



Description of *Coffea arabica* materials and their tolerance to coffee leaf rust (*Hemileia vastatrix*) under conditions of Amatlán de los Reyes, Veracruz

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ABSTRACT

Backgrounds/Objective. Coffee cultivation is at risk due to the effects of climate change, which has created favorable conditions for the proliferation of diseases such as coffee leaf rust (*Hemileia vastatrix*). One of the most cost-effective and efficient control measures has been the use of materials that are tolerant or resistant to this fungus. The objective of this study was to analyze the response of 32 promising *Coffea arabica* accessions to coffee leaf rust and to describe their morphological characteristics, relating them to disease severity, under conditions prevailing in the municipality of Amatlán de los Reyes, Veracruz.

Experimental development. A total of 32 *C. arabica* accessions were evaluated in a completely randomized block design with three replications, compiling a descriptive profile of the visible, identifiable, and measurable morphological traits of each evaluated accession. The incidence of coffee leaf rust (*Hemileia vastatrix*) was assessed on a five-level severity scale on a monthly basis over a two-year period. An ordinal mixed-effects model and post hoc tests were computed to identify significant differences in rust incidence. Hierarchical cluster analysis was carried out to group the materials according to susceptibility or severity level, and the relationship between morphological traits and infestation level was analyzed using multiple correspondence analysis.

Results. The materials showed significant differences in tolerance to coffee leaf rust. Tukey's test ($\alpha = 0.05$) identified three groups based on the severity of rust damage; the Pacamara variety was the most affected, while the H1 Centroamericano, Parainema, Catigua MG2, Col 1, EC 15, IPR 103, Kartila 1, Lempira, Paraíso, S795, and the Arabusta SLN 5B varieties were the least affected. The remaining varieties showed an intermediate severity of infestation.

Conclusion. Under the conditions prevailing at the experimental site of the Colegio de Postgraduados Campus Córdoba, 11 *C. arabica* materials showed a favorable response to the severity of *Hemileia vastatrix* (H1 Centroamericano, Parainema, Catigua MG2, Col 1, EC 15, IPR 103, Kartila 1, Lempira, Paraíso, S795, and the Arabusta SLN 5B). This contributes to the options available to coffee growers in terms of production and plant health management against coffee leaf rust.

Keywords: Coffee farming, Climate change, Plant health, Food security



INTRODUCTION

Coffee belongs to the Rubiaceae family, in the *Coffea* genus, with more than 120 species described, the most noteworthy of which are *Coffea arabica* and *C. canephora* (Reyes *et al.*, 2020). This crop requires specific tropical conditions for its establishment and development, such as high humidity levels (60-80%) and temperatures of 18-22 °C (Lozano, 2019). *Coffea arabica* is a self-fertile allotetraploid, resulting from the spontaneous hybridization between *C. canephora* on the male side and *C. eugenoides* as the female parent (Villalta and Gatica-Arias, 2019). Self-pollination in *C. arabica* reports percentages of over 95%, generating a low genetic diversity in the plantations (Julca Otiniano *et al.*, 2023), which makes them susceptible to devastating effects caused by diseases, pests, water stress and environmental change (Spinoso-Castillo *et al.*, 2021).

In the last three decades, a new generation of *C. arabica* has been developed from commercial lines, such as the Sarchimores in combination with wild Ethiopian germplasm (Duangsodsri *et al.*, 2020), in order to ensure a sustainable production, with varieties adapted to diversified shade systems, highly productive, resistant to coffee leaf rust and with a high quality in the end-product (Koutouleas *et al.*, 2022). Morphological descriptors established by the International Union for the Protection of New Varieties of Plants (UPOV), are standardized tools for the identification and differentiation of plant varieties, based on observable and measurable morphological and physiological characters. These descriptors are applicable to *C. arabica*, *C. canephora* and their hybrids. The varietal characterization must be applied in healthy and vigorous plants, with a minimal evaluation period of two productive cycles, and include at least five individuals in plant propagation materials or twenty individuals, when it concerns propagation by seed (UPOV, 2008).

Mexico is the eleventh coffee producer worldwide, contributing around 4.5 million 60-kg bags per cycle (OIC, 2024). Due to the entry of the orange coffee rust and its subsequent crisis in 2013, the country's coffee production decreased by half between 2014 and 2018 (SIACON, 2024), since many coffee plants (approximately 50%) were unable to survive the orange rust infestation, leading to situations of vulnerability for farmers who depend economically on this activity (Parada *et al.*, 2020; Gasperín-García *et al.*, 2023). The little intensity in crop management, in a climate change scenario, displays the need to evaluate technologies that help maintain or improve the productive conditions in the country, such as the evaluation and selection of new pest- and disease-resistant varieties (Mendez *et al.*, 2025).

Orange coffee rust is found in all coffee-producing countries, and it is caused by the biotrophic fungus *Hemileia vastatrix*, of the order *Pucciniales* in the Basidiomycota phylum. The disease is considered of high economic relevance in worldwide coffee production (Castro *et al.*, 2025). It was first reported in Mexico in 1981, without causing major damage (Guerrero-Parra *et al.*, 2022). Between 2012 and 2014, the climate in the coffee-producing areas of the country created adequate conditions (at least three days with a high level of humidity (> 90%), low light (< 30%) and ideal temperatures (between 21 and 25 °C) for the appearance of massive rust outbreaks (Parada *et al.*, 2020), affecting more than 50% of the varieties planted in Mexico, and leading to a reduction in national production, in later years, nearly 50%.

The most common phytosanitary measures to control the disease are based on preventative actions, such as the control of the plantation density and reduction of excess shade, limiting the germination and sporulation of *H. vastatrix* (Salazar Navarro *et al.*, 2024). The most inexpensive control measures, and with the lowest impact, are biological

ones, which include the use of bioactive compounds with antifungal activity, such as neem (*Azadirachta indica*) oil, the use of living organisms, through mechanisms such as niche competition, antibiosis or parasitism, using, for example, species from the *Lecanicillium* genus, as well as the introduction of varieties and hybrids that are resistant or tolerant to the attack of orange coffee rust (Aguirre-Vega *et al.*, 2022; Pinedo-Mas *et al.*, 2026). The aim of this investigation was to analyze the response of 32 promising *C. arabica* materials against the attack of coffee rust, and describe the morphological characteristics of these materials, associating them with the severity of the disease in the municipal area of Amatlán de los Reyes, Veracruz.

EXPERIMENTAL DEVELOPMENT

Study site. The study was carried out in Amatlán de los Reyes, Veracruz (18°51'35''N, 96°51'29''W), at 640 m. a. s. l. The area has a characteristically warm humid climate with abundant rainfalls in the summer, with a mean annual rainfall of 2,000 mm and a mean annual temperature of 22 °C. The terrain has a slope of < 5% and haplic vertisol soil, with abundant sedimentary rocks (INEGI, 2010). The experimental site has a level of shade of 40 to 60%, with a predominance of coverage species such as *Azadirachta indica*, *Musa* sp. and *Inga* sp. Before establishing the coffee plantation, the site of study had not been cultivated for over five years.

Plant material. The coffee plants used in the study are part of the International Multilocation Variety Trial (IMTV), promoted in 2015 by the non-governmental organization World Coffee Research (WCR), as an initiative to evaluate different *C. arabica* materials in 18 countries, including Mexico, to document the best adapted varieties, in order to ensure the future of the coffee industry (WCR, 2025). Thirty-two *C. arabica* varieties (treatments) were used, 21 dwarf-sized and 11 tall-sized varieties (Table 1). The evaluated materials were planted in 2018 in a completely randomized block design, with three repetitions (blocks). The experimental unit was composed of 10 plants from the same genetic material. There was a total of 30 coffee plants per material (treatment).

Morphological description of the plant material. The morphological description was carried out with a modified version of the practical guidelines for the Examination of Distinctness, Uniformity and Stability (DUS), proposed by UPOV in 2008 (Table 2), in which only the most representative morphological characteristics for the visual identification of coffee varieties were evaluated. The descriptive variables of the morphology were qualitative, and their potential association with the severity of orange rust observed in the materials under study was analyzed using multiple correspondence analysis.

Table 1. Description of *Coffea arabica* materials assessed for resistance to coffee leaf rust.

Material	Country of origin	Breeder	Size	Genetic group
AB3	Indonesia	ICCRI	Tall	Native Ethiopian variety
Batian	Kenya	CRI	Tall	Introgressed Catimor
Bourbon	Yemen	Ninguno	Tall	Bourbon group
BP432A	Indonesia	ICCRI	Dwarf	Introgressed Catimor
Catigua MG2	Brazil	EMBRAPA	Dwarf	Introgressed Catimor
Catuai V IAC144	Brazil	EMBRAPA	Dwarf	Typica + Bourbon group
Col 1	Colombia	CENICAFE	Dwarf	Introgressed Catimor
Col 2	Colombia	CENICAFE	Dwarf	Introgressed Catimor
Col 3	Colombia	CENICAFE	Dwarf	Introgressed Catimor
Col 4	Colombia	CENICAFE	Dwarf	Introgressed Catimor
EC 14	Central America	ECOM	Dwarf	Introgressed F1 hybrid
EC 15	Central America	ECOM	Dwarf	Introgressed F1 hybrid
EC 16 (Mundo Maya)	Central America	ECOM	Dwarf	Introgressed F1 hybrid
Garnica	Mexico	INMECAFE	Dwarf	Red Mundo Novo + Yellow Caturra
Geisha	Panama	F. Sarracín	Dwarf	Native Ethiopian variety
H1 Centroamericano	Central America	PROMECAFE	Tall	Introgressed F1 hybrid
IPR 103	Brazil	EMBRAPA	Dwarf	Icatú introgression
IPR 107	Brazil	EMBRAPA	Dwarf	Introgressed Sarchimor
K7	Kenya	CRI	Dwarf	Bourbon group
Kartila 1	Indonesia	ICCRI	Tall	Introgressed Catimor
Lempira	Honduras	IHCAFE	Dwarf	Introgressed Catimor
Marsellesa	Central America	ECOM	Dwarf	Introgressed Sarchimor
Mundo Novo 379/19	Brazil	EMBRAPA	Dwarf	Typica + Bourbon Group
Oro azteca	Mexico	INIFAP	Tall	Introgressed Catimor
Pacamara	El Salvador	PROCAFE	Dwarf	Typica + Bourbon Group
Parainema	Honduras	IHCAFE	Dwarf	Introgressed Sarchimor
Paraíso	Brazil	EMBRAPA	Dwarf	Introgressed Catimor
S4808	India	CCRI	Dwarf	Introgressed Catimor
S795	India	CCRI	Tall	Introgressed Liberica
SL 28	Kenya	CRI	Tall	Bourbon Group
SLN 5B	India	CCRI	Tall	Introgressed Liberica
SLN 6	India	CCRI	Tall	Introgressed Arabusta

Evaluation of the infestation severity. The severity of the coffee rust was evaluated every month during the 2023/2024 and 2024/2025 cycles using an ordinal visual scale with five categories (Figure 1), based on the proportion of affected foliar tissue and the level of sporulation (Table 3), according to Avelino *et al.* (2019) and Capucho *et al.* (2011).

Table 2. Morphological descriptors as defined by UPOV (2008) for varieties of *C. arabica*.

Characteristic	Criteria	Examples / Description
Plant: shape	Conical Ellipsoidal Cylindrical	Conical: Acaia, Laurina Ellipsoidal: Pluma Hidalgo Cylindrical: Catuai
Plant: height	Very short Short Medium Long Very long	Very short: < 2 m Short: 2 - 2.5 m Medium: 2.5 - 3 m Tall: 3 - 4 m Very tall: > 4 m
Plant: canopy diameter	Very small Small Medium Large Very large	Very small: < 1 m Small: 1 - 1.5 m Medium: 1.5 - 2 m Large: 2 - 2.5 m Very large: > 2.5 m
Plagiotropic primary branch: internode length	Short Medium Long	Short: < 4 cm Medium: 4 - 6 cm Long: > 6 cm
Plagiotropic primary branch: branching intensity	Very weak Weak Medium Strong Very strong	Very weak: Bourbon Weak: Acaia Medium: Mundo Novo Strong: Catuai, Rubí Very strong: San Ramón
Leaf: shape	Lanceolate Oval Elliptical	Lanceolate: Typica Oval: Maragogipe Elliptical: San Ramón
Leaf: length	Very short Short Medium Long Very long	Very short: 5-10 cm Short: 10-15 cm Medium: 15-20 cm Long: 20-25 cm Very long: > 25 cm
Leaf: width	Very narrow Narrow Medium Wide Very wide	Very narrow: 2-4 cm Narrow: 4-5 cm Medium: 5-7 cm Wide: 6-9 cm Very wide: > 10 cm
Young leaf: anthocyanin pigmentation	Absent or weak Medium Strong	Absent or weak: light green (Bourbon) Medium: bronze (Typica) Strong: reddish (Purpuracens)
Leaf: edge curling	Very weak Weak Medium Strong	Very weak: Garena Weak: Geisha Medium: Mundo Novo Strong: Typica
Leaf: depth of secondary veins	Shallow Medium Deep	Shallow: Laurina Medium: Mundo Novo Deep: Maragogipe
Inflorescence: number of flowers	Low Medium High	Low: Typica Medium: Bourbon High: Topázio
Fruit: size	Very small Small Medium Large Very large	Very small: < 1 cm Small: 1 - 1.25 cm Medium: 1.25 - 1.5 cm Large: 1.5 - 2 cm Very large: > 2 cm
Fruit: shape	Elliptical Circular Oblong	Elliptical: Pacamara Circular: Ibairi Oblong: Mundo Novo
Fruit: adherence to the branch	Weak Medium Strong	Weak: Mundo Novo Medium: Catuai Strong: Icatu Amarelo IAC 29-44

Table 3. Scale of severity for coffee leaf rust.

Symptoms	Assigned infection grade (IG)
No rust spots	1
Some rust spots without sporulation	2
Some rust spots with sporulation	3
Most leaves with rust spots, sporulation and slight defoliation	4
Most leaves with rust spots, sporulation and severe defoliation	5

Source: Avelino *et al.* (2019) modified.

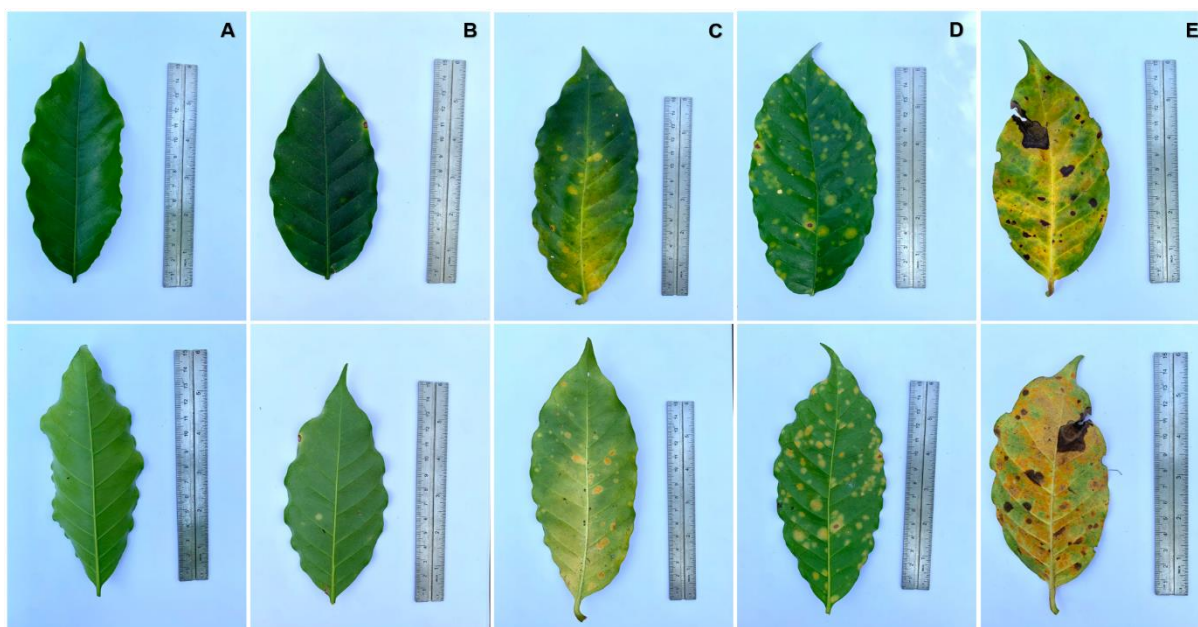


Figure 1. A visual guide to assessing the severity of coffee leaf rust based on the proposal by Capucho *et al.* (2011). **A.** Healthy leaf with no rust spots (IG 1). **B.** Infected leaf with chlorotic spots without sporulation covering around 2 per cent of the leaf area (IG 2). **C.** Infected leaf with sporulating lesions covering around 20 per cent of the leaf area (IG 3). **D.** Infected leaf with sporulating lesions covering around 45 per cent of the leaf area (IG 4). **E.** Infected leaf with sporulating lesions covering more than 70 per cent of the leaf area (IG 5).

Statistical analysis. In the data analysis, the degree of severity was considered an interval variable based on the scale by Avelino *et al.* (2019). The data were analyzed using a mixed ordinal model in which varieties were considered fixed effects and the different evaluation dates, as random effects. Subsequently, post hoc tests were performed to identify significant differences in the degree of severity presented by the materials (Tukey, $\alpha = 0.05$). With a hierarchical cluster analysis, the materials were separated into susceptibility groups or severity level. After the data for severity and morphology were obtained, a multiple correspondence analysis was performed to determine whether there are morphological variables (among all those evaluated) that relate to the level of severity that plants presented. The analyses were carried out using the open-source software RStudio version 4.3.1.

Morphological evaluation. The morphological findings were divided into three categories: plant morphology (Table 4), leaf morphology (Table 5) and fruit morphology (Table 6). All evaluated materials displayed red fruits, with the exception of the Paraíso variety. Likewise, all evaluated materials presented domatia in their foliar structures.

Table 4. Morphological description of *C. arabica* materials in accordance with the UPOV (2008) guidelines.

Material	Type of breeder's licence	Propagation method	Plant shape	Plant height	Diameter of the foliage canopy	Internode length on plagiotropic branches	Branching intensity on plagiotropic branches
AB3	Public domain	Seed	Conical	Long	Very large	Long	Strong
Batian	Licence required	Seed	Cylindrical	Long	Medium	Short	Medium
Bourbon	Public domain	Seed	Cylindrical	Long	Medium	Short	Weak
BP432A	Licence required	Seed	Cylindrical	Long	Medium	Medium	Strong
Catigua MG2	Public domain	Seed	Cylindrical	Medium	Large	Short	Strong
Catuai V IAC144	Public domain	Seed	Cylindrical	Long	Medium	Medium	Strong
Col 1	Licence required	Seed	Ellipsoidal	Short	Small	Medium	Medium
Col 2	Licence required	Seed	Cylindrical	Short	Small	Short	Weak
Col 3	Licence required	Seed	Cylindrical	Short	Medium	Short	Strong
Col 4	Licence required	Seed	Ellipsoidal	Medium	Large	Medium	Strong
EC 14	Licence required	Asexual	Cylindrical	Medium	Medium	Medium	Medium
EC 15	Licence required	Asexual	Cylindrical	Medium	Medium	Medium	Strong
EC 16 (Mundo Maya)	Licence required	Asexual	Cylindrical	Long	Medium	Short	Medium
Garnica	Public domain	Seed	Cylindrical	Long	Medium	Medium	Medium
Geisha	Public domain	Seed	Cylindrical	Long	Large	Medium	Strong
H1 Centroamericano	Licence required	Asexual	Cylindrical	Long	Large	Short	Strong
IPR 103	Public domain	Seed	Cylindrical	Medium	Large	Medium	Strong
IPR 107	Public domain	Seed	Cylindrical	Long	Large	Long	Very strong
K7	Licence required	Seed	Cylindrical	Long	Medium	Long	Weak
Kartila 1	Licence required	Seed	Cylindrical	Long	Large	Medium	Very strong
Lempira	Public domain	Seed	Cylindrical	Medium	Small	Short	Weak
Marsellesa	Licence required	Seed	Cylindrical	Long	Medium	Short	Strong
Mundo Novo 379/19	Public domain	Seed	Cylindrical	Very long	Very large	Long	Medium
Oro azteca	Licence required	Seed	Cylindrical	Medium	Small	Short	Weak
Pacamara	Public domain	Seed	Cylindrical	Long	Large	Long	Very strong
Parainema	Public domain	Seed	Cylindrical	Medium	Large	Medium	Medium
Paraíso	Public domain	Seed	Cylindrical	Long	Large	Short	Strong
S4808	Licence required	Seed	Cylindrical	Long	Large	Medium	Strong
S795	Licence required	Seed	Cylindrical	Long	Large	Long	Medium
SL 28	Licence required	Seed	Cylindrical	Very long	Large	Long	Strong
SLN 5B	Licence required	Seed	Cylindrical	Long	Small	Medium	Medium
SLN 6	Licence required	Seed	Cylindrical	Long	Large	Long	Strong

Table 5. Morphological description of the leaf of *C. arabica* materials according to the UPOV (2008) guidelines.

Material	Leaf shape	Length	Width	Anthocyanin pigmentation in young leaves	Edge curling	Depth of secondary veins
AB3	Elliptical	Medium	Narrow	Medium	Strong	Medium
Batian	Elliptical	Medium	Medium	Strong	Weak	Shallow
Bourbon	Elliptical	Short	Narrow	Strong	Strong	Deep
BP432A	Elliptical	Medium	Medium	Medium	Strong	Medium
Catigua MG2	Elliptical	Medium	Medium	Strong	Medium	Deep
Catuai V IAC144	Lanceolate	Medium	Wide	Weak	Strong	Deep
Col 1	Elliptical	Short	Narrow	Weak	Medium	Shallow
Col 2	Elliptical	Short	Very narrow	Strong	Medium	Deep
Col 3	Elliptical	Medium	Medium	Weak	Medium	Medium
Col 4	Lanceolate	Medium	Narrow	Strong	Strong	Medium
EC 14	Elliptical	Medium	Medium	Weak	Weak	Medium
EC 15	Elliptical	Medium	Medium	Strong	Strong	Deep
EC 16 (Mundo Maya)	Elliptical	Long	Wide	Weak	Strong	Deep
Garnica	Elliptical	Medium	Wide	Weak	Medium	Deep
Geisha	Elliptical	Long	Medium	Weak	Strong	Deep
H1	Elliptical	Long	Wide	Weak	Medium	Medium
Centroamericano						
IPR 103	Lanceolate	Long	Wide	Strong	Strong	Deep
IPR 107	Elliptic	Long	Wide	Strong	Medium	Deep
K7	Elliptic	Long	Wide	Strong	Medium	Medium
Kartila 1	Elliptic	Long	Wide	Weak	Strong	Deep
Lempira	Elliptic	Long	Narrow	Strong	Weak	Shallow
Marsellesa	Lanceolate	Medium	Medium	Strong	Medium	Deep
Mundo Novo	Elliptic	Long	Medium	Weak	Medium	Medium
379/19						
Oro azteca	Elliptic	Medium	Medium	Strong	Strong	Shallow
Pacamara	Lanceolate	Medium	Very wide	Strong	Strong	Deep
Parainema	Lanceolate	Long	Medium	Weak	Strong	Deep
Paraíso	Elliptic	Long	Wide	Medium	Medium	Deep
S4808	Elliptic	Medium	Medium	Strong	Strong	Medium
S795	Elliptic	Medium	Medium	Strong	Strong	Deep
SL 28	Elliptic	Long	Medium	Strong	Medium	Deep
SLN 5B	Elliptic	Medium	Medium	Strong	Medium	Medium
SLN 6	Elliptic	Medium	Medium	Strong	Medium	Medium

Table 6. Morphological description of fruits from *C. arabica* materials according to the UPOV (2008) guidelines.

Material	Number of flowers	Fruit shape	Fruit size	Adherence to the branch
AB3	Medium	Elliptical	Large	Strong
Batian	Low	Oblong	Large	Strong
Bourbon	Medium	Elliptical	Small	Medium
BP432A	High	Elliptical	Small	Medium
Catigua MG2	High	Circular	Small	Weak
Catuai V IAC144	Medium	Circular	Small	Weak
Col 1	Medium	Elliptical	Small	Medium
Col 2	Medium	Circular	Small	Weak
Col 3	High	Elliptical	Small	Weak
Col 4	High	Elliptical	Medium	Weak
EC 14	High	Elliptical	Small	Weak
EC 15	High	Oblong	Large	Weak
EC 16 (Mundo Maya)	High	Elliptical	Medium	Weak
Garnica	High	Elliptical	Small	Weak
Geisha	High	Elliptical	Medium	Strong
H1 Centroamericano	High	Oblong	Large	Weak
IPR 103	High	Circular	Large	Medium
IPR 107	High	Elliptical	Medium	Weak
K7	Low	Oblong	Large	Medium
Kartila 1	High	Elliptical	Medium	Strong
Lempira	Medium	Elliptical	Small	Weak
Marsellesa	Medium	Elliptical	Small	Weak
Mundo Novo 379/19	Medium	Oblong	Medium	Weak
Oro azteca	Low	Oblong	Small	Weak
Pacamara	Medium	Oblong	Very large	Weak
Parainema	High	Circular	Medium	Weak
Paraíso	High	Circular	Small	Medium
S4808	High	Oblong	Medium	Medium
S795	Low	Elliptical	Medium	Medium
SL 28	Medium	Elliptical	Large	Medium
SLN 5B	Medium	Circular	Small	Medium
SLN 6	Low	Elliptical	Medium	Medium

The *C. arabica* materials presented diverse morphology, attributable to the genetic material in the experimental area's typical environmental conditions, characterized by high temperatures in the spring (30-39 °C), intense rainfall in the summer (June to September) and days with fog between October and January. According to Manzani-Lisboa *et al.* (2021), leaf anatomy can be influenced by environmental factors such as water availability for plants, which may explain discrepancies found regarding the World Coffee Research Variety Catalog (2025), in materials IPR 107 and Batian, that presented young leaves with a strong anthocyanin pigmentation. Morphological aspects such as plant height, fruit length and diameter usually present a lower variation in regard to one same variety (Malau and Pandiangan, 2018), which coincides with the results by this study. A morphological aspect related to the productivity of the materials is the number of flowers, where, in general terms, materials with a high number of flowers were observed to present small or medium fruits, which may indicate the potential of the nutritional management of the coffee plant as a measure to increase the productivity of these materials. Under extensive management conditions (without fertilization and with diversified shade) materials EC 15, H1 Central American and IPR 103 can be viable alternatives, due to the low level of infestation by rust they presented in the years evaluated (Table 7).

Interaction of morphological features with the degree of infestation of coffee rust. The multiple correspondence analysis (Figure 2) shows that, with two dimensions, it is possible to explain 21% of the total variability found in the morphological variables evaluated. Leaf size, in its variables of leaf width (very narrow vs very wide) and foliar coverage (small vs very big), is what contributes the most to the definition of dimension 1. This dimension shows that the varieties with very broad leaves and very large foliar coverage tend to display greater levels of rust than the varieties with very narrow leaves and a small foliar coverage.

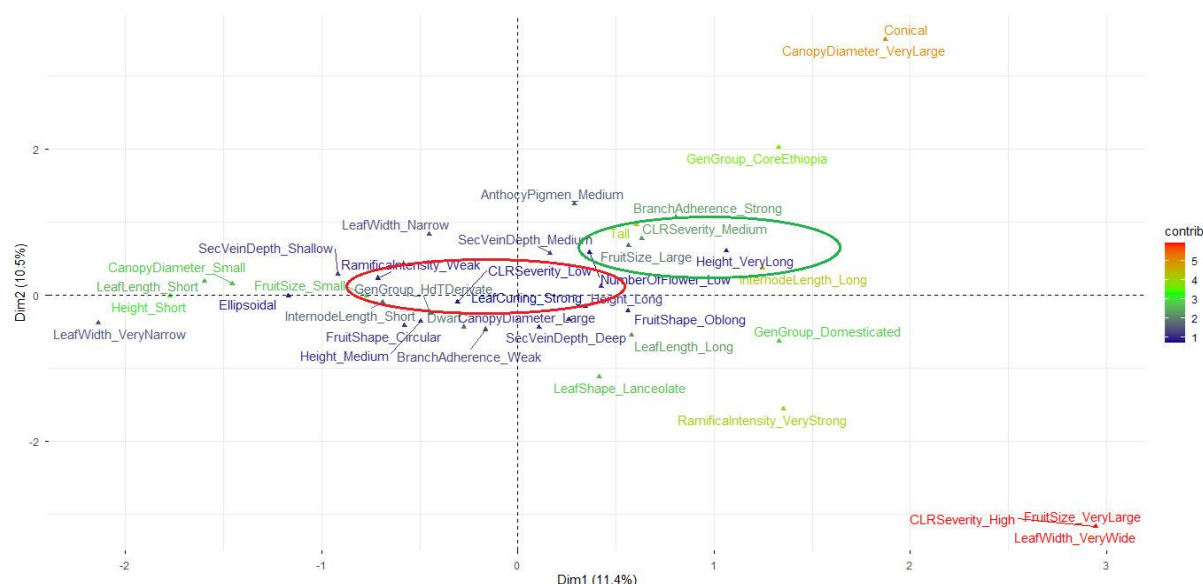


Figure 2. Map of morphological variables of the coffee plant and their relationship with the level of coffee leaf rust infestation.

Delimited by the red ellipse, the variable CLRSeverity_Low (low rust severity level) is associated with variable GenGroup_HdT (Timor Hybrid genetic group), indicating the inheritance of these materials in the transfer of orange rust-tolerance genes, as well as by the variables: dwarf size, weak adherence of the fruit to the branch, high number of flowers and the variable of deep secondary veins in leaves. The materials Catigua MG2, EC 15, EC 16 and Parainema coincide with these morphological characteristics, although as pointed out by Berny *et al.* (2025), there is a genotype x environment interaction in terms of resistance to orange rust, with relevant variables such as the nutritional state of the coffee plant, level of water stress and level of shade of the coffee plants, affecting the morphological characteristics of the plants, leaves and fruits. On the other hand, the variable CLRSeverity_Medium (medium rust severity level), marked by the light green ellipse, displays proximity with the morphological variables of tall size, very long plant height, long internodes on plagiotropic branches, strong adherence of fruits to the branch and large fruit size. The Batian, K7 and SL 28 materials partially matched this description, whereas the AB3 variety coincides with these four morphological variables.

Evaluation of severity. The analysis of variance, followed by a mean separation technique (Tukey, $\alpha = 0.05$), helped to classify the 32 materials into three groups, depending on the level of average severity they reached during the two seasons evaluated (Table 7). The severity data presented fluctuating behaviors throughout both cycles, with more severe infestations between October and February, coinciding with the days with fog, high relative humidity and little light, creating the proper conditions for the proliferation of the fungus

that causes orange rust (SENASICA, 2016). Between October and November, there is a significant change in the mean monthly rainfall on the study site, going from 310.1 to 62.8 mm in 2023, and from 162.1 to 37.0 mm in 2024, respectively. These months also coincide with the entry of cold fronts, which create foggy days when they combine with high environmental humidity.

Table 7. Groups by severity level (mean $\pm$ standard deviation) of coffee leaf rust on coffee materials during the 2023/24 and 2024/25 growing seasons in Amatlán de los Reyes, Veracruz (Tukey, $P \leq 0.05$).

Group	Severity level	Materials
a	High	Pacamara (2.83 ± 1.34)
ab	Medium	K7 (2.25 ± 0.62), Garnica (2.17 ± 1.03), Mundo Novo 379/19 (2.17 ± 1.03), EC 14 (2.08 ± 1.08), SL28 (2.08 ± 1.00), AB3 (2.00 ± 0.60), Catuai V IAC144 (2.00 ± 1.20), Batian (1.92 ± 0.67), Col 3 (1.92 ± 0.67), Geisha (1.92 ± 0.29), Col 2 (1.83 ± 0.58), S4808 (1.83 ± 0.83), Bourbon (1.75 ± 0.62), Col 4 (1.75 ± 0.96), EC 16 (1.75 ± 0.62), Marsellesa (1.75 ± 0.45), SLN 6 (1.75 ± 0.45), BP432A (1.67 ± 0.65), Oro Azteca (1.67 ± 0.65), IPR 107 (1.5 ± 0.52)
b	Low	H1 Centroamericano (1.42 ± 0.51), Parainema (1.42 ± 0.51), S795 (1.42 ± 0.51), SLN 5B (1.42 ± 0.51), Catigua MG2 (1.33 ± 0.49), Col 1 (1.33 ± 0.49), EC 15 (1.33 ± 0.49), IPR 103 (1.33 ± 0.49), Kartila 1 (1.33 ± 0.49), Lempira (1.33 ± 0.49), Paraíso (1.33 ± 0.49)

Group *a*, highly susceptible to the severity of orange rust, consists only of the domesticated variety Pacamara (Berny *et al.*, 2025), which is the result of the cross between the varieties Pacas and Maragogipe, both catalogued as susceptible to the attack by coffee leaf rust (Lalangui-Sarmiento and Rivera-Castillo, 2023). This variety is characterized for having very broad leaves and a very large foliar coverage, coinciding with findings from the multiple correspondence analysis.

Severity group *ab*, which covers the highest number of evaluated materials, presented intermediate tolerance to orange rust, includes the variety of the genetic group Bourbon-Típica, K7, which Ngare (2021) describes as tolerant. It also includes the varieties of the same genetic group: Geisha and Bourbón, which Ruiz de Oña Plaza and Merlín-Urbe (2021) report as tolerant and susceptible, respectively, displaying a possible genotype $\times$ environment interaction against the incidence of orange rust in Bourbón. Domesticated varieties Mundo Novo 379/19, Garnica, SL 28, AB3 and Catuai V IAC 144, derived from the varieties Bourbon, Caturra and Mundo Novo, considered susceptible, displayed similar results as those reported by Julca-Otiniano *et al.* (2023). The materials derived from Timor Hybrid, which is resistant to orange coffee rust (Cardoza-Sánchez *et al.*, 2025), EC 14, Batian, Col 3, Col 2, S4808, Col 4, EC 16, Marsellesa, BP432 A, Oro Azteca and IPR 107, displayed moderate severity levels in the range of 1.5 to 1.92. The inherent resistance of Timor Hybrid is attributable to the high genetic variability and resistance provided by the species *C. canephora* (Moreira *et al.*, 2015). Variety SLN 6, from the progeny Arabusta, displayed intermediate tolerance with an average severity of 1.75, attributable to the nature of the cross between the varieties S.274 of *C. canephora* and the arabica variety Kent, reported by Prakash *et al.* (2011) as a resistant variety against the attack of coffee leaf rust.

Low-level severity group *b* (Figures 3 and 4), includes nine materials derived from the Timor Hybrid (H1 Central American, Parainema, Catigua MG2, Col 1, EC 15, IPR 103, Kartila 1, Lempira and Paraíso), which share at least two of the following morphological characteristics: dwarf size, weak adherence of the fruit to the branch, a high number of

flowers and deep secondary veins in leaves, which the multiple correspondence analysis found as characteristics associated to materials with a low rust severity level. Severity group *b* also includes domesticated variety S795 and the Arabusta variety SLN 5B. Despite the materials of group *b* having displayed good tolerance to the severity of the rust, no material was found to be immune to the attack.



Figure 3. Materials from *C. arabica* with a lower level of severity of coffee leaf rust. **A.** Lempira. **B.** EC 15. **C.** Col 1. **D.** IPR 103.



Figure 4. Materials from *C. arabica* with a lower level of severity of coffee leaf rust. **A.** Paraíso. **B.** Catigua MG2. **C.** Kartila 1. **D.** H1 Centroamericano.

The Garnica (2.17 ± 1.03) and Bourbon (1.75 ± 0.62) control treatments for dwarf- and tall-sizes, respectively, were located in the ab intermediate susceptibility group, whereas in other locations, they are reported as highly susceptible (Escamilla-Prado *et al.*, 2021). These varieties are appreciated in Mexico, as they are associated to a high-quality beverage. Their level of susceptibility to rust can be modulated with the cultural and nutritional management of the coffee plants.

Similarly to the analysis of variance, the cluster analysis also differentiated three severity groups (Figure 5). The first group, defined by the blue box, only includes the Pacamara variety, which had a very susceptible behavior to orange rust, coinciding with group *a* of the analysis of variance. The Salvadorean Pacamara variety is the result of the crossing of the Pacas variety, a mutation of Bourbon, with the Maragogipe variety, a mutation of Typica. Therefore, it inherited susceptibility to orange rust from its parents.

This variety is appreciated by coffee producers due to the outstanding size of its coffee beans (> 17/64 inch).

The second cluster, defined by the green box, integrates the Catuai V IAC 144, Mundo Novo 379/19, Garnica, Col 3 and K7 varieties, which belong to pure Arabic materials, except for Col 3, which descends from the Timor Hybrid. They are characterized by high mean severity levels, although not as high as those observed in Pacamara, consistent with findings reported by Berny *et al.* (2025).

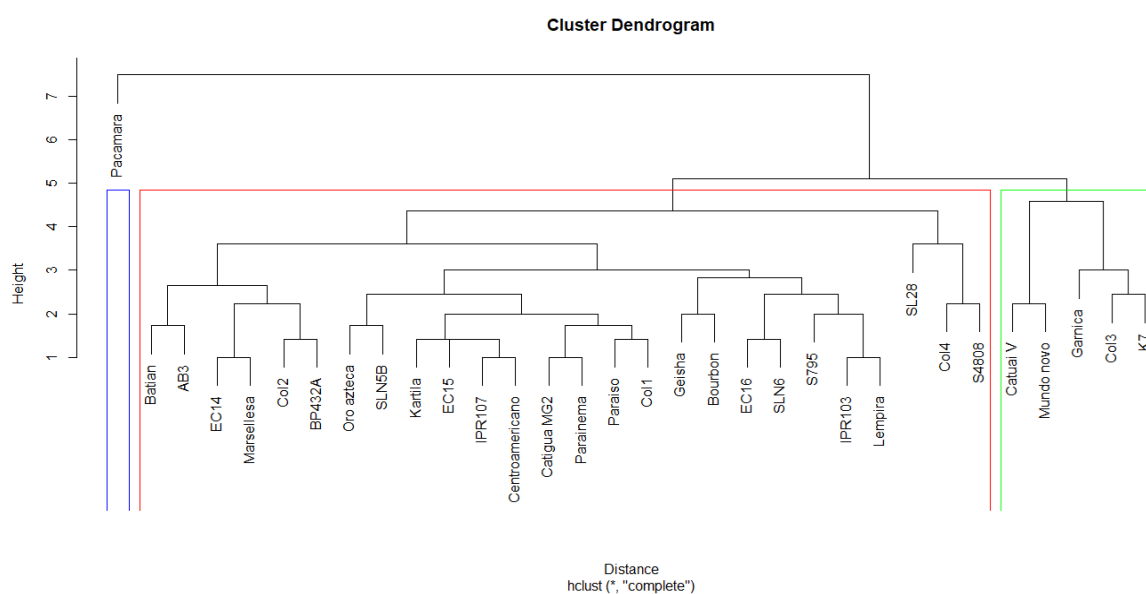


Figure 5. Grouping of *C. arabica* materials based on their susceptibility to coffee leaf rust.

The cluster defined by the red box is subdivided into two groups, where the materials with the least infections by rust were located. In the subgroup on the left side are 23 materials, out of which Batian, EC14, EC15, EC16, Marsellesa, Col 1, Col 2, BP432A, Oro Azteca, Kartila 1, IPR 103, IPR 107, Central American H1, Catigua MG2, Parainema, Paraíso and Lempira are materials developed from the Timor Hybrid, which may explain its rust-tolerant behavior. Likewise, this subgroup also contains the selections of the Arabusta group: SLN 5B and SLN 6, as well as the Ethiopian variety AB3 and the traditional variety Bourbon. In the subgroup on the right, materials Col4 and S4808 are derived from the Timor Hybrid, and SL28 is classified as a domesticated variety (Berny *et al.*, 2025). It is worth mentioning that some of the materials described in the group with the highest tolerance are in the public domain, such as Parainema (IHCAFE, Honduras), Catigua MG2 (EMBRAPA, Brazil), IPR 103 (EMBRAPA, Brazil), Lempira (IHCAFE, Honduras) and Paraíso (EMBRAPA, Brazil), facilitating the access to these materials for producers from areas nearby the experimental site, contributing to strengthening farmer families in coffee-producing lands in Veracruz.

Selecting genetic material. The use of coffee leaf rust-tolerant materials can be the best medium- and long-term strategy to control this increasingly frequent phytosanitary condition (Pérez-Fernández *et al.*, 2024). Generating information on the performance of coffee materials in the face of orange rust is crucial to ensure the activity remains viable in the coffee-growing areas. It is important to note that some of the materials evaluated in this study are F1 hybrids (Table 1), which may be highly productive and rust-tolerant although

not recommended for propagation by seed; therefore, caution should be taken when recommending their use.

CONCLUSIONS

Under the cultivation conditions evaluated (without nutrient management or fertilization, under diversified shade, with 40-60% shade cover, and at a low altitude of 640 m. a. s. l.) it is possible to conclude that there are significant differences in the behavior of the 32 materials evaluated against the severity of orange coffee rust. The materials that displayed a lower rate of rust infection come from crosses between diverse varieties and the Timor Hybrid: Central American H1, Parainema, Catigua MG2, Col 1, EC 15, IPR 103, Kartila 1, Lempira and Paraíso, as well as domesticated variety S795 and the variety Arabusta SLN 5B. The most tolerant materials were varieties Catigua MG2, IPR 103, Lempira and Paraíso. The materials that displayed the highest severity levels were Pacamara, K7, Garnica, Mundo Novo, SL 28, AB3 and Catuai V IAC 144, which belong to pure Arabic lines and to the group Bourbon-Típica. These could reduce severity with a different cultural management, that includes shade control, nutrition, weed control and plant tissue management (pruning). The relation between the morphological traits and the level of rust severity found can be a starting point to identify tolerant materials from the beginning of the development of these plants.

Limitations. The study was carried out during two productive cycles (2023/2024 and 2024/2025) under rustic management conditions (without fertilization) and at a low plantation altitude (640 m a. s. l.), therefore, it is considered that the behavior of the materials can have changes in time, based on environmental conditions and plantation management. In turn, the sanitary evaluation is limited to the effect of the severity from *Hemileia vastatrix*, without considering other sanitary and productive conditions, which should be addressed in future studies.

Conflict of interest. The authors declare that they have no conflicts of interest regarding the research, authorship, and/or publication of this Note.

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