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Breeding Programs Against Coffee Leaf Rust in Brazil: A Review

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Abstract

Leaf rust caused by *Hemileia vastatrix* Berk & Br. is the main disease that attack coffee plants all over the world. The disease causes 35-50% of yield loss in average in Brazil. The disease is present in all the countries that cultivate coffee (*Coffea arabica* L. and *C. canephora* L.). Resistance of coffee to leaf rust is the main method of disease control. But the great variability of the pathogen makes it very difficult. In the world and in Brazil there are more than 50 and 16 races of the pathogen, respectively. In Brazil there are seven research institutions that have been working with breeding programs against coffee leaf rust. The main source of resistance to coffee leaf rust used by all the research institutions in Brazil came from 'Centro de Investigação das Ferrugens do Cafeeiro-CIFC' in Oeiras, Portugal. They are: Híbrido de Timor (HdT) CIFC 832-1 and HdT CIFC 832 and HdT CIFC 2570. Crosses were made at CIFC with a variety Caturra and Vila Sarchi and sent to Brazil, Colombia and some countries of Central America and Caribean. The countries that received the germplasm of CIFC back crossed them with varieties Catuai and Mundo Novo. Crossing HdT with Caturra originated the group Catimor and HdT with Vila Sarchi the group Sarchimor. Other source of resistance to leaf rust came from *Coffea canephora* crossed with *C. arabica* originating the cultivar Icatu. But the great majority of the resistant cultivar came from Catimor and Sarchimor. More than 50 coffee varieties have been launched with resistance to the leaf rust in the last 40 years in Brazil. But only few of them remain with vertical resistance to all the races of *H. vastatrix*. Horizontal resistance is more common on *C. canephora* var. *conilon* and *C. canephora* var. *robusta* than in *C. arabica.* This revision has the purpose to relate to the scientific comunity the breeding programs against coffee leaf rust in Brazil.

Keywords: *Coffea arabica* L., *Hemileia vastatrix*, Híbrido de Timor, *Coffea canephora* L., Catimor, Sarchimor, vertical resistance

1. Introduction

In nearly all parts of the world where Arabica coffee was cultivated, the plant was attacked and suffered from leaf rust caused by *Hemileia vastatrix* Berk & Br. The disease infect the leaves, causes die back of the branches and gradually kills the coffee tree. The disease was first appeared in Srilanka at the end of 1860 following Sumatra-Indonesia in 1876 and probably in Timor-Leste in 1880. As a consequence of this disease most of the Arabica coffee plantation in Indonesia were abandoned and, in many cases, substituted to Robusta coffee plantations. In Srilanka coffee plantation was substituted by tea due to leaf rust.

In the America's the disease was first discovered in Brazil in 1970; then leaf rust spreads to all Latin and Central America countries, Caribean, Mexico and recently to Hawaii. Coffee leaf rust caused an epidemic in Brazil in 1970, and still causes 30-50% yield loss (Zambolim, 2016). Genetic resistance is the main measure of coffee leaf rust control. But the main problem is to find genetic resistance source to the disease in the world due to the genetic variability of the fungus *H. vastatrix.* There are mor than 50 races identified of the pathogen in the world; in Brazil there are 16 races of *H. vastatrix* identified (Varzea et al., 2005; Zambolim et al., 2005; Zambolim & Caixeta, 2021). Hopefully the portuguese's scientist's, back in the decade of 1920, discovered the Hibrido de Timor (HDT) plant, in the island of Timor-east resistant to coffee leaf rust, which is now the main source of genetic resistance to the disease all over the world. In this revision it will be presented all the breeding programs against coffee leaf rust.

2. Importance of Hybrido de Timor for Coffee Breeding Against Leaf Rust

Coffee appears to have been introduced into Timor-east in the middle of the eighteenth century. The first coffee plantations in Timor-east were from the Arabica species, a variety of Typica. The highlands of Timor-east were a refugee for Arabica coffee plantations where the incidence of the disease was less severe than in lowland. To obtain a plant resistant to the disease is an obstacle because *Coffea canephora* var. *robusta*, which tolerates the disease has a number of chromosomes of 2n = 2x = 22 while the chromosome of *C. arabica* is 2n = 4x = 44. In fact, to develop a plant that is resistant to the disease it can only be done through the duplication of the number of chromosomes of *Coffea canephora* var. *robusta* or natural crosses between different chromosomes of these two species. The latter situation occurred in Timor-east, allowing the appearance of a new coffee plant called 'Hibrido de Timor' (HDT) which is resistant to *Hemileia vastatrix*. The original plant of HDT is unique in the world because it resulted from unexpected crosses (by nature) and the plant has an incalculable historical value. The natural hybridization of HDT was confirmed by the former Portuguese Agronomic Studies Overseas Mission (MEAU) in Timor-east. According to the MEAU, the segregation of phenotypes occurred in progenies of HDT were some are closer to *C. arabica* and others closer to *Coffea canephora* var. *robusta*. This led to the assumption that HDT exist as a result of natural crosses between *C. arabica* and *C. canephora* var. *robusta*, in which probably an unreduced gamete of Robusta had combined with a normal from Arabica. It is assumed that the existence of the populations of HDT had originated from an unique plant which was part of an initial plantation of *C. arabica*, variety of Typica established in 1917s or in 1927 in an altitude between 800 and 820 meters above sea level. The original plant is located in a coffee plantation located at Mata Nova, area of Malhui, suco Fatobessi, sub district Hatolia, Ermera district. In various observations made from 1962 to 1975 suggested that the HDT plant was resistant to *Hemileia vastatrix* Berk. & Br., while devastating attacks were observed in the surrounding plantation of *Coffea arabica*. The discovery of the HDT provided an impetus for the establishment of the Centro de Investigação das Ferrugens do Cafeeiro (CIFC). This centre established in 1955 in Portugal with the support from the governments of Portugal and USA. The involvement of the USA in this project was due to the fact that there was a fear of a possible outbreak of coffee leaf rust in coffee production areas of Central and South America that potentially led to an economic crisis in these states.

The HDT was proved to be immune to 23 physiologies races of *H. vastatrix* at that time and this was demonstrated by CIFC, on the possibility of immunity transmission to F1, when crossing with *Coffea arabica* L., a high yield variety.

Nowadays almost 95 per cent of rust resistant coffee varieties cultivated around the world were directly or indirectly resulted from the studies conducted by CIFC, based on the 'Hibrido de Timor'. The resistance manifested in HDT to *H. vastatrix* suggested that Timor-east coffee production become a determinant factor in the worldwide diffusion of the seeds of HDT. The diffusion of the seeds of HDT was begun in 1955, after its restricted utilization during 10 years by the firm property of the plantation where the original plant of the hybrid first appeared. The first seeds were sent to CIFC in 1955 and were used by the CIFC to establish clones and progenies of HDT. Following this, from 1960, the seeds of HDT were distributed to the experimental stations in coffee production countries such as India, Tanzania, Kenya, Angola, Brazil, Costa Rica and Colombia. The populations of HDT are, naturally marked with a clear heterogeneity regarding the morphologic appearance, although the higher size is a constant characteristic, resistance to the coffee rust easily checked in the plantations and confirmed by CIFC, seed uniformity and productivity.

The general characteristic of the descendants of the original plant is to have a phenotype of *C. arabica* L., being predominant the tetraploid forms with 44 chromosomes, presenting the product appreciable organoleptic qualities, remarkable chemical similarity with Arabic, in exports has been commercially treated as Arabica and marked resistance to *H. vastatrix*.

The original HDT has had a very important direct use value, both for Timor-east and for all Arabica coffee producing countries, because it allowed to obtaining coffee varieties (either pure HDT varieties or crossed) resistant to rust. These new varieties have increased the production of Arabica coffee and increasing producers' income. For all above reasons, all producing and consuming countries of Arabica coffee owe a debt of gratitude to the nature of Timor-east, as this nature managed to do a miracle cross between two species with different chromosomes; one with diploid and the other with tetraploid. The objective of this review is to report the evolution of the breeding program of coffee varieties, resistant to leaf rust, from the HDT and other coffee sources (*C. canephora*) in several research institutions in Brazil.

3. Breeding Program of the Instituto Agronomico de Campinas

The first coffee breeding program in Brazil began in the 1930s at the Instituto Agronomico de Campinas (IAC) by Dr. Alcides Carvalho. National and international coffee growers owe a lot to Dr. Carvalho, as he dedicated his entire life to the improvement of coffee in the country. Later, Drs. Luiz C. Fazuoli, Herculano P. Medina Filho, Oliveiro G. Filho and Wallace Gonçalves joined the team. In its beginning, the IAC breeding program was aimed at the selection of more productive, rustic, long-lived and good quality cultivars. Thus, the cultivars Bourbon Vermelho, Bourbon Amarelo and Mundo Novo were chronologically selected (Carvalho et al., 1952). At a later stage, dwarfism genes from the Caturra variety were transferred to the 'New World', giving rise to the cultivars Catuaí Vermelho and Catuaí Amarelo (Carvalho & Monaco, 1972). The innovation drastically changed the system of conducting and managing crops, allowing greater density and facilitating the harvesting of plants. In 1950, a study was initiated with the objective of transferring rust-resistant alleles of *Hemileia vastatrix* from the species *C. canephora*, diploid (2n = 2x = 22 chromosomes) to the species *C. arabica*, tetraploid (2n = 4x = 44 chromosomes). The chromosomes of the species *C. canephora* diploid were duplicated to be crossed with *C. arabica* tetraploide. As previously mentioned, the disease only became a problem in Brazil almost 20 years later, but at that time it was already feared that it would be introduced in the country and the damage it could cause. From the result of the cross between the cultivar 'Robusta' of *C. canephora* and the Bourbon Vermelho cultivar of *C. arabica*, crossbred in 1956 with coffee plants selected from the cultivar Mundo Novo of *C. arabica*, it was found that several of the combinations showed rust-resistant plants in tests carried out at the CIFC in Oeiras, Portugal. Selected coffee trees derived from the first backcross to 'Mundo Novo' were, in 1960, crossed again in Oeiras, Portugal. In 1960, selected coffee plants derived from the first backcross to 'Mundo Novo' were crossed again with plants of this cultivar. The set of populations resulting from these hybridizations, with two or three backcrosses to 'Mundo Novo', was given the generic name of 'Icatu'. The coffee plants selected in the various backcrossing cycles were sent to the CIFC, so that the selection could be carried out there for resistance to rust, because at that time the disease had not yet been introduced in Brazil. The hybrid combinations obtained by IAC were vigorous and productive, although in some progenies a high number of aneuploid plants was noted. The selected coffee plants were resistant to most physiological races of *H. vastatrix*. In this material it was obtained immune coffee plants to those with only a slight attack, in which pustules and sporulation were minimal, and others with more intense sporulation. The tall cultivars called Icatu Vermelho, Icatu Amarelo and Icatu Precoce were launched in 1992 and were characterized by incomplete resistance to *H. vastatrix*. From the end of the 1970s, this vast selection program had the important support of the Food and Agriculture Organization of the United Nations (FAO) and began to count on the fundamental participation of Albertus Eskes, Jaap Hoogstraten and Masako Toma-Braghini. Coffee rust had not yet been detected in Brazil, which occurred only in 1970. Already anticipating the problem, the IAC, in the early 1950s, introduced a valuable and diverse collection of accessions from the United States Department of Agriculture (USDA), encompassing exotic varieties from various countries and diverse germplasm of Arabica coffee carriers S_H1 to S_H4 genes of resistance to the pathogen. Numerous hybridizations were carried out with the introduced germplasm and the cultivars from Brazil existing at the time. With this strategy, in the early 1970s, the IAC distributed to producers the cultivars Iarana-C 73 and Iarana-C 74 consisting of mechanical mixtures of coffee seeds with individual alleles S_H1, S_H2, S_H3 and S_H4 (Carvalho et al., 1975). In support of this vast programme, from 1956 onwards, a fruitful exchange of information on the genetic resistance of the coffee plant to *Hemileia vastatrix* Berk & Br began between the IAC and the Centro Internacional das Ferrugens do Cafeeiro (CIFC), in Oeiras, Portugal. At that time, the CIFC sent to the IAC a new collection of coffee accessions, to be tested in relation to their adaptation and productivity (Bettencourt & Carvalho, 1968). From the material received in 1971, several selections of coffee known as Hybrido de Timor (HdT) stood out, as well as descendants of hybridizations carried out in Portugal, between (HdT) and other sources of resistance to rust, such as a series of differentiating coffee trees for the races of *H. vastatrix*, known at the time (Bettencourt & Fazuoli, 2008). The HdT is the result of a natural cross between *Coffea arabica* and *C. canephora*; its selections, especially those with CIFC prefixes 832/1 and 832/2, showed resistance to the races of *H. vastatrix* known at that time and easily interbreed with cultivars of *C. arabica*.

The valuable germplasm forwarded by the CIFC was used in various hybridizations by the IAC (Bettencourt & Fazuoli, 2008) and gave rise to the cultivars Obatã IAC 1669-20, Tupi IAC 1669-33, both released in the year 2000 and IAC 125 RN and IAC Obatã 4739, registered in the National Registry of Cultivars of the Ministry of Agriculture and Supply (RNC/MAPA) in 2012. Although new races of *H. vastatrix* have broken the resistance of the cultivars Obatã IAC 1669-20 and Tupi IAC 1669-33, the cultivars IAC 125 RN and IAC RN e IAC Obatã 4739 are still resistant to all races of *H. vastatrix* identified in Brazil.

Finally, in 2016, IAC launched the IAC Catuaí S_H3 cultivar, with vertical resistance to coffee leaf rust. The cultivar comes from the introgression of the S_H3 gene of *C. liberica*, present in the BA 10 accession, from India, used in hybridizations with the cultivar Catuaí Vermelho IAC 46 (Fazuoli et al., 2019). In addition to being resistant to all races of the fungus identified in Brazil so far, the cultivar has a good level of tolerance to water deficit.

The following rust-resistant materials, released by the Instituto Agronômico de Campinas, are on Table 1.

According to the Table 1 there are four varieties with vertial or quantitative resistance to coffee leaf rust. The others present horizontal or quantitative resistance.

Table 1. Coffee lines released by the Instituto Agronômico de Campinas (IAC)

Rust-resistant tall cultivars		
Icatu Vermelho	Initial cross between *C. canephora* DP and Bourbon Vermelho, with two backcrosses to 'Mundo Novo', released by the IAC in 1992.	Moderately susceptible
Icatu Amarelo	Initial cross between 'Icatu Vermelho' and 'Bourbon Amarelo' or 'Mundo Novo Amarelo' released by the IAC in 1992.	Moderately susceptible
Icatu Precoce IAC 3282	Initial cross between 'Icatu Vermelho' and 'Bourbon Amarelo', selected and released by the IAC in 1996.	Moderately susceptible
Rust-resistant undersized cultivars		
Obatã IAC 1669-20	Initial cross between 'Villa Sarchí' and the Híbrido de Timor CIFC 832/2, with natural backcrossing to 'Catuaí Vermelho', was released by the IAC in 2000.	Moderately resistant
Tupi IAC 1669-33.	Initial cross between Híbrido de Timor CIFC 832/2 and Villa Sarchí (H361-4) carried out by CIFC, having been selected and released by IAC in 2000.	Resistant
IAC Obatã 4739	The cultivar IAC Obatã 4739 is derived from the cross between the coffee plant IAC 1669-20-1 and the cultivar Catuaí Amarelo IAC 62.	Resistant
IAC 125 RN	Initial cross between Híbrido de Timor CIFC 832/2 and Villa Sarchí carried out at CIFC (H 361-4), with subsequent selection by IAC	Resistant to leaf rust and to races 1 and 2 of *Meloidogyne exigua* (Fazuoli et al., 2018) and races 1 and 3 of *M. incognita* (Fazuoli et al., 2018).
IAC Catuaí SH3	IAC Catuaí SH3 was obtained by the genealogical method, from the recombination between the coffee plant H 2077-2-5-46, from the Catuaí Vermelho germplasm and the accession IAC 1110-8, from the exotic cultivar BA10. The cultivar IAC Catuaí SH3 (Fazuoli et al., 2019).	Resistant

4. Breeding Program to Leaf Rust of the Universidade Federal de Viçosa (UFV)

The Coffee Breeding Program began at the Universidade Federal de Viçosa (UFV) shortly after the coffee rust was found in Bahia, Brazil in 1970. The professors who started the improvement program were Geraldo Martins Chaves and João da Cruz Filho. Later Professor Laércio Zambolim and Dr. Antonio Alves Pereira from the Empresa de Pesquisa Agropecuária do Estado de Minas Gerais (Epamig) was incorporated in Program.

The Coffee Germplasm Bank of the UFV, located in Viçosa, State of Minas Gerais, was created in 1970/71, initially with about 450 accessions, containing great genetic variability including sources of resistance to *Hemileia vastatrix* and *Meloidogyne exigua*. These introductions came from the Coffee Rust Research Centre (Centro de Investigação das Ferrugens do Cafeeiro, CIFC), Portugal, the National Coffee Research Centre (CENICAFÉ), Colombia, the Inter-American Institute of Agricultural Sciences (IICA), Costa Rica and the Agronomic Institute of Campinas (IAC), Brazil, and were planted at the Fundão Experimental Station at the Universidade Federal de Viçosa. After the arrival of the coffee germplasm, resistant to coffee leaf rust derived from Catimor (Caturra vermelho × CIFC Híbrido de Timor 832-1) and Sarchimor (Villa Sarchi × CIFC Híbrido de Timor 832-2) from CIFC in the F1, F2, F3, the advancement of generations and backcrosses with agronomically adapted varieties of *C. arabica* began (Catuaí Vermelho and Mundo Novo).

Accessions of the germplasm were also sent to other Brazilian research (Epamig, Procafé and Incaper) and to coffee farmers to be studied in different regions of the country. In 2006, 1,036 accessions were incorporated to the germplasm bank. The new accessions were planted at the Experimental Station located near the Airport at the Universidade Federal de Viçosa. This germplasm included 200 new accessions of *Coffea arabica* of the varieties Bourbon Vermelho, Bourbon Amarelo, Sumatra, San Ramon, Caturra, Botucatu Amarelo, Laurina, São Bernardo, Típica, Pacas, Vila Lobos, Geisha and others. Several accessions of Híbrido de Timor, their derivatives (Catimor, Sarchimor, Cachimor and Cavimor) and Catindu were also planted in this location, to preserve this importante genetic variability. Numerous materials from Central America (Costa Rica and Turrialba) were also incorporated into the program.

The first variety launched as leaf rust resistant by UFV was named Oeiras, in honor of the city of Oeiras, Portugal where the Coffee Rust Research Center (CIFC) is located. This variety is also drought tolerant. From then on, the UFV Germplasm Bank was used in several coffee genetic improvement in Brazil, enabling the development of new cultivars such as Paraíso MG H419-1, MGS Paraíso 2, Catiguá MG1, Catiguá MG2, MGS Catiguá 3, MGS Ametista, MGS Aranãs, MGS Turmalina, Sacramento MG1, Pau-Brasil MG1, Araponga MG1, Sarchimor MG8840, among others in partnership with Dr. Antônio Alves Pereira from Epamig and Dr. Antônio Carlos Baião de Oliveira from Embrapa (Table 2).

From the year 2000, Professor Laércio Zambolim stablished a collection of Híbrido de Timor, at the Universidade Federal de Viçosa and, today the germplasm has 156 accessions, cultivated at the experimental center of Fundão (UFV). All clones were characterized by molecular markers and resistance to races $\mathbf{II_{v5}}$ and $XXXIII_{v5,7,9}$ of *H. vastatrix.* There is no known collection of Híbrido de Timor in the world that contains this large number of accesses.

The best accessions of Híbrido de Timor resistant to leaf rust were crossed and backcrossed with *C. arabica* to develop new varieties. In view of the valuable coffee germplasm, from the cross between the Caturra variety with the Híbrido de Timor (Catimor) and the Villa Sarchi variety with the Híbrido de Timor (Sarchimor) existing at UFV the coffee biotechnology program was initiated at UFV in cooperation with Embrapa. The coffee biotechnology program was initiated by Dr. Eveline Teixeira Caixeta (Embrapa) and Professors Ney Sussumu Sakiyama and Laércio Zambolim (UFV) at the UFV. From 2003, molecular technologies, such as molecular markers and genomics, has been applied in germplasm conservation, in genetic breeding, in genealogy analysis and in the cultivar identification. The molecular tools allowed development and availability of different molecular markers, as well as, cloning and characterization of genes involved in rust resistance. Besides, genomic data on coffee plants and their pathogens has been available to provide opportunities for large-scale discovery of new targets for disease control. All these tolls have allowed the integration of phenotypic and genotypic data for selection of superior and rust resistant coffee genotypes. Thus, molecular approaches are being applied in the coffee breeding program to assist in the parent selection, superior genotypes assisted selection and increase the efficiency of the new cultivar development. The potential of the applied molecular methodologies lies not only in the time reduction of the program, but also in the solid scientific basis that can explain the genetics and biochemistry of the changes that have occurred or that may occur in the genetic breeding process.

Table 2 shows that five varieties had vertical and three had horizontal resistance to *H. vastatrix*, respectively to race $XXXIII_{v5,7,9}$. A hundred per cent of the varieties came from the group of coffee denominated Catimor.

Table 2. Coffee germplasm released by the Universidade Federal de Viçosa in cooperation with the Empresa de Pesquisa Agropecuária do Estado de Minas Gerais with vertical and horizontal resistance to *H. vastatrix* race $XXXIII_{v5,7,9}$

Germplasm	Crossing	Type of resistance to race $XXXIII_{v5,7,9}$
Oeiras	Caturra vermelho (CIFC 19/1) × Hibrido de Timor (CIFC 832/1)	Horizontal or quantitative
Paraíso MG H419-1	Catuaí amarelo IAC 30 × Híbrido de Timor 445-46	Vertical or qualitative
Catiguá MG-1	Catuaí Amarelo IAC 86 × Híbrido de Timor UFV 440-10	Vertical or qualitative
Catiguá MG-2	Catuaí Amarelo IAC 86 × Híbrido de Timor UFV 440-10	Vertical or qualitative
Catiguá MG 3	Catuaí Amarelo IAC 86 × Híbrido de Timor UFV 440-10	Vertical or qualitative
Sacramento MG-1	Catuaí vermelho IAC 81 × Híbrido de Timor 438-52	Horizontal or quantitative
Pau-Brasil MG-1	Catuaí vermelho IAC 141 × Híbrido de Timor 442-34	Vertical or qualitative
Araponga MG-1	Catuaí Amarelo IAC 86 × Híbrido de Timor UFV 446-08	Horizontal or quantitative

5. Genetic Improvement Aimed at Rust Resistance at the Instituto de Desenvolvimento Rural do Paraná-IAPAR-EMATER (IDR-Paraná)

The coffee breeding program of the Instituto de Desenvolvimento Rural do Paraná-IAPAR-EMATER (IDR-Paraná) began its research on genetic improvement for rust resistance with Dr. Tumoru Sera in 1975. In the year 2012 Dr. Gustavo H. Sera joined the group of researchers. The main breeding method used by IDR-Paraná was genealogical and *bulk* and backcrosses were used in some cases. The sources of resistance most used by the IDR-Paraná breeding program were coffee plants derived from: Híbrido de Timor (HdT), Sarchimor, Catimor, Icatu, BA-10, wild accessions from Ethiopia and landraces. HdT, Sarchimor, Catimor and Icatu are Arabica coffee plants carry *C. canephora* genes, while BA-10 is an Arabica coffee plant that carries *C. liberica* genes. Ethiopia's wild accesses and landraces (*e.g.*, Geisha, Rume Sudan, Java, etc.) are pure Arabica coffee trees. The main coffee germoplasm employed by IDR-Paraná were HdT CIFC 832/1, HdT CIFC 832/2 and HdT CIFC 2570. The HdT CIFC 832/2 were the most used germplasm in genetic improvement and, currently, several progenies of HdT CIFC 2570 are also being used as sources of resistance to *H. vastatrix*. These sources of resistance have major genes that promote qualitative resistance to leaf rust pathogen. Quantitative-type resistance is expressed when major genes are broken down by new rust races (Sera et al., 2022a). In general, some varieties derived from HdT as well as all coffee plants with S_H3 gene, still maintain high level of resistance to rust in Brazil. On the other hand, the qualitative resistance has already been broken in coffee plants derived from Icatu, wild accessions of Ethiopia and *landraces*, and currently have intermediate level of resistance. Fifteen cultivars resistant to coffee leaf rust were released by the IDR-Paraná (Sera et al., 2022b). The Coffee germoplasm released by the Instituto de Desenvolvimento Rural do Paraná-IAPAR-EMATER (IDR-Paraná) are on the Table 3.

Table 3 shows that six varieties had vertical and nine horizontal resistance to *H. vastatrix*, respectively. IAPAR 59, IPR 97, IPR 98, IPR 104, IPR 107 and IPR Pérola have qualitative resistance genes (major SH genes) that have not yet been broken by physiological rust races present in the field in Brazil. IPR 101 and IPR 105 are carriers of the major S_H3 gene and for this reason are also highly resistant to rust. Although IPR 100 is a derivative of BA-10 coffee, this cultivar is susceptible to leaf rust because it is not carry the gene S_H3.

The resistance of the cultivars IPR 99, IPR 102 and IPR Alvorada was broken in some places in Brazil, while the resistance of IPR 103, IPR 106 and IPR 108 has already been broken in most coffee regions of the country. These six cultivars have intermediate level of resistance due to the action of minor genes. Currently, IDR-Paraná is developing cultivars with high resistance to rust from the combination of the genes S_H3, S_H5, S_H6, S_H7, S_H8, S_H9, $S_H?$, originated from the coffee plants Sarchimor and BA-10, aiming at durable qualitative resistance. Selection assisted by molecular markers associated with S_H3 has been routinely adopted in the IDR-Paraná. In order to increase the amount of minor resistance genes, with a consequent increase in the intermediate resistance level. Several progenies were developed from crosses between the Sarchimor, Icatu, Ethiopian wild accessions and landraces.

Table 3. Coffee germplasm released by the Instituto de Desenvolvimento Rural do Paraná-IAPAR-EMATER (IDR-Paraná)

Germplasm	Crossing	Type of resistance
IAPAR 59, IPR 97, IPR 98, IPR 104	Sarchimor group: Villa Sarchi CIFC 971/10 × HdT CIFC 832/2	Vertical or qualitative
IPR 101, IPR 105	Catuai Vermelho × (Catuaí × BA-10)	High horizontal or quantitative
IPR 100	Catuai Vermelho × (Catuaí × BA-10)	Low horizontal or quantitative
IPR 106	Spontaneous cross between Icatu IAC 925 × Unknown coffee	Horizontal or quantitative
IPR Alvorada	IAPAR 59 × Mundo Novo IAC 376-4	Horizontal or quantitative
IPR 107, IPR Perola	IAPAR 59 × Mundo Novo IAC 376-4	Vertical or qualitative
IPR 108	IAPAR 59 × (Icatu anão × Catuaí)	Horizontal or quantit.
IPR 102, IPR 103	Icatu Anão × Catuaí Vermelho	Horizontal or quantitative
IPR 99	C. arábica 'Villa Sarchi' CIFC 971/10 × 'Hibrido e Timor' CIFC 832/2	Horizontal or quantitative

6. Genetic Improvement Program Against Coffee Leaf Rust Developed by Empresa de Pesquisa Agropecuária do Estado de Minas Gerais (Epamig)

The use of genetic resistance of coffee plants to *Hemileia vastatrix* Berk. & Br. was the main long-term goal for controlling leaf rust. In the State of Minas Gerais, research began at the Universidade Federal de Viçosa (UFV) and later the Empresa de Pesquisa Agropecuária do Estado de Minas Gerais (Epamig) joined the program. Since 1971/72, in a close partnership with UFV, Epamig developed an intense and aggressive research program aimed at genetic control of leaf rust as well as other diseases such root-knot nematodes. Breeding research, aiming to obtain rust-resistant cultivars, was initiated in 1970/71 by the Departamento de Fitopatologia (DFP) da UFV, Minas Gerais, Brazil, under the leadership of Professor Geraldo M. Chaves and Professors. João da Cruz Filho and Laércio Zambolim with the introduction of a vast and valuable coffee germplasm carrying genes of resistance to *H. vastatrix* from the Centro de Investigação das Ferrugens do Cafeeiro-CIFC, Oeiras, Portugal and from the National Centre for Coffee Research-CENICAFÉ, Chinchina, Colômbia, the Inter-American Institute for Cooperation on Agriculture (IICA), Turrialba, Costa Rica, and the Instituto Agronômico de Campinas (IAC), Campinas, Brazil. The introduced material initially totaled about 450 accessions, including sources of resistance to coffee leaf rust. The introduced germplasm was tested for resistance to *H. vastratrix* at the DFP of UFV using mixture of uredospores harvested in the field. The resistant plants were planted in an experimental area of DFP/UFV, to constitute the *Coffea* spp. germplasm bank, to be used in the Coffee Genetic Improvement Program developed by UFV, in partnership with Epamig. Thus, this program was developed according to the following scheme: evaluation and selection of the introduced germplasm and synthesis of new genetic combinations of rust-resistant coffee plants. The new commercial coffee cultivars resistant plants obtained were planted in an experimental area of DFP/UFV, to constitute the *Coffea* spp. Germplasm Bank, to be used in the Coffee Genetic Improvement Program developed by UFV, in partnership with Epamig.

From 2005, Epamig started the implementation of a germplasm bank (BAG) of *Coffea* spp. in the Experimental Field of Patrocínio-CEPC. The CEPC is geographically located in the Alto Paranaíba region of the State of Minas Gerais, at an approximate altitude of 950 to 1,000 meters, latitude of 19°57′09″S and longitude of 46°28′12″W, with an average annual temperature of 20.7 °C, an average maximum annual temperature of 27.9 °C and an average minimum annual temperature of 14.8 °C. In this bank, a vast germplasm of *Coffea* spp. is being preserved, consisting mainly of most of the commercial cultivars, older cultivars as well as selections of HdT existing in Brazil and promising progenies of the various populations generically called Catimor, Sarchimor, Cavimor, Cachimor, Catindu and other selections bearing the rust resistance factors S_H1 to S_H10. In addition to this, the bank has accessions of other species of the genus Coffea, such as *C. canephora*, *C. racemosa*, *C. liberica*, *C. stenophylla*, among others. The collection currently consists of 1626 accessions from the Universidade Federal de Viçosa, private properties located in the states of Minas Gerais, São Paulo, Paraná and Espírito Santo, Experimental Research Center Café Elói Carlos Heringer, in Martins Soares-MG, of the Experimental Center Pioneers of Coffee of the Cerrado, in Patrocínio, of the Instituto Agronomico de Campinas, Campinas-SP, Experimental Field of Machado (CEMA/EPAMIG) and of the IDR-Paraná. Epamig has six Experimental Fields located in the municipalities of Patrocínio, Machado, São Sebastião do Paraíso, Três Pontas, Oratórios and Leopoldina, in the state of Minas Gerais. In these Fields and in private properties breeding research program is carried out aiming at resistance to leaf rust and other agronomic characteristics. In addition to rust, several accessions of the Epamig germplasm bank are carriers of genes for resistance to nematodes, fungal and bacterioses that attack the coffee plants (Nadaleti et al., 2022; Fassio et al., 2020). Several cultivars have already been registered and launched for commercial plantations in the state of Minas Gerais and in other

states. Some of these cultivars are even being planted in other countries, located in Central America and the Caribbean and in other parts of the world. The cultivars with resistance to rust and/or nematodes developed by the program so far are on the Table 4 (Botelho et al., 2022; Salgado et al., 2022).

Table 4 shows that four of the varieties have vertical and one horizontal resistance to *H. vastatrix*, respectively. All the vertical resistance varieties came from the resistance source Catimor (CIFC 832/1).

Table 4. Cultivars with resistance to rust and/or nematodes developed by the Empresa de Pesquisa do Estado de Minas Gerais (Epamig)

Cultivar	Crossing	Type of Resistance to *H. vastatrix*
MGS Aranãs	Catimor UFV 1603-215 × Icatu IAC H3851-2	Vertical or qualitative
MGS Ametista	Catuaí Amarelo IAC 86 × Híbrido de Timor UFV 446-08	Vertical or qualitative
MGS Paraíso 2	Catuaí Amarelo IAC 30 × Híbrido de Timor UFV 445-46	Vertical or qualitative
Sarchimor MG 8840	Villa Sarchi (CIFC 971/10) × Híbrido de Timor CIFC 832/2)	Vertical or qualitative
MGS Catucaí Pioneira	Icatu × Catuaí	Horizontal or quantitative
MGS Vereda	Catuaí Vermelho × Amphillo MR 2-161	*Meloidogyne paranaenses*
MGS Guaiçara	Catuaí Vermelho × Amphillo MR 2-474	*Meloidogyne paranaenses*

7. Genetic Improvement Program Against Coffee Leaf Rust Developed by the Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural (Incaper)

The species *Coffea canephora* has great economic and social importance in the State of Espírito Santo, the second largest coffee producer in the country and the largest national producer of the species. In addition, it is currently a basic genetic material in Brazil for studies of resistance to rust and nematodes, mechanisms that determine drought tolerance, among others. The species *C. canephora* var. *conilon* and *C. canephora* var. *robusta* have been cultivated in Brazil, but in state of Espirito Santo only *C. canephora* var. *conilon*. The introduction of this coffee specie in the state until the 90's occurred through the sexual multiplication of mother plants selected by the farmers themselves, over the years. This provided the establishment of populations with wide genetic variability. The performance of Conilon crop in the state has shown great evolution in the last 20 years, due to the technologies that were developed by Incaper such as: genetic improvement, management of programmed cycle pruning, nutrition, irrigation, among others. The genetic improvement program initiated in 1985, using as an initial strategy the selection of plants with desirable phenotypic characteristics in several municipalities in the northern region of the state, cloning of the selected plants and evaluation of them in clone competition trials in the Incaper experimental station. Based on the experimental results and genetic compatibility tests, four clonal varieties and one seminal variety (Emcapa 8111, Emcapa 8121, Emcapa 8131, Emcapa 8141-Robustão Capixaba) and one for seed propagation (Emcaper 8151-Robusta Tropical) was released (Table 5). In the late 1990s until 2020, Incaper released the following varieties of *C. canephora* var. *conilon*: variety Vitória Incaper 8142 (formed by thirteen clones); Variety Marilândia (formed by 12 clones); Diamante variety (formed by nine clones); Jequitibá variety (formed by nine clones) and Centenária variety (formed by eight clones) (Table 5). In 2017, another seminal variety, the Conquista Incaper 8152 was released (Table 5). The Active Bank of Coffee Germplasm of the Incaper, located at the Marilândia Experimental Station has the purpose of conservation and evaluation of the superior genetic material of *C. canephora* with 576 accessions, with 10 plants/accession. These materials representatives of the Conilon or Kouilou group of *C. canephora* were selected from crops in different municipalities in the north of the states of Espírito Santo, Minas Gerais, Bahia, Rondônia and São Paulo (IAC). The genetic improvement program started with Dr. Romário G. Ferrão and then the program had the inclusion of Dr. Maria A. G. Ferrão and Dr. Aimbiré Fonseca. Later, Dr. Abraão C. Verdin Filho and Paulo C. Volpi joined the team. The species *C. canephora* is native to the lowlands of the equatorial region of Africa, located in the areas from Guinea to Uganda, Central.africa and especially Congo. There are two low collections with the genus diploid Coffea. The first is maintained in Madagascar and the second in Ivory Coast, for coffees originating on the African continent. The accessions conserved in the Incaper germplasm bank have been characterized primarily through the evaluation of morphological traits, based on descriptors defined a priori for the species and of direct interest to growers. However other complementary characterization techniques have been used, such as molecular and biochemical. There is a great concern about the maintenance of the genetic materials, since the use of clonal varieties provides a significant reduction in the diversity of the cultivated material. The introduction of the germplasm from Guinea, Uganda and Angola was done once. For this reason, the genetic basis of existing populations is considered to be narrow. More divergent germplasm from

these countries should be introduced in the state. The increase in genetic variability was done through the introduction of materials from other institutions, such as the 26 new genotypes of the species *Coffea canephora* belonging to genetic groups distinct from conilon in October 2003 and 65 new genotypes of *Coffea canephora* belonging to distinct genetic groups of Conilon from the Instituto Agronômico de Campinas. The great majority belongs to distint groups of Conilon from Universidade Federal de Viçosa. These materials, added to eight other genotypes characteristic of the genetic group known as "robusta" and rescued in the state itself, were introduced into the Germplasm Bank in order to know their behavior in all the coffee regions, as well as to provide conditions for the identification of characteristics of interest that can later be transferred to materials with agronomic and commercial characteristics already known.

Seven clonal varieties and two propagated by seeds presented horizontal resistance to *H. vastatrix* under field conditons (Table 5). But observations of the clones of the varieties cultivated in several regions of the Espirito Santo state showed that some of them presented vertical resistance. Each clones of the varieties is planted in rows.

Table 5. Cultivars with resistance to leaf rust developed by the Instituto Capixaba de Pesquisa e Extensão Rural do Estado do Espírito Santo (Incaper)

Cultivar	Number of clones used in the formation of the cultivar	Type of Resistance to *H. vastatrix*
Emcapa 8111	9	Horizontal or quantitative
Emcapa 8121	14	Horizontal or quantitative
Emcapa 8131	9	Horizontal or quantitative
Emcapa 8141-Robustão Capixaba	10	Horizontal or quantitative
Emcaper 8151-Robusta Tropical (seed propagation)	Open pollination of 53 elite clones	Horizontal or quantitative
Vitória Incaper 8142	13	Horizontal or quantitative
Diamante ES 8112, ES 8122	9	Horizontal or quantitative
Jequitibá	9	Horizontal or quantitative
Centenária ES 8132	8	Horizontal or quantitative
Conquista	Propagation via seeds	Horizontal or quantitative

8. Genetic Improvement Program Against Coffee Leaf Rust Developed by the Fundação de Apoio Tecnológico à Cafeicultura (Fundação Procafé)

The agronomists who initiated the Procafé program were: José B. Matiello, Saulo R. de Almeida, Roque A. Ferreira and Maurício A. Bento. Sometime later, the following agronomists joined the team Dr. Carlos H. S. de Carvalho. Most of the germplasm bank is maintained at the 'Estação Experimental de Varginha, State of Minas Gerais (FEV). This experimental farm was set up in 1976. Genetic materials selected for the breeding program were also evaluated in different locations in the states of Minas Gerais, São Paulo, Espírito Santo and Bahia. In these states, partnerships were established with coffee growera. Currently, the Foundation has a germplasm bank with about 600 accessions, most of which are genetic materials from *Coffea arabica* with different degrees of inbreeding, and part of these materials is used in genetic improvement. In this database, it is possible to find accessions of cultivars that participated in the history of coffee culture in Brazil, as well as accessions of great importance as a source of agronomic interest, such as drought tolerance, resistance to pests, diseases and nematodes, special beverage and seed size. The breeding program developed by the Ministério da Agricultura /Foundation released for commercial planting are: Acauã, Acauã Novo, Arara, Azulão, Catucaí 785-15, Catucaí Amarelo 785-15, Catucaí Amarelo 2015479, Catucaí Amarelo 2SL, IBC-Palma-1, IBC-Palma-2, Japy, Sabiá Tardio and Saíra resistant to leaf rust (Table 5) (Carvalho et al., 2022; Sera et al., 2022a). The program also works with the development of cultivars with resistance to the leaf miner: cultivars Siriema AS1 (seed propagation), and clonal cultivar Siriema VC4 (Table 6) (Carvalho et al., 2022). Two varieties had vertical resistance to *H. vastatrix*; the great majority had horizontal resistance. The group of coffee plants that originated most of the resistant varieties was Sarchimor (CIFC 832/2). Thirteen varieties originated from Sarchimor and four from Catimor (Table 6).

Table 6. Most importante commercial varieties resistant to leaf rust released by the Fundação Procafé

Variety	Crossing	Type of resistance
Acauã	Mundo Novo IAC 388-17 × Sarchimor IAC 1668	Vertical or qualitative
Acauãma	Catucaí amrelo × Acauã (natural crossing)	Horizontal or quantitative
Acauã Novo	Sarchimor 1668 × Mundo Novo	Vertical or qualitative
Arara	Catuaí amarelo × Obatã (natural crossing)	High horizontal or quantitative
Azulão (Catucaí vermelho 36/6-366	Catuaí vermelho × Icatu vermelho 785	High horizontal or quantitative
Catucaí vermelho 36/6-366	Catuaí vermelho × Icatu vermelho 785	Horizontal or quantitative
Catucaí 785-15	Catuaí vermelho × Icatu vermelho 785	Horizontal or quantitative
Catucaí Amarelo 06/30	Catuaí vermelho × Icatu vermelho 785	Horizontal or quantitative
Catucaí Amarelo 24/137	Catuaí vermelho × Icatu vermelho 785	Very low horizontal or quantitative resistance
Catucaí Amarelo 20/15-479	Catuaí vermelho × Icatu vermelho 785	Horizontal or quantitative
Catucaí Amarelo 20/15-476	Catuaí vermelho × Icatu vermelho 785	Horizontal or quantitative
Catucaí Amarelo 2SL	Catuaí× Icatú (natural crossing|)	Horizontal or quantitative
IBC-Palma-1, Palma 2	Catuaí vermelho IAC 82 × Catimor UFV 353	Horizontal or quantitative
Japy	Selection of Catucaí vermelho 19/8	Horizontal or quantitative
Sabiá Tardio	Acaia × Catimor UFV 386	Horizontal or quantitative
Saíra	Catuaí amarelo IAC 86 × Catindú (UFV 374 cv 643)	Horizontal or quantitative
Siriema 842	*Coffea arabica* × *C. racemosa* Crossed again with Catimor UFV 417	Horizontal or quantitative High resistance to leaf minor

9. Genetic Improvement Against Coffee Leaf Rust in Embrapa Rondônia

In July 1975, the Unidade de Execução de Pesquisa de Âmbito de Territorial (UEPAT), Porto Velho, RO) was created. Through partnerships and demands from the newly settled settlers, pioneering experiments in agronomic evaluations of cultivars and lines of Arabica coffee trees were implemented in selected rural plots (IAC Mundo Novo). At the beginning of the colonization the technicians detected a focus of the leaf rust fungus. Soon the disease disseminated in the emerging coffee-producing regions, attacking coffee plants of the cultivars of *C. arabica* L. (cv. Mundo Novo) and *C. canephora* Pierre ex. Froehner (Conilon botanical variety of unknown genetic origin). The epidemiological cycle was estimated and temporal spraying programs were determined for the chemical control of leaf rust currently the main foliar disease in coffee plants in Rondônia. Since this time, leaf rust has been considered the main key disease of coffee plants in the Northwest (Mato Grosso and Rondônia, States), causing direct damage to young and adult plants due to intense defoliation and reduction in coffee bean yield. Significant decreases in grain production had been observed, reaching up to 40% (compared to control treatment), under environmental conditions favorable to leaf rust (Veneziano et al., 1983). The results of the epidemiological studies showed that *H. vastatrix* initiated in December-January and increased the severity until March-April. Then, in the dry season, the disease progressively declined until August, stabilizing at a low rate until October.

In the epidemiological cycle of *C. arabica* rust, determined in the Aw environment of the village of Cacoal-Rondonia, it was noted that the evolution of the disease would occur in the period between September to November.

After 20 years, the technological reality of the state's coffee growing has changed markedly. Coffee cultivation based on the production of arabica ceased to exist due to economic unfeasibility and correlated factors. Farmers mostly started to explore technified clonal coffee cultivation based on conilon. At Embrapa Rondônia, since 2000, the focus on the medium-long term genetic improvement program with the coffee species *Coffea canephora* Pierre ex. Froehner has been the selection of plants with high productive potential, structural architecture compatible with dense planting, uniform fruit maturation cycle, superior quality of the beverage. In addition to environmental sustainability and the damage the disease cause to coffee production, the phytosanitary selection criteria adopted prioritized genetic resistance (total or partial) to the main diseases of coffee cultivation in the Western Amazon Region caused by fungal pathogens, especially leaf rust (*H. vastatrix* Berk & Br.) and brown spot (*Cercospora coffeicola* Berk. & Cook) and root-knot nematodes (Meloidogyne spp.). In order to achieve the objectives proposed by the program for the genetic improvement of coffees (*C. canephora* and *C. arabica*) of Embrapa Rondônia, the potential genetic variability was mantained in the Active Germplasm Bank (BAG-Cafés), at the Experimental Station of Ouro Preto do Oeste (10°43′44.51″S; 62°15′09.78″W; 249 m; clia Aw) and central-eastern region of Rondônia. BAG-Café (*C. arabica*) was installed in 1982 with 50 accessions

(commercial cultivars and unregistered lineages). Due to the lack of demand for Arabica coffee due to the climate conditions, researchers deactivated the program. BAG-Cafés (*C. canephora*) in Rondonia was installed in 1988. The number of active accessions (seminal and clonal) of the two botanical *C. canephora* var. *robusta* and *C. canephora* var *conilon* fluctuates over time. A total of 450 accessions of *C. canephora* var. *robusta* (R) and *conilon* (C) and spontaneous intervarietal hybrids [R×C]) are maintained and characterized by phenotypic, genetic descriptors and biochemical response to leaf rust and root-knot nematode as well as quality of the beverate (Fonseca et al., 2022).

Currently, 30% of the clonal accessions are of conilon from spontaneous hybrids pre-selected from among 780 clones collected in commercial coffee plantations in several municipalities in Rondônia, during the three prospecting expeditions carried out in the years 1985 to 1988. As a result of the field collections a multiclonal cultivar Conilon 'BRS Ouro Preto', formed by the grouping of 15 superior clones (Ramalho, et al., 2016). Was released for the growers The BRS cultivar Ouro Preto was registered (RNC/MAPA Nº 29486 on 04/05/2012) and protected (Nº 20130061 as of 10/09/2012) at the National Service for the Protection of Plant Varieties-SNPC/MAPA. The phytosanitary criteria of selection and characterization adopted for clones of 'Conilon' prioritized resistance or tolerance to the main diseases of the regional coffee plants: leaf rust (*H. vastatrix* Berk. et Br), brown eye spot (*Cercospora coffeicola* Berk. & Cook), leaf spot and blight (Colletotrichum spp.) and root-knot nematodes (*Meloidogyne exigua*).

Nowadays approximately 50% of clonal and seminal accessions are pure 'robustas' and intergroup hybrids. These accessions are the result of stratified mass selection in the progenies of robustas and seminal conilons from the IAC in 1983. These genotypes were evaluated in Rondônia during 10 harvests for resistance or high genetic tolerance to leaf rust and root-knot nematodes (Veneziano, 1993; Rocha et al., 2021).

10. Conclusions

(1) The main source of resistance to coffee leaf rust used by all the research institutions in Brazil came from 'Centro de Investigação das Ferrugens do Cafeeiro-CIFC' in Oeiras, Portugal. They are: Híbrido de Timor (HdT) CIFC 832-1 and HdT CIFC 832 and HdT CIFC 2570. Other source of resistance to leaf rust came from *Coffea canephora* crossed with *C. arabica* originating.

(2) *Coffee liberica* L. with the gene S_H3 is another source of resistance to leaf rust.

(3) The great majority of the resistant cultivar came from Catimor and Sarchimor. More than 50 coffee varieties have been launched with resistance to the leaf rust in the last 40 years in Brazil.

(4) The great majority of the varieties released by the research institutions in Brazil, with vertical resistance was broken after eight to ten years under field conditions.

(5) After the loss of vertical resistance in the field, the varieties presented different levels of horizontal resistance.

(6) The great varieties released with vertical resistance was from the group Sarchimor.

(7) Horizontal resistance is more common on *C. canephora* var. *conilon* and *C. canephora* var. *robusta* than in *C. arabica*.

(8) *Coffea canephora* var. *conilon* and *C. canephora* var. *robusta* shows more drought tolerance than *C. arabica* in the field.

(9) The great variability of *H. vastatrix* affects the durability of the coffee cultivars in the field. No Brazil there are more than 16 races of the pathogen.

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Authors Contributions

Author Laércio Zambolim coordinated all the review and in the interpretation of the results of *Coffea arabica* and *Coffea canephora*. Eveline Teixeira Caixeta helped in the interpretation of the data. Oliveiro Guerreiro Filho collected the data of *Coffea arabica*. Gustavo Sera collected the data of *Coffea arabica*. Tumoro Sera collected the data of *Coffea arabica*. Antônio Alves Pereira collected the data of *Coffea arabica*. Antônio Carlos Baião de Oliveira collected the data of *Coffea arabica*. Abração Carlos Verdin Filho collected the data of *Coffea canephora*. Carlos Henrique de Carvalho collected the data of *Coffea arabica*. André Ramalho collected the data of *Coffea canephora*. All authors read and approved the final manuscript.

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