method for managing the disease in the long term, also as well as organic systems [19,40]. In spite of this, many coffee growers still plant traditional cultivars (rust-susceptible), such as Typica, Bourbon, Mundo Novo, and Caturra; even when they choose resistant cultivars, the replacement of susceptible ones is very slow [24,41]. The delay in adopting resistant cultivars by coffee growers can be attributed to little knowledge about the advantages of new cultivars, as well as limited lines of credit for financing inputs and replanting, inefficiency in the multiplication and distribution of new cultivars, and skepticism among coffee traders regarding the cup quality of resistant cultivars [42].

In countries where most of the planted cultivars are susceptible, such as Honduras, Mexico, and Brazil, an alternative to reconcile rust resistance and cup quality is the diversification of production between susceptible and resistant cultivars [43,44]. In Brazil, several research institutions (EPAMIG, Fundação Procafé, IAC and IAPAR) recently launched *C. arabica* cultivars with rust resistance, good agronomic performance, and good cup quality [45–48]. The cultivars Araponga MG 1, Catiguá MG 2, and Pau-Brasil MG 1 (highly resistant to rust) and progenies Icatu V. IAC 4040 × IAC 5002 and Icatu A. IAC 2944 × IAC 5002 (progenies in the F3 generation with partial resistance) are those that stand out.

As an example of the differences in rust incidence in susceptible and resistant cultivars in agroecosystems with organic coffee production, Martins et al. [49] evaluated the susceptible cultivar Catuaí Vermelho and the resistant one Icatu Amarelo. The rust incidence surpassed 10% in the susceptible cultivar, while, in the resistant one, rust incidence was not observed and, consequently, did not reach the economic damage level. The rust severity was assessed in 10 coffee cultivars in San Ramón (Chanchamayo, Peru), and the cultivar Pacamara showed the lowest disease severity [50]. The genotype resistance is related to the combination of rust resistance genes (SH) with higher (major genes) and lower (minor genes) effects. The strategy of combining resistance genes is commonly used in breeding programs to develop cultivars with durable resistance to rust. Thus, the main rust-resistant coffee cultivars planted in organic coffee-producing countries are detailed in Table 1.

Due to pathogen diversity, the selection of isolates or even new pathogenic strains can occur in resistant cultivars. The occurrence of rust in cultivars classified as disease-resistant in Central America was reported by Perla [51]. This resistance breakdown can be explained by the high genotypic diversity associated with a high gene flow in the population of *H. vastatrix* [22], and, because of this breakdown of resistance in genotypes traditionally resistant to rust, such as Timor Hybrid (HDT)-derived genotypes [52,53], new resistance strategies and sources are being investigated to obtain new cultivars. In Honduras, after the rust epidemic of 2011, the organic coffee growers increased the cultivar diversity and the plantation of rust-resistant cultivars [41].

A strategy for obtaining durable resistance to the high genetic and pathogenic variability of *H. vastatrix* is the use of cultivars with horizontal resistance, which, unlike vertical resistance, is not specific to a particular strain of the fungus [22]. A variety developed in Central America and considered a promising one is the "hybrid of first-generation (F1)", which is adapted to different environmental conditions and displays a production from 30% to 60% higher than traditional cultivars [54]. Another rust-resistant variety reported in Central America is the Marsellesa, a hybrid of Sarchimor, developed by the Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD) and ECOM Trading [55].

Table 1. Rust-resistant coffee cultivars planted in different countries producing organic coffee and organic area by country 2019 [1].

Coffee Cultivars	
Mexico [2] (72.900 ha)	Colombia [3] (12.773 ha)
Costa Rica 95	Colombia
Sarchimor (T 5296)	Castillo
Iapar 59	
Oro Azteca	El Salvador [3] (1.522 ha)
Anacafe 14	Catisic
Nicaragua [3] (31.094 ha)	Costa Rica [3] (591 ha)
Catrenic	Costa Rica 95
Honduras [4] (23.500 ha)	Brazil [5] (576 ha)
Catimor	Pau-Brasil MG 1
Lempira	Paraíso MG H419-1
Ihcafe-90	Catiguá MG 1, MG 2 and MG 3
Icatu	Araponga MG 1
Obatã	Catucaí 20/15-479; 2 SL e 785/15
Parainema	Obatã IAC 1669-20
Revoltijo	Tupi IAC 1669-33
Cuba	Iapar 59
Sarchimor	Acauã
Paisano	Icatu Vermelho and Icatu Amarelo

Sources: [1] [4]; [2] [56]; [3] [37,56]; [4] [41]; [5] [22].

In Central America, another two species that have been recently studied are the *C. charrieriana* and *C. anthonyi*, which can be sources of new rust resistance genes combined with other characteristics, such as cup quality [54]. Today, the development of new rust-resistant varieties can be accelerated by using DNA-based tools such as molecular markers [54].

3.2. Crop Management

Crop management is one of the principal methods of disease control in the organic coffee system, being considered economically viable since adequate agronomic practices can also contribute to increasing production [19]. As a cultural practice, the emphasis will be on the effects of shading and plant nutrition in the management of coffee rust. The effect of shading on rust incidence was verified by Ehrenbergerová et al. [57] in the Catimor and Caturra varieties in the Pasco region, Peru. According to the authors, the influence of shading on the incidence of coffee leaf rust was not steadfast in the varieties and conditions evaluated. That is, it can either reduce or increase the disease progress rate. Therefore, one must analyze the cost–benefit in adopting this system, analyzing several points such as disease control, productivity, and the amount to be paid by consumers in this type of production system.

In addition to hindering crop mechanization, an irreversible trend in Brazil due to the cost of labor, shading of coffee trees can reduce both the temperature and the photosynthesis of the leaves, causing a decrease in productivity. Consequently, the added value of the product bag or coffee production should be greater, helping producers to maintain not only environmental sustainability but also financial sustainability. Moreover, shading can increase the progress rate of coffee rust, since the fungus needs both shading and a longer moistened period on the leaf surface to germinate [58].

Nutrition is another important aspect in rust management, especially in the organic system, since the susceptibility to rust is associated with the nutritional status of the plant [41]. Mineralization and the slow nutrient release by organic fertilizers to the coffee trees can cause a temporary nutritional imbalance during the production cycle, favoring the progress of rust [59]. Balanced proportions of nitrogen (N) and potassium (K) reduced the rust severity in coffee seedlings [60]. Increasing the dose of N caused a reduction in the disease severity, mainly at higher doses of K. The effect of different doses of boron (B), zinc (Zn), and manganese (Mn) on the severity of coffee rust in plants growing in nutrient solution was evaluated by Pérez et al. [61]. The three nutrients influenced the disease severity, and the reduction was observed with a dose of 2.0 mg/L of Zn. The results of these studies demonstrated the importance of balanced mineral nutrition as a rust management strategy, reducing the disease progress rate. It is noteworthy that, in crops already in production, the coffee tree nutrition must be reinforced in years of high pending load since there is a strong metabolic drain directed to the fruits in such conditions, which weakens the leaves and makes them more susceptible to rust and other leaf diseases.

The application of silicates or silicon-based products is also characterized as an alternative for the management of rust [22]. These products are allowed in disease management in organic crops as long as the maximum limits for heavy metals in their composition are not exceeded. The foliar application of potassium silicate affected the process of infection of the rust fungus, resulting in lower colonization of *H. vastatrix* in leaves sprayed with potassium silicate than in control plants [62]. It is noteworthy that potassium silicate also induces resistance against *Cercospora coffeicola* (brown eye spot), another relevant disease in coffee crop [63].

Different nutritional sources from animals or plants can be used to fertilize the organic plantations [64]. Nonetheless, nitrogen (N) still remains a nutrient that is usually found at low levels in organic coffee plantations, and its low availability is directly related to rust intensity [60]. Ricci et al. [65] evaluated six cultivars of *C. arabica* with different levels of rust resistance cultivated with and without *Crotalaria juncea*. The authors found that the use of *C. juncea* can be an alternative for the producer as a source of N in organic systems, as long as it is properly monitored and incorporated into the soil at the right time.

In a comparative study of coffee cultivars with different levels of rust resistance in an organic cultivation system in Zona da Mata Mineira, Brazil, Moura et al. [66] found low incidence of rust in the cultivars Sabiá 708, Catucaí Amarelo 24/137, IBC Palma 1, Paraíso MG H 419-1, Catucaí Vermelho 36/6 and Oeiras MG 6851. According to the authors, in addition to genetic factors, the use of castor cake and *C. juncea* as sources of nitrogen and balanced fertilization may have contributed to this result. The influence of the application of castor bean cake in association with coffee husks and coffee husks with swine manure on rust incidence in the organic system was studied by Santos et al. [59], who observed disease reductions of 31% and 21% when compared to the untreated control, respectively.

3.3. Biorationals

The use of organic substances, such as plant extracts, can reduce the damage caused by coffee leaf rust [67] (Table 2). Aqueous extracts of branches of *Solanum lycocarpum* (known as "lobeira" in Brazil) infected with *Crinipellis perniciosa* reduced the incidence and severity of rust by 28% and 27%, respectively [68]. Most likely, fungal elicitors present in the extract may be acting as resistance inducers against rust in coffee, which are compounds that activate chemical defense in plants [69]. Resistance induction is a promising alternative in disease management, and several compounds have been reported as resistance inducers, such as chemical inducers (acibenzolar-*S*-methyl (ASM) and salicylic acid), bacterial elicitors (flagellin and pectinases), fungal elicitors (chitin, chitosan, and poly- and oligoglucans), algal extracts, and extracts of higher plants [70].

In another study, Cerna-chávez et al. [71] applied extracts of *Cinnamomum verum* and *Citrus sinensis* in the Caturra variety and found a 90% and 92% reduction in disease severity, respectively. Aqueous extracts of coffee leaves, suspensions of fungal conidia and bacterial cells, foliar fertilizers, hypochlorites, and the resistance inducer ASM were evaluated in the cultivar Catuaí Vermelho IAC 144 under greenhouse conditions [72]. The extracts of coffee leaves, ASM, *Bacillus subtilis*, and *Pseudomonas putida* reduced the infection caused by *H. vastatrix* by more than 77%. However, the importance of carrying out such assessments in the field is emphasized.

Formulations based on natural products (Greenforce Cuca and Fitoforce Full formulations based on byproducts of the coffee industry) have shown efficacy for the control of coffee rust [73–75]. The promising results of these formulations for disease management may be related to their properties, such as a high content of chlorogenic acid and caffeine and the presence of other compounds such as nicotinic acid, trigonelline, tocopherol, and cafestol [76], which lead to the activation of plant defense responses [73].

Biofungicides based on *Azadirachta indica*, *Melaleuca alternifolia*, and the combination of *Bacillus subtilis* with *A. indica* and *Syzygium aromaticum* were evaluated in coffee rust management for the cultivars Garnica and Typica under field conditions [77]. The authors observed that the plants of the two cultivars sprayed with *M. alternifolia* showed reductions in the incidence and apparent infection rate of the disease in plants of both cultivars sprayed with *M. alternifolia*.

Table 2. Studies of biorational control strategies for coffee rust management.

Biorationals	Results
Plant extracts	
Extract of rust-infected coffee leaf and extract of *Solanum lycocarpum* infected with *Crinipellis perniciosa* [68]	Reduction of 31% and 27% in rust severity, respectively
Extracts of *Cinnamomum verum* and *Citrus sinensis* [71]	Reduction of 90% and 92% in rust severity, respectively
Aqueous extracts of coffee leaves [72]	Reduction in rust infection by more than 97%
Formulations based on natural products	
Greenforce Cuca (product of coffee industry + copper and calcium salt) [73]	Control of rust: protective effect
Greenforce Cuca [74]	Reduction of 48% in rust incidence (mean of 2 years)
Fitoforce Full: product of coffee industry + P_2O_5 (15.1%) and Cu (2.85%) [75]	Control of 47% in rust severity (mean of 2 years)
Resistance inducers	
Acibenzolar-*S*-methyl (ASM) [72]	Control of 53% in rust severity (mean of 2 years)

Table 2. *Cont.*

Biorationals	Results
ASM [78]	Reduction of 12.1% in rust severity
K phosphonate 1: P_2O_5 (35%) and K_2O(25%); K phosphonate 2: P_2O_5 (33.6%) and K_2O (29.0%) [74]	Control of 47% and 74% in rust severity (mean of 2 years)
Mn phosphonate: P_2O_5 (51.0%) and Mn (9.7%) [74]	Control of 62% in rust severity (mean of 2 years)
Cu phosphonate: P_2O_5 (20.3%) and Cu (4.0%) [74]	Control of 37% in rust severity (mean of 2 years)
Biofungicides	
Plants sprayed with *Melaleuca alternifolia* [77]	Reduction regarding the control of 20.9% (incidence), 14.2% (AUDPC [1]), and 39.1% (apparent infection rate)
Essential oils	
Clove and lemongrass essential oils [78]	Reduction of 67.9% and 67.7% in rust severity, respectively
Tea tree and cinnamon oils [78]	Reduction of 55.4% and 45.3% in rust severity, respectively
Thyme and citronella oils [78]	Reduction of 37.5% and 32.7% in rust severity, respectively
Eucalyptus citriodora, *E. Camaldulensis*, and *E. grandis* essential oils [79]	Inhibited 100% of the germination of *H. vastatrix* spores

[1] AUDPC: Area under the rust incidence progress curve.

The use of essential oils from different plant species has shown promising results in coffee rust management. Essential oils of cinnamon, citronella, lemongrass, cloves, tea tree, thyme, and eucalyptus inhibited the urediniospore germination, and the oils of thyme, clove, and citronella were the most efficient in controlling the disease [78]. The essential oils from four species of *Eucalyptus* (*Eucalyptus citriodora*, *E. camaldulensis*, *E. grandis*, and *E. microcorys*) showed antifungal activities against *H. vastatrix* in for most of the oils evaluated, except for *E. microcorys* oil [79]. Nonetheless, additional studies must be carried out to measure the percentage of control of these products in the field.

3.4. Biological Control

Studies on the biological control of *H. vastatrix* are underway (Table 3), and some products are already registered for its control. In Brazil, for instance, we have the example of the product Biobac®, which features *Bacillus subtilis* Y1336 in its composition. Several authors have investigated the use of biological agents for coffee rust control. Haddad et al. [18] evaluated seven bacterial isolates, copper hydroxide, and calcium silicate in organic coffee plants located in Minas Gerais, Brazil. The isolate B157 from *Bacillus* sp. reduced the intensity of rust and was as effective as copper hydroxide. Another microorganism with potential to control *H. vastatrix* is the fungus *Lecanicillium lecanii*, reported in different studies [80,81].

The occurrence of microorganisms antagonistic to *H. vastatrix* isolated from organic crops in Brazil was studied by Haddad et al. [82]. A total of 393 microbial isolates were evaluated, and 17 of them presented a reduction in the infection occurrence and number of *H. vastatrix* urediniospores produced per leaf by 70%. Daivasikamani et al. [83] evaluated the effect of antagonist bacteria isolated from the rhizosphere of coffee crops on rust control. According to the authors, *Bacillus subtilis* and *Pseudomonas fluorescens* inhibited the urediniospore germination and reduced the disease infestation by approximately 43% and 34%, respectively. In the study by Gómez-De La Cruz et al. [84], potential mycoparasites of *H. vastatrix* were isolated and identified for rust biological control on Arabica coffee leaves. The authors observed 23 microorganism isolates associated with the pustules: *Lecanicillium* spp. (seven), *Calcarisporium* sp. (four), *Sporothrix* sp. (four), and *Simplicillium* spp. (eight). All isolates showed mycoparasitism to the urediniospores in vitro, with *Simplicillium* sp. and *Lecanicillium* sp. being those with the highest percentages of mycoparasitism.

The endomycorrhizal populations present in the Typica variety with and without rust symptoms were characterized by Monroy et al. [85]. The authors identified 37 species corresponding to 14 genera of endomycorrhizae, and the results indicated that plants that interact in symbiosis with mycorrhizae can better tolerate biotic stress. The potential of 217 strains of endophytic bacteria from coffee tissues to control rust in coffee seedlings was assessed by Silva et al. [86]. The bacterial strains 64R, 137G, and 3F (*Brevibacillus choshinensis*), 14F (*Salmonella enterica*), 36F (*Pectobacterium carotovorum*), 109G (*Bacillus megaterium*), 115G (*Microbacterium testaceum*), and 116G and 119G (*Cedecea davisae*) significantly reduced the disease severity when applied either 72 or 24 h before exposing the plant to *H. vastatrix*.

The efficiency of rust biological control in the cultivars Icatu and Mundo Novo using foliar spraying with *Bacillus subtilis* under field conditions was assessed in the Brazil [87]. The microorganism utilized controlled rust by 24% and 17% for Icatu and Mundo Novo, respectively. *Pichia membranifaciens* is a yeast strain isolated from the soil that produces carboxylic acids with fungicidal action to control rust [88]. The solution containing these acids slowed the progress of the disease, even in places where the initial incidence was high, and it reduced the *H. vastatrix* spore viability.

Table 3. Studies of biological control strategies for coffee rust management.

Biological Control	Results
Seven bacterial isolates (*Bacillus* sp.—B10, B25, B157, B175, B205, and B281; *Pseudomonas* sp.—P286) [18]	The isolate B157 reduced the intensity of rust and was as effective as copper hydroxide
Entomopathogenic and mycoparasitic fungus *Lecanicillium lecanii* [80]	Significant suppression of *H. vastatrix*
Bacterial and fungal strains [82]	The isolates (*Bacillus* spp., *Pseudomonas* sp., *Fusarium* spp., *Penicillium* spp., *Aspergillus* sp., *Acremonium* sp., and *Cladosporium* sp.) reduced the infection frequency and the number of *H. vastatrix* urediniospores by more than 70%
Antagonist bacteria isolated from the rhizosphere of coffee crops [83]	*Bacillus subtilis* and *Pseudomonas fluorescens* inhibited the urediniospores germination and reduced the rust infestation by 43% and 34%, respectively
23 isolates of microorganisms associated with rust pustules: *Lecanicillium* spp., *Calcarisporim* sp., *Sporothrix* sp., and *Simplicillium* spp. [84]	The highest percentages of mycoparasitism in rust uredospores were obtained with *Simplicillium* sp. (89%) and *Lecanicillium* sp. (68%)
Strain of endophytic bacteria (*Brevibacillus choshinensis*) [86]	Urediniospore germination was reduced 66% by strain 3F
Foliar spraying with *Bacillus subtilis* under field conditions [86]	The microorganism controlled rust by 24% and 17% for Icatu and Mundo Novo, respectively
Carboxylic acids (CA) produced by *Pichia membranifaciens* [88]	CA exhibited antifungal activity and slowed down the rate of coffee rust progress

Despite the several promising results in coffee rust biological control, Alwora et al. [89] emphasized the need for strategies, such as partnerships between different institutions, for the transformation of these biocontrol agents into viable commercial products. Furthermore, information such as the environmental conditions and culture growth stage to apply the products must always be analyzed and described in the studies. Although biological control presents a lower percentage of control, it must be integrated with resistant cultivars and crop management to obtain good levels of coffee rust control, capable of avoiding extreme defoliation and maintaining productivity at satisfactory levels.

3.5. Cupric Fungicides

Cupper is an essential element in organic agriculture, where disease control depends almost exclusively on its use [90]. The advantages of using copper solutions or suspensions in disease management are the high toxicity to pathogens, low cost, low toxicity to mammals, chemical stability, and long residual period [91]. Cupric products are normally used as a preventive management measure (protective mode of action) since they have no systemic activity. The protective action of copper will only have a good performance if the product has a reactive chemical formula, inherent fungitoxicity, resistance to being washed away by the rain or irrigation, high adhesive capacity on the sprayed surface, and low surface tension, among other characteristics, which make a protective fungicide ideal [92].

In Brazil, legislation 54, published on 15 March 2021, which regulates substances and practices for organic agriculture, allows the use of copper in the forms of hydroxide, oxychloride, sulfate, oxide, and octanoate up to a limit dose of 6 kg/ha/year [93]. Legislation on organic farming in other countries also mentions the possible use of copper hydroxide, copper oxychloride, Bordeaux mixture (mixture of lime and copper sulfate pentahydrate), and copper salts [94,95].

The Viçosa mixture, a product developed in Brazil based on research carried out at the Federal University of Viçosa, is also listed as authorized for organic coffee cultivation. Its composition is based on the Bordeaux mixture and is characterized by a colloidal suspension of salts partially neutralized with calcium hydroxide, whose composition contains copper sulfate pentahydrate, zinc and magnesium sulfate, boric acid, potassium sulfate, and calcium hydroxide. Coffee growers from various organic coffee-producing countries use this product, as well as the Bordeaux mixture [36,96–99].

Different studies have reported the use of the Viçosa mixture to control coffee leaf rust. Androcioli et al. [100] found a reduction in the area under the rust incidence progress curve (AUDPC) in coffee plants sprayed with the Viçosa mixture. In addition to rust control, the Viçosa mixture provides mineral elements for the plant, such as zinc, copper, and boron [101]. Today, some cooperatives of organic coffee producers in the State of Minas Gerais, Brazil, encourage their members to add raw materials containing silicon to the mixture, aiming to improve the resistance-inducing effect against rust.

The effectiveness of various rust control treatments, such as alcoholic thyme extract 2% (plant extract), silicate clay, copper hydroxide 0.58% + silicate clay, aqueous extract of coffee husk, potassium nitrate 1%, calcium nitrate 1%, potassium silicate 0.66%, and the Viçosa mixture, was evaluated by Carvalho et al. [102]. According to the authors, the Viçosa mixture alone was efficient in controlling the disease, reducing the area under the disease progress curve by more than 60% when compared to the control.

Moreover, the potential of using copper nanoparticles has been mentioned, which can contribute to reducing the amount of metallic copper applied per hectare, due to an increase in the contact area, with good results in the management of pests and diseases [103,104]. This reduction is aligned with new global laws that try to minimize the impact of the use of metallic compounds in agriculture in many countries [105].

Despite the positive results in rust management, the use of copper in disease management is becoming increasingly restricted in several countries due to copper being able to accumulate in toxic levels in the soil, food chain, and food products [105,106], since it is usually applied in large quantities and several times a year.

4. Conclusions and Final Remarks

The commercialization of organic coffee, a more environmentally sustainable product when compared to conventional coffee, is characterized as a market opportunity. Nevertheless, among the challenges in producing organic coffee, rust management, the main disease of the crop, stands out as one of the difficulties in obtaining high productivity. The use of rust-resistant cultivars as the main control measure for rust management should be prioritized, with incentive programs to replace crops with susceptible cultivars in the various organic coffee-producing countries. Moreover, the importance of integrating rust management measures, such as cultural, biological, and chemical control, should be highlighted according the use of active principles permitted by the different certifiers present in organic coffee-producing countries. Some of the rust management tactics are already proven to be efficient, whereas others still need further studies, such as the resistance induced by biotic and abiotic agents, which lack a better understanding of the defense mechanisms activated in the coffee trees and the possible metabolic cost involved in the process. Even with all these technological approaches in the organic production system, it is possible that the organic farmers will get a smaller quantity of coffee when compared to the conventional system; in this case, they must receive financial compensation to avoid the loss of sustainability in the organic system.

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References

1. Hurtado-Barroso, S.; Tresserra-Rimbau, A.; Vallverdú-Queralt, A.; Lamuela-Raventós, R.M. Organic Food and the Impact on Human Health. *Crit. Rev. Food Sci. Nutr.* **2019**, *59*, 704–714. [CrossRef]
2. Poudel, K.L.; Johnson, T.G.; Yamamoto, N.; Gautam, S.; Mishra, B. Comparing Technical Efficiency of Organic and Conventional Coffee Farms in Rural Hill Region of Nepal Using Data Envelopment Analysis (DEA) Approach. *Org. Agric.* **2015**, *5*, 263–275. [CrossRef]
3. International Coffee Organization. *World Coffee Consumption*; International Coffee Organization: London, UK, 2021.
4. FiBL; IFOAM. *The World of Organic Agriculture: Statistics & Emerging Trends 2021*; IFOAM-Organics International: Bonn, Germany, 2021.
5. dos Santos, J.B.; Ramos, A.C.; Azevedo Júnior, R.; de Oliveira Filho, L.C.I.; Baretta, D.; Cardoso, E.J.B.N. Soil Macrofauna in Organic and Conventional Coffee Plantations in Brazil. *Biota Neotrop.* **2018**, *18*. [CrossRef]
6. Estevez, C.L.; Bhat, M.G.; Bray, D.B. Commodity Chains, Institutions, and Domestic Policies of Organic and Fair Trade Coffee in Bolivia. *Agroecol. Sustain. Food Syst.* **2018**, *42*, 299–327. [CrossRef]
7. Ibanez, M.; Blackman, A. Is Eco-Certification a Win–Win for Developing Country Agriculture? Organic Coffee Certification in Colombia. *World Dev.* **2016**, *82*, 14–27. [CrossRef]
8. Blackman, A.; Naranjo, M.A. Does Eco-Certification Have Environmental Benefits? Organic Coffee in Costa Rica. *Ecol. Econ.* **2012**, *83*, 58–66. [CrossRef]
9. Minten, B.; Dereje, M.; Engida, E.; Tamru, S. Tracking the Quality Premium of Certified Coffee: Evidence from Ethiopia. *World Dev.* **2018**, *101*, 119–132. [CrossRef]
10. Dietz, T.; Grabs, J.; Chong, A.E. Mainstreamed Voluntary Sustainability Standards and Their Effectiveness: Evidence from the Honduran Coffee Sector. *Regul. Gov.* **2019**. [CrossRef]
11. Folch, A.; Planas, J. Cooperation, Fair Trade, and the Development of Organic Coffee Growing in Chiapas (1980–2015). *Sustainability* **2019**, *11*, 357. [CrossRef]
12. Valkila, J. Fair Trade Organic Coffee Production in Nicaragua—Sustainable Development or a Poverty Trap? *Ecol. Econ.* **2009**, *68*, 3018–3025. [CrossRef]
13. Tumwebaze, S.B.; Byakagaba, P. Soil Organic Carbon Stocks under Coffee Agroforestry Systems and Coffee Monoculture in Uganda. *Agric. Ecosyst. Environ.* **2016**, *216*, 188–193. [CrossRef]
14. Malta, M.R.; de Theodoro, V.C.A.; de Chagas, S.J.R.; Guimarães, R.J.; de Carvalho, J.G. Caracterização de Lavouras Cafeeiras Cultivadas Sob o Sistema Orgânico No Sul de Minas Gerais. *Ciênc. Agrotec.* **2008**, *32*, 1402–1407. [CrossRef]
15. Lee, K.H.; Bonn, M.A.; Cho, M. Consumer Motives for Purchasing Organic Coffee: The Moderating Effects of Ethical Concern and Price Sensitivity. *Int. J. Contemp. Hosp. Manag.* **2015**, *27*, 1157–1180. [CrossRef]
16. Dabbert, S.; Lippert, C.; Zorn, A. Introduction to the Special Section on Organic Certification Systems: Policy Issues and Research Topics. *Food Policy* **2014**, *49*, 425–428. [CrossRef]
17. Samoggia, A.; Riedel, B. Coffee Consumption and Purchasing Behavior Review: Insights for Further Research. *Appetite* **2018**, *129*, 70–81. [CrossRef] [PubMed]
18. Haddad, F.; Maffia, L.A.; Mizubuti, E.S.G.; Teixeira, H. Biological Control of Coffee Rust by Antagonistic Bacteria under Field Conditions in Brazil. *Biol. Control.* **2009**, *49*, 114–119. [CrossRef]
19. Ayalew, T. Characterization of Organic Coffee Production, Certification and Marketing Systems: Ethiopia as a Main Indicator: A Review. *Asian J. Agric. Res.* **2014**, *8*, 170–180. [CrossRef]
20. Cerda, R.; Allinne, C.; Gary, C.; Tixier, P.; Harvey, C.A.; Krolczyk, L.; Mathiot, C.; Clément, E.; Aubertot, J.N.; Avelino, J. Effects of Shade, Altitude and Management on Multiple Ecosystem Services in Coffee Agroecosystems. *Eur. J. Agron.* **2017**, *82*, 308–319. [CrossRef]
21. Talhinhas, P.; Batista, D.; Diniz, I.; Vieira, A.; Silva, D.N.; Loureiro, A.; Tavares, S.; Pereira, A.P.; Azinheira, H.G.; Guerra-Guimarães, L.; et al. The Coffee Leaf Rust Pathogen *Hemileia Vastatrix*: One and a Half Centuries around the Tropics. *Mol. Plant Pathol.* **2017**, *18*, 1039–1051. [CrossRef]
22. Zambolim, L. Current Status and Management of Coffee Leaf Rust in Brazil. *Trop. Plant Pathol.* **2016**, *41*, 1–8. [CrossRef]
23. Capucho, A.S.; Zambolim, L.; Lopes, U.N.; Milagres, N.S. Chemical Control of Coffee Leaf Rust in *Coffea canephora* Cv. Conilon. *Australas. Plant Pathol.* **2013**, *42*, 667–673. [CrossRef]
24. van der Vossen, H.; Bertrand, B.; Charrier, A. Next Generation Variety Development for Sustainable Production of Arabica Coffee (*Coffea arabica* L.): A Review. *Euphytica* **2015**, *204*, 243–256. [CrossRef]

25. van der Vossen, H.A.M. A Critical Analysis of the Agronomic and Economic Sustainability of Organic Coffee Production. *Exp. Agric.* **2005**, *41*, 449–473. [CrossRef]
26. Rana, J.; Paul, J. Health Motive and the Purchase of Organic Food: A Meta-Analytic Review. *Int. J. Consum. Stud.* **2020**, *44*, 162–171. [CrossRef]
27. Gustavsen, G.W.; Hegnes, A.W. Individuals' Personality and Consumption of Organic Food. *J. Clean. Prod.* **2020**, *245*, 118772. [CrossRef]
28. Luomala, H.; Puska, P.; Lähdesmäki, M.; Siltaoja, M.; Kurki, S. Get Some Respect—Buy Organic Foods! When Everyday Consumer Choices Serve as Prosocial Status Signaling. *Appetite* **2020**, *145*, 104492. [CrossRef] [PubMed]
29. Rizzo, G.; Borrello, M.; Guccione, G.D.; Schifani, G.; Cembalo, L. Organic Food Consumption: The Relevance of the Health Attribute. *Sustainability* **2020**, *12*, 595. [CrossRef]
30. Popa, M.E.; Mitelut, A.C.; Popa, E.E.; Stan, A.; Popa, V.I. Organic Foods Contribution to Nutritional Quality and Value. *Trends Food Sci. Technol.* **2019**, *84*, 15–18. [CrossRef]
31. Sosa, M.L.; Escamilla, P.E.; Diaz, S. Organic Coffee. In *Coffee: Growing, Processing, Sustainable Production: A Guidebook for Growers, Processors, Traders, and Researchers*; Wintgens, J.N., Ed.; WILEY-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2004; pp. 1–976, ISBN 9783527307319.
32. Azevedo Junior, R.R.; dos Santos, J.B.; Baretta, D.; Ramos, A.C.; Otto, R.; Façanha, A.R.; Nogueira Cardoso, E.J.B. Discriminating Organic and Conventional Coffee Production Systems Through Soil and Foliar Analysis Using Multivariate Approach. *Commun. Soil Sci. Plant Anal.* **2019**, *50*, 651–661. [CrossRef]
33. Consonni, R.; Polla, D.; Cagliani, L.R. Organic and Conventional Coffee Differentiation by NMR Spectroscopy. *Food Control* **2018**, *94*, 284–288. [CrossRef]
34. Bravo-Monroy, L.; Potts, S.G.; Tzanopoulos, J. Drivers Influencing Farmer Decisions for Adopting Organic or Conventional Coffee Management Practices. *Food Policy* **2016**, *58*, 49–61. [CrossRef]
35. Menegueli, H.O.; Ferrari, J.L.; de Siqueira, H.M.; Batista, R.S. Economic Analysis of a Productive Unit of Family-Based Organic Coffee. *Coffee Sci.* **2019**, *14*, 261. [CrossRef]
36. Velmourougane, K. Impact of Organic and Conventional Systems of Coffee Farming on Soil Properties and Culturable Microbial Diversity. *Scientifica* **2016**, *2016*, 1–9. [CrossRef] [PubMed]
37. Avelino, J.; Cristancho, M.; Georgiou, S.; Imbach, P.; Aguilar, L.; Bornemann, G.; Läderach, P.; Anzueto, F.; Hruska, A.J.; Morales, C. The Coffee Rust Crises in Colombia and Central America (2008–2013): Impacts, Plausible Causes and Proposed Solutions. *Food Secur.* **2015**, *7*, 303–321. [CrossRef]
38. Libert Amico, A.; Ituarte-Lima, C.; Elmqvist, T. Learning from Social–Ecological Crisis for Legal Resilience Building: Multi-Scale Dynamics in the Coffee Rust Epidemic. *Sustain. Sci.* **2020**, *15*, 485–501. [CrossRef]
39. Belan, L.L.; de Jesus Junior, W.C.; de Souza, A.F.; Zambolim, L.; Filho, J.C.; Barbosa, D.H.S.G.; Moraes, W.B. Management of Coffee Leaf Rust in *Coffea canephora* Based on Disease Monitoring Reduces Fungicide Use and Management Cost. *Eur. J. Plant Pathol.* **2020**, *156*, 683–694. [CrossRef]
40. Shigueoka, L.H.; Sera, G.H.; Sera, T.; Fonseca, I.C.D.B.; Mariucci, V.; Andreazi, E.; Carvalho, F.G.; Gonçalves Gardiano, C.; Cesar Carducci, F. Seleção de Progênies de Café Arábica Com Resistência à Ferrugem Alaranjada. *Crop. Breed. Appl. Biotechnol.* **2014**, *14*, 88–93. [CrossRef]
41. Ward, R.; Gonthier, D.; Nicholls, C. Ecological Resilience to Coffee Rust: Varietal Adaptations of Coffee Farmers in Copán, Honduras. *Agroecol. Sustain. Food Syst.* **2017**, *41*, 1081–1098. [CrossRef]
42. van der Vossen, H.A.M. The Cup Quality of Disease-Resistant Cultivars of Arabica Coffee (*Coffea arabica*). *Exp. Agric.* **2009**, *45*, 323–332. [CrossRef]
43. Valencia, V.; García-Barrios, L.; Sterling, E.J.; West, P.; Meza-Jiménez, A.; Naeem, S. Smallholder Response to Environmental Change: Impacts of Coffee Leaf Rust in a Forest Frontier in Mexico. *Land Use Policy* **2018**, *79*, 463–474. [CrossRef]
44. Cabral, P.G.C.; Maciel-Zambolim, E.; Oliveira, S.A.S.; Caixeta, E.T.; Zambolim, L. Genetic Diversity and Structure of *Hemileia vastatrix* Populations on *Coffea* spp. *Plant Pathol.* **2016**, *65*, 196–204. [CrossRef]
45. Dias, R.A.; Ribeiro, M.R.; de Carvalho, A.M.; Botelho, C.E.; Mendes, A.N.G.; Ferreira, A.D.; Fernandes, F.C. Selection of Coffee Progenies for Resistance to Leaf Rust and Favorable Agronomic Traits. *Coffee Sci.* **2019**, *14*, 10. [CrossRef]
46. de Oliveira Fassio, L.; Malta, M.; Carvalho, G.; Liska, G.; de Lima, P.; Pimenta, C. Sensory Description of Cultivars (*Coffea arabica* L.) Resistant to Rust and Its Correlation with Caffeine, Trigonelline, and Chlorogenic Acid Compounds. *Beverages* **2016**, *2*, 1. [CrossRef]
47. de Carvalho, A.M.; Mendes, A.N.G.; Rezende, F.V.; Botelho, C.E.; Carvalho, G.R.; Ferreira, A.D. Selection of Coffee Progenies of Catucaí Group. *Coffee Sci.* **2016**, *11*, 244–254. [CrossRef]
48. de Carvalho, A.M.; de Abreu Cardoso, D.; Carvalho, G.R.; de Carvalho, V.L.; Pereira, A.A.; Ferreira, A.D.; Carneiro, L.F. Behavior of Coffee Cultivars under the Incidence of Diseases of Rust and Gray Leaf Spot in Two Cultivation Environments. *Coffee Sci.* **2017**, *12*, 100–107. [CrossRef]
49. Martins, M.; Mendes, A.N.G.; Alvarenga, M.I.N. Incidência de Pragas e Doenças Em Agroecossistemas de Café Orgânico de Agricultores Familiares Em Poço Fundo-MG. *Ciênc. Agrotecnologia* **2004**, *28*, 1306–1313. [CrossRef]

50. Alvarado-Huamán, L.; Borjas-Ventura, R.; Castro-Cepero, V.; García-Nieves, L.; Jiménez-Dávalos, J.; Julca-Otiniano, A.; Gómez-Pando, L. Dynamics of Severity of Coffee Leaf Rust (*Hemileia vastatrix*) on Coffee, in Chanchamayo (Junin-Peru). *Agron. Mesoam.* **2020**, *31*, 517–529. [CrossRef]
51. De Perla, M.J.D. Variabilidade Patotípica de *Hemileia vastatrix* e Resistência Do Cafeeiro a Ferrugem. Ph.D. Thesis, Universidade Federal de Viçosa, Viçosa, Brazil, 2018.
52. Prakash, N.; Bhat, S.S.; Hanumantha, B.T.; Várzea, V.M.P.; Marques, D.; Silva, M.C. Break down of rust resistance in some HdT introductions and its derivatives in India-New challenges for Arabica coffee breeding in the light of increasing pathogen virulence. In Proceedings of the International Conference on Coffee Science (ASIC), Bali, Indonesia, 3–8 October 2010.
53. Capucho, A.S.; Zambolim, E.M.; Freitas, R.L.; Haddad, F.; Caixeta, E.T.; Zambolim, L. Identification of race XXXIII of *Hemileia vastatrix* on *Coffea arabica* Catimor derivatives in Brazil. *Australas. Plant Dis. Notes.* **2012**, *7*, 189–191. [CrossRef]
54. Torres Castillo, N.E.; Melchor-Martínez, E.M.; Ochoa Sierra, J.S.; Ramirez-Mendoza, R.A.; Parra-Saldívar, R.; Iqbal, H.M.N. Impact of Climate Change and Early Development of Coffee Rust—An Overview of Control Strategies to Preserve Organic Cultivars in Mexico. *Sci. Total Environ.* **2020**, *738*, 140225. [CrossRef]
55. Georget, F.; Marie, L.; Alpizar, E.; Courtel, P.; Bordeaux, M.; Hidalgo, J.M.; Marraccini, P.; Breitler, J.C.; Déchamp, E.; Poncon, C.; et al. Starmaya: The First Arabica F1 Coffee Hybrid Produced Using Genetic Male Sterility. *Front. Plant Sci.* **2019**, *10*, 1–13. [CrossRef]
56. Silva, M.D.C.; Várzea, V.; Guerra-Guimarães, L.; Azinheira, H.G.; Fernandez, D.; Petitot, A.S.; Bertrand, B.; Lashermes, P.; Nicole, M. Coffee Resistance to the Main Diseases: Leaf Rust and Coffee Berry Disease. *Braz. J. Plant Physiol.* **2006**, *18*, 119–147. [CrossRef]
57. Ehrenbergerová, L.; Kučera, A.; Cienciala, E.; Trochta, J.; Volařík, D. Identifying Key Factors Affecting Coffee Leaf Rust Incidence in Agroforestry Plantations in Peru. *Agrofor. Syst.* **2018**, *92*, 1551–1565. [CrossRef]
58. Pozza, E.A.; Carvalho, L.V.; Chalfoun, S.M. Sintomas e injúrias causadas por doenças em cafeeiro. In *Semiologia do Cafeeiro: Sintomas de Desordens Nutricionais, Fitossanitárias e Fisiológicas*; Guimarães, R.J., Mendes, A.N.G., Baliza, D.P., Eds.; UFLA: Lavras, Brazil, 2010; pp. 68–106.
59. Santos, F.D.S.; de Souza, P.E.; Pozza, E.A.; Miranda, J.C.; Carvalho, E.A.; Fernandes, L.H.M.; Pozza, A.A.A. Organic Fertilization, Nutrition and the Progress of Brown Eye Spot and Rust in Coffee Trees. *Pesqui. Agropecu. Bras.* **2008**, *43*, 783–791. [CrossRef]
60. Pérez, C.D.P.; Pozza, E.A.; Pozza, A.A.A.; de Freitas, A.S.; Silva, M.G.; da Silva Gomes Guimarães, D. Impact of Nitrogen and Potassium on Coffee Rust. *Eur. J. Plant Pathol.* **2019**, *155*, 219–229. [CrossRef]
61. Pérez, C.D.P.; Pozza, E.A.; Pozza, A.A.A.; Elmer, W.H.; Pereira, A.B.; da Guimarães, D.S.G.; Monteiro, A.C.A.; de Rezende, M.L.V. Boron, Zinc and Manganese Suppress Rust on Coffee Plants Grown in a Nutrient Solution. *Eur. J. Plant Pathol.* **2020**, *156*, 727–738. [CrossRef]
62. Carré-Missio, V.; Rodrigues, F.A.; Schurt, D.A.; Resende, R.S.; Souza, N.F.A.; Rezende, D.C.; Moreira, W.R.; Zambolim, L. Effect of Foliar-Applied Potassium Silicate on Coffee Leaf Infection by *Hemileia vastatrix*. *Ann. Appl. Biol.* **2014**, *164*, 396–403. [CrossRef]
63. Amaral, D.R.; Resende, M.L.V.; Ribeiro Júnior, P.M.; Borel, J.C.; Mac Leod, R.E.O.; Pádua, M.A. Silicato de potássio na proteção do cafeeiro contra *Cercospora coffeicola*. *Trop. Plant Pathol.* **2008**, *33*, 425–431. [CrossRef]
64. International Federation of Organic Agriculture Movements. *The IFOAM NORMS for Organic Production and Processing—Version 2014*; Die Deutsche Bibliothek: Bonn, Germany, 2014.
65. dos Ricci, M.S.F.; Alves, B.J.R.; de Miranda, S.C.; de Oliveira, F.F. Taxa de Crescimento e Estado Nutricional Do Cafeeiro Em Sistema de Produção Orgânico. *Sci Agric.* **2005**, *62*, 138–144. [CrossRef]
66. De Moura, W.M.; de Lima, P.C.; Fazuoli, L.C.; Teixeira Condé, A.B.; Campos Silva, T. Desempenho de Cultivares de Café Em Sistema de Cultivo Orgânico Na Zona Da Mata Mineira. *Coffee Sci.* **2013**, *8*, 256–264.
67. Bacon, C.M.; Sundstrom, W.A.; Stewart, I.T.; Beezer, D. Vulnerability to Cumulative Hazards: Coping with the Coffee Leaf Rust Outbreak, Drought, and Food Insecurity in Nicaragua. *World Dev.* **2017**, *93*, 136–152. [CrossRef]
68. Santos, F.S.; Souza, P.E.; Resende, M.L.V.; Pozza, E.A.; Miranda, J.C.; Ribeiro, P.M.; Manerba, F.C. Effect of Vegetal Extracts on the Progress of Foliar Diseases in Organic Coffee. *Fitopatol. Bras.* **2007**, *32*, 59–63. [CrossRef]
69. Oliveira, M.D.M.; Varanda, C.M.R.; Félix, M.R.F. Induced resistance during the interaction pathogen x plant and the use of resistance inducers. *Phytochem. Lett.* **2016**, *15*, 152–158. [CrossRef]
70. Burketova, L.; Trda, L.; Ott, P.G.; Valentova, O. Bio-based resistance inducers for sustainable plant protection against pathogens. *Biotechnol. Adv.* **2015**, *33*, 994–1004. [CrossRef]
71. Cerna-chávez, E.; Magaña-arteaga, R.; Velázquez-guerrero, J.J.; María, Y. Evaluación de Extractos Vegetales Sobre Incidencia y Severidad de *Hemileia vastatrix* En Cultivo de Café. *Ecosistemas Recur. Agropecu.* **2019**, *6*, 557–563. [CrossRef]
72. Costa, M.J.N.; Zambolim, L.; Rodrigues, F.A. Avaliação de Produtos Alternativos No Controle Da Ferrugem Do Cafeeiro. *Fitopatol. Bras.* **2007**, *32*, 150–155. [CrossRef]
73. Possa, K.F.; Silva, J.A.G.; Resende, M.L.V.; Tenente, R.; Pinheiro, C.; Chaves, I.; Planchon, S.; Monteiro, A.C.A.; Renaut, J.; Carvalho, M.A.F.; et al. Primary Metabolism Is Distinctly Modulated by Plant Resistance Inducers in *Coffea arabica* Leaves Infected by *Hemileia vastatrix*. *Front. Plant Sci.* **2020**, *11*, 309. [CrossRef]
74. Silva, J.A.G.; Resende, M.L.V.; Monteiro, A.C.A.; Pádua, M.A.; Guerra-Guimarães, L.; Medeiros, F.L.; Martins, S.A.; Botelho, D.M.S. Resistance Inducers Applied Alone or in Association with Fungicide for the Management of Leaf Rust and Brown Eye Spot of Coffee under Field Conditions. *J. Phytopathol.* **2019**, *167*, 430–439. [CrossRef]

75. Costa, B.H.G.; de Resende, M.L.V.; Ribeiro Júnior, P.M.; Mathioni, S.M.; Pádua, M.A.; da Silva Júnior, M.B. Suppression of Rust and Brown Eye Spot Diseases on Coffee by Phosphites and By-Products of Coffee and Citrus Industries. *J. Phytopathol.* **2014**, *162*, 635–642. [CrossRef]
76. Esquivel, P.; Jiménez, V.M. Functional Properties of Coffee and Coffee By-Products. *Food Res. Int.* **2012**, *46*, 488–495. [CrossRef]
77. Fajardo-Franco, M.L.; Aguilar-Tlatelpa, M.; Guzmán-Plazola, R.A. Biofungicides Evaluation in Two Coffee Cultivars for *Hemileia vastatrix* Control. *Rev. Mex. Fitopatol.* **2020**, *38*, 293–306. [CrossRef]
78. Pereira, R.B.; Lucas, G.C.; Perina, F.J.; Alves, E. Essential Oils for Rust Control on Coffee Plants. *Cienc. Agrotecnologia* **2012**, *36*, 16–24. [CrossRef]
79. Caetano, A.R.S.; Chalfoun, S.M.; Resende, M.L.V.; Angélico, C.L.; Santiago, W.D.; Magalhães, M.L.; de Carvalho Selvati Rezende, D.A.; Soares, L.I.; Nelson, D.L.; das Graças Cardoso, M. Chemical Characterization and Determination of in vivo and in vitro Antifungal Activity of Essential Oils from Four Eucalyptus Species against the *Hemileia vastatrix* Berk and Br Fungus, the Agent of Coffee Leaf Rust. *Aust. J. Crop Sci.* **2020**, *14*, 1379–1384. [CrossRef]
80. Jackson, D.; Skillman, J.; Vandermeer, J. Indirect Biological Control of the Coffee Leaf Rust, *Hemileia vastatrix*, by the Entomogenous Fungus *Lecanicillium lecanii* in a Complex Coffee Agroecosystem. *Biol. Control* **2012**, *61*, 89–97. [CrossRef]
81. Vandermeer, J.; Perfecto, I.; Liere, H. Evidence for Hyperparasitism of Coffee Rust (*Hemileia vastatrix*) by the Entomogenous Fungus, *Lecanicillium lecanii*, through a Complex Ecological Web. *Plant Pathol.* **2009**, *58*, 636–641. [CrossRef]
82. Haddad, F.; Saraiva, R.M.; Mizubuti, E.S.G.; Romeiro, R.S.; Maffia, L.A. Isolation and Selection of *Hemileia vastatrix* Antagonists. *Eur. J. Plant. Pathol.* **2014**, *139*, 763–772. [CrossRef]
83. Daivasikamani, S. Rajanaika Biological Control of Coffee Leaf Rust Pathogen, *Hemileia vastatrix* Berkeley and Broome Using *Bacillus subtilis* and *Pseudomonas fluorescens*. *J. Biopestic.* **2009**, *2*, 94–98.
84. Gómez-De La Cruz, I.; Pérez-Portilla, E.; Escamilla-Prado, E.; Martínez-Bolaños, M.; Carrión-Villarnovo, G.L.L.; Hernández-Leal, T.I. Selección *in vitro* de Micoparásitos Con Potencial de Control Biológico Sobre Roya Del Café (*Hemileia vastatrix*). *Rev. Mex. Fitopatol.* **2017**, *36*, 172–183. [CrossRef]
85. Monroy, S.H.; Brindis, R.C.; Pérez, J.; Valdés, E. Diversidad Endomicorrícica En Plantas de Café (*Coffea arabica* L.) Infestadas Con Roya (*Hemileia vastatrix*). *Nova Sci.* **2019**, *11*, 102–123. [CrossRef]
86. Silva, H.S.A.; Tozzi, J.P.L.; Terrasan, C.R.F.; Bettiol, W. Endophytic Microorganisms from Coffee Tissues as Plant Growth Promoters and Biocontrol Agents of Coffee Leaf Rust. *Biol. Control.* **2012**, *63*, 62–67. [CrossRef]
87. Cacefo, V.; de Araújo, F.F.; Pacheco, A.C. Biological Control of *Hemileia vastatrix* Berk. & Broome with *Bacillus subtilis* cohn and Biochemical Changes in the Coffee. *Coffee Sci.* **2016**, *11*, 567–574. [CrossRef]
88. Melchor, R.L.A.; Rosales, V.G.; Pérez, M.C.G.; Fernández, S.P.; Álvarez, G.O.; Mastache, J.M.N. Effectiveness of Carboxylic Acids from *Pichia membranifaciens* against Coffee Rust. *Cienc. Agrotecnologia* **2018**, *42*, 42–50. [CrossRef]
89. Alwora, G.O.; Gichuru, E.K. Advances in the Management of Coffee Berry Disease and Coffee Leaf Rust in Kenya. *J. Renew. Agric.* **2014**, *2*, 5. [CrossRef]
90. La Torre, A.; Iovino, V.; Caradonia, F. Copper in Plant Protection: Current Situation and Prospects. *Phytopathol. Mediterr.* **2018**, *57*, 201–236. [CrossRef]
91. Cha, J.S.; Cooksey, D.A. Copper Resistance in *Pseudomonas syringae* Mediated by Periplasmic and Outer Membrane Proteins. *Proc. Natl. Acad. Sci. USA* **1991**, *88*, 8915–8919. [CrossRef] [PubMed]
92. Reis EM, R.A.; Carmona, M. *Manual de Fungicidas: Guia Para o Controle Químico de Doenças de Plantas*, 6th ed.; UPF: Florianópolis, Brazil, 2010.
93. Portaria N° 52, de 15 Março de 2021. Available online: https://www.in.gov.br/en/web/dou/-/portaria-n-52-de-15-de-marco-de-2021-310003720 (accessed on 9 May 2021).
94. Comisión Europea. *Reglamento (CE) N° 889/2008 DE LA COMISIÓN de 5 de Septiembre de 2008 Por El Que Se Establecen Disposiciones de Aplicación Del Reglamento (CE) No 834/2007 Del Consejo Sobre Producción y Etiquetado de Los Productos Ecológicos, Con Respecto a La Producción*; Diario Oficial de la Unión Europea: Spain, 2008; Volume 250, pp. 1–84.
95. Comisión Europea. *Reglamento (CE), N. y el R. para la A.O. de la U. REGLAMENTO (CE) No 834/2007 DEL CONSEJO de 28 de Junio de 2007 Sobre Producción y Etiquetado de Los Productos Ecológicos y Por El Que Se Deroga El Reglamento (CEE) No 2092/91*; Diario Oficial: Spain, 2007; Volume 834, pp. 1–37.
96. Ramírez-Rodríguez, R.F.; Castañeda-Hidalgo, E.; Robles, C.; Santiago-Martínez, G.M.; Pérez-León, M.I.; Lozano-Trejo, S. Efectividad de Biofungicidas Para El Control de La Roya En Plántulas de Café. *Rev. Mex. Cienc. Agric.* **2020**, *11*, 1403–1412. [CrossRef]
97. Filho, E.D.V.; Domian, C.A. Prevention and Control of Coffee Leaf Rust. In *Handbook of Best Practices for Extension Agents and Facilitators*; de Filho, E.M.V., Domian, C.A., Eds.; Tropical Agricultural Research and Higher Education Center (CATIE): Turrialba, Costa Rica, 2019; p. 96.
98. Hernández-Martínez, G.; Velázquez-Premio, T. Análisis Integral Sobre La Roya Del Café y Su Control. *Rev. Int. Desarro. Reg. Sustentable* **2016**, *1*, 92–99.
99. Luzinda, H.; Nelima, M.; Wabomba, A.; Kangire, A.; Musoli, P.C.; Musebe, R. Farmer Awareness, Coping Mechanisms and Economic Implications of Coffee Leaf Rust Disease in Uganda. *Uganda J. Agric. Sci.* **2016**, *16*, 207. [CrossRef]
100. Androcioli, H.G.; de Oliveira, A.; Júnor, M.; Hoshino, A.T.; Androcioli, L.G. Produtos Alternativos No Controle Da *Hemileia vastatrix* (Berkeley & Broome) e *Cercospora coffeicola* (Berkeley & Cooke) Em Cafeeiros. *Coffee Sci.* **2012**, *7*, 187–197.

101. Zambolim, L.; Capucho, A.; Silva, M. *Ferrugem Do Cafeeiro Conilon (Coffea Canephora)*; Partelli, F., Giles, J., Silva, M., Eds.; CAUFES: Alegre, Brazil, 2015.
102. Carvalho, V.L.; da Cunha, R.L.; Silva, N.R.N. Alternativas de Controle de Doenças Do Cafeeiro. *Coffee Sci.* **2012**, *7*, 42–49.
103. Pariona, N.; Mtz-Enriquez, A.I.; Sánchez-Rangel, D.; Carrión, G.; Paraguay-Delgado, F.; Rosas-Saito, G. Green-Synthesized Copper Nanoparticles as a Potential Antifungal against Plant Pathogens. *RSC Adv.* **2019**, *9*, 18835–18843. [CrossRef]
104. Rai, M.; Ingle, A.P.; Pandit, R.; Paralikar, P.; Shende, S.; Gupta, I.; Biswas, J.K.; da Silva, S.S. Copper and Copper Nanoparticles: Role in Management of Insect-Pests and Pathogenic Microbes. *Nanotechnol. Rev.* **2018**, *7*, 303–315. [CrossRef]
105. Van Bruggen, A.H.C.; Finckh, M.R. Plant Diseases and Management Approaches in Organic Farming Systems. *Annu. Rev. Phytopathol.* **2016**, *54*, 25–54. [CrossRef] [PubMed]
106. Senkondo, Y.H.; Tack, F.M.G.; Semu, E. Copper Accumulations in Soils, Coffee, Banana, and Bean Plants Following Copper-Based Fungicides in Coffee Farms in Arusha and Kilimanjaro Regions, Tanzania. *Commun. Soil Sci. Plant Anal.* **2014**, *45*, 2032–2045. [CrossRef]