

# Effect of Leaf Rust Disease on Berry Yield in *Coffea liberica*: A Two-Year Study of New Clonal Responses in MARDI Kluang, Malaysia

## ABSTRACT

**Aims:** Coffee leaf rust (CLR), caused by *Hemileia vastatrix*, is the most important coffee disease worldwide. Although *Coffea liberica* contributes <1% of global coffee production, it dominates Malaysia's industry, yet information on its resistance to CLR and associated yield impacts remains scarce. This study evaluated the effects of CLR on berry yield in five newly developed Liberica clones under Malaysian field conditions.

**Study design:** A randomized complete block design with three replicates.

**Place and Duration of Study:** The study was conducted at the MARDI research station, Kluang, Johor, Malaysia over two years (July 2021–June 2023).

**Methodology:** Berry yield, disease incidence (INC) and disease severity index (DSI) were recorded monthly. Data were analyzed using ANOVA (Tukey's test,  $p \leq 0.05$ ) and Pearson's correlation to evaluate relationships between yield and disease parameters.

**Results:** Significant clonal variability was observed. Clone 213 consistently achieved the highest yields (1.420 kg/tree in Year 1; 0.623 kg/tree in Year 2) with the lowest disease levels (INC 27.2–19.4%; DSI 9.2–4.6%). Clone 222 was most susceptible (lowest yield, highest DSI), while clone 224 exhibited tolerance in Year 1 but declined sharply in Year 2. Control MKL 7 performed moderately but was disease-sensitive. Yield–disease correlations strengthened in Year 2, reflecting biennial bearing and climatic stress.

**Conclusion:** This study provides the first field-based evidence of CLR impacts on Liberica in Malaysia. CLR substantially reduces productivity, but clone 213 emerges as a resistant, high-yielding candidate for sustainable cultivation.

**Keywords:** *Coffea liberica*, *Hemileia vastatrix*, coffee leaf rust, disease resistance, yield stability, Malaysia

**Commented [AJ1]:** Use words that are not in the article title.  
Maximum 5 words

## 1. INTRODUCTION

Coffee is one of the world's most popular drinks and the second most traded commodity after crude oil (Haile & Kang, 2019). It is grown in more than 80 tropical and subtropical countries and supports the livelihoods of over 25 million smallholder farmers. In 2020/21, global production reached almost 172 million 60-kg bags, while demand continued to rise to more than 166 million bags (ICO, 2022). The industry not only sustains millions of rural households but also plays a vital role in national economies, especially in producing countries such as Brazil, Vietnam, Indonesia, and Colombia, which together dominate international markets.

**Commented [AJ2]:** It is better to insert the reference at the end of each paragraph

The genus *Coffea* (Rubiaceae) comprises 130 species (Davis & Rakotonasolo, 2021), but only a few are cultivated commercially: *Coffea arabica*, *Coffea canephora* (Robusta), *Coffea liberica* and *Coffea excelsa* (Cao et al., 2014). *C. arabica* and *C. canephora* dominate global trade, accounting for approximately 60% and 40% of the global coffee production in 2022, respectively (ICO, 2022). *C. liberica* that has gained popularity in recent years represents less than 1% of global output yet is highly significant in Malaysia and the Philippines (Davis et al., 2020). In Malaysia, it constitutes nearly 90% of national production due to its adaptability to local soils, tolerance to marginal environments and distinctive flavour that appeals to niche markets (Wahab & Nor, 2016). Historically, *C. liberica* was introduced into Southeast Asia in the late 19th century following the devastating coffee leaf rust (CLR) epidemic that decimated *C. arabica* plantations in Ceylon, Java, and Malaya (McCook, 2006; Silva et al., 2022). Its resilience to marginal environments, tolerance to some diseases, and distinctive flavour profile have ensured its persistence in Malaysia, despite its relatively low global importance. More recently, Liberica coffee has gained renewed interest in specialty markets due to its unique sensory attributes and potential for niche branding.

**Commented [AJ3]:** It is better to insert the reference at the end of each paragraph

Despite these advantages, *C. liberica* faces major production challenges that limit its long-term potential. Like other coffee species, it follows a biennial bearing cycle—years of heavy fruiting are often followed by lighter harvests, as resources used for fruiting reduce vegetative growth and next year's yield (Bernardes et al., 2012). Productivity is further influenced by external factors soil fertility, climate variability, and pest and disease pressure (Partelli et al., 2018). Among these, diseases have emerged as one of the most critical constraints to sustainable coffee production globally (Cerdeira et al., 2017).

Coffee leaf rust (CLR), caused by the biotrophic fungus, *Hemileia vastatrix* is the most important disease that global coffee cultivation. Since emerging in the late 19th century, CLR has reshaped global coffee production systems (Silva et al., 2022). The disease triggers premature leaf drop, severely reducing photosynthetic capacity and carbohydrate assimilation (Avelino et al., 2006). As a result, less energy is available for fruit filling, leading to smaller beans and reduced berry set (Djuikem et al., 2021). Severe defoliation also disrupts branch growth and bud initiation, compromising fruiting in subsequent years. Under epidemic conditions, yield losses can reach 75%, with extensive leaf fall and sharp reductions in berry production (Bebber et al., 2016; McCook, 2006). Moreover, CLR intensifies biennial bearing by depleting leaf reserves after high-yielding years, limiting plant recovery and exacerbating yield fluctuations (Brown et al., 1995; Costa et al., 2006). Beyond agronomic impacts, CLR imposes serious socio-economic burdens, particularly on smallholder farmers with limited access to control measures (Avelino et al., 2015).

Tolerance levels vary among *Coffea* species with *C. arabica* is highly susceptible, while *C. canephora* and *C. liberica* show greater resilience. Nonetheless, CLR remains a significant threat across all cultivated coffee (Talhinhas et al., 2017). Field observations confirm that CLR can still reduce flower initiation, fruit retention, and final yield, especially under favorable climatic conditions (Hinnah et al., 2018; Talhinhas et al., 2017). With climate change expected to intensify disease pressure through rising temperatures, altered rainfall and increased humidity (Avelino et al., 2015; Bunn et al., 2015), the risk to Liberica cultivation in Southeast Asia is growing. Yet, despite its economic importance in Malaysia, little is known about how CLR affects *C. liberica* yield under field conditions.

**Commented [AJ4]:** It is better to insert the reference at the end of each paragraph

Global coffee research has focused primarily on *C. arabica* and *C. canephora*, reflecting their dominant market share. As a result, *C. liberica* has been largely neglected in breeding, agronomy, and disease management studies (Davis et al., 2020). The few reports available suggest partial tolerance to CLR, but field-based evidence quantifying yield impacts under natural infection pressure is lacking. This knowledge gap is particularly critical for Malaysia, where *C. liberica* accounts for the majority of national production. While the Malaysian Agricultural Research and Development Institute (MARDI) has developed several new Liberica clones to enhance yield and adaptability, their performance under CLR pressure has not been fully assessed.

This study, therefore, evaluated the impact of coffee leaf rust on berry yield in newly developed *C. liberica* clones under field conditions at MARDI Kluang, Malaysia, over a two-year period. Specifically, the study evaluates the disease incidence, severity and their relationship with yield performance, with the aim of identifying clones that combine high productivity with tolerance to CLR. The findings are expected to contribute to breeding strategies, guide cultivar selection for farmers, and strengthen the long-term sustainability of Malaysia's coffee industry.

**Commented [AJ5]:** It is better to insert the reference at the end of each paragraph

## 2. MATERIAL AND METHODS

### 2.1 Study location

The experiment was conducted at the MARDI research station in Kluang, Johor, Malaysia (1°94'N, 103°36'E; altitude 100 m a.s.l.), which is characterized by a humid tropical climate with an annual rainfall of >2,200 mm and mean temperature of  $27 \pm 2$  °C. The soils were classified as the Rengam Series soil, and the pH ranged between 5 and 6.

### 2.2 Coffee clones

Five *Coffea liberica* clones were assessed: four newly developed clones (211, 213, 222, and 224) and one control clone (MKL 7), previously released by MARDI in 2008. All trees were approximately seven years old at the start of the trial. The planting distance was 2.5 m between trees within rows and 3.0 m between rows. Standard agronomic practices recommended for Liberica coffee cultivation (weeding, fertilization and pruning) were applied uniformly across all treatments, and no fungicides were used to allow natural disease development.

### 2.3 Disease and yield measurement

Data on disease incidence and severity coffee leaf rust (CLR) and also berry yield were collected monthly for two consecutive years: July 2021–June 2022 (Year 1) and July 2022–June 2023 (Year 2). To minimise border effects, disease and yield measurements were taken from trees located at the centre of each plot, while outer rows served as guard plants.

#### Yield measurement

Ripe coffee berries were manually harvested at monthly intervals from July 2021 to June 2023. Harvesting was performed at peak physiological maturity, identified by a uniform transition in skin colour from orange-red to full-red. Immediately after collection, fresh berries were weighed using a digital balance ( $\pm 0.01$  g accuracy) to determine yield per tree.

Yield was expressed as mean fresh berry weight per tree per month. Cumulative annual yield for each clone was calculated by summing monthly harvests across the 12-month cycle. Yield stability between years was assessed by comparing mean annual values for Year 1 and Year 2.

#### Disease assessment

Coffee leaf rust (CLR) incidence and severity were assessed monthly on each tree throughout the study period (July 2021–June 2023). For incidence, fully expanded leaves were sampled from the four canopy quadrants at three vertical positions (upper, middle, and lower plagiotropic branches). The number of symptomatic and asymptomatic leaves was recorded, and disease incidence (DI) was calculated as:

$$DI (\%) = \frac{\text{Total number of infected leaves}}{\text{Total number of sampled leaves}} \times 100$$

Rust severity was assessed visually using the 0–9 scale (Eskes and Toma-Braghini, 1981), where 0 = no visible symptoms and 9 = severe sporulation and tissue damage. The disease severity index (DSI) was calculated following (Capucho et al., 2011):

$$DSI (\%) = \frac{\sum(a \times b)}{Z \times N} \times 100$$

where a = number of symptomatic leaves, b = severity score, Z = maximum severity score (9), and N = total number of sampled leaves.

### 2.4 Experimental design and data analysis

The experiment was arranged in a completely randomised block design with three replicates. Each block contained five plots, representing the five clones, with each plot comprising at least 20 uniform coffee trees.

The assumptions of normality and homogeneity of variances were tested prior to analysis. Data on yield, disease incidence and disease severity index were subjected to analysis of variance (ANOVA). When significant differences were detected, mean separation was performed using Tukey's test at the 5% probability level. Pearson's correlation coefficients (r) were

calculated to assess the relationships between berry yield and disease parameters (incidence and severity). All statistical analyses were performed using SAS version 9.4 (Statistical Analysis System, Cary, NC, USA).

### 3. RESULTS AND DISCUSSION

#### 3.1 Yield dynamics of Liberica coffee clones in relation to disease severity

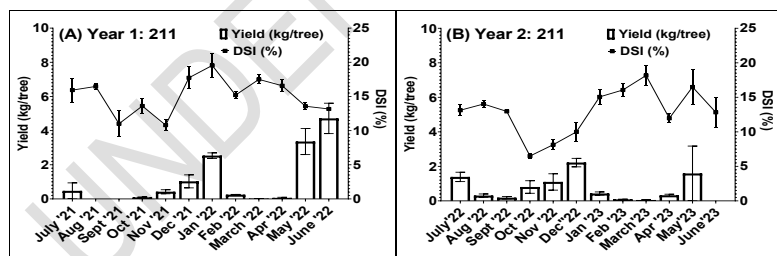
The monthly progression of coffee leaf rust (CLR) severity and berry yield across five *Coffea liberica* clones (211, 213, 222, 224, and MKL 7) over two years revealed distinct clonal differences in disease response and productivity (Figure 1).

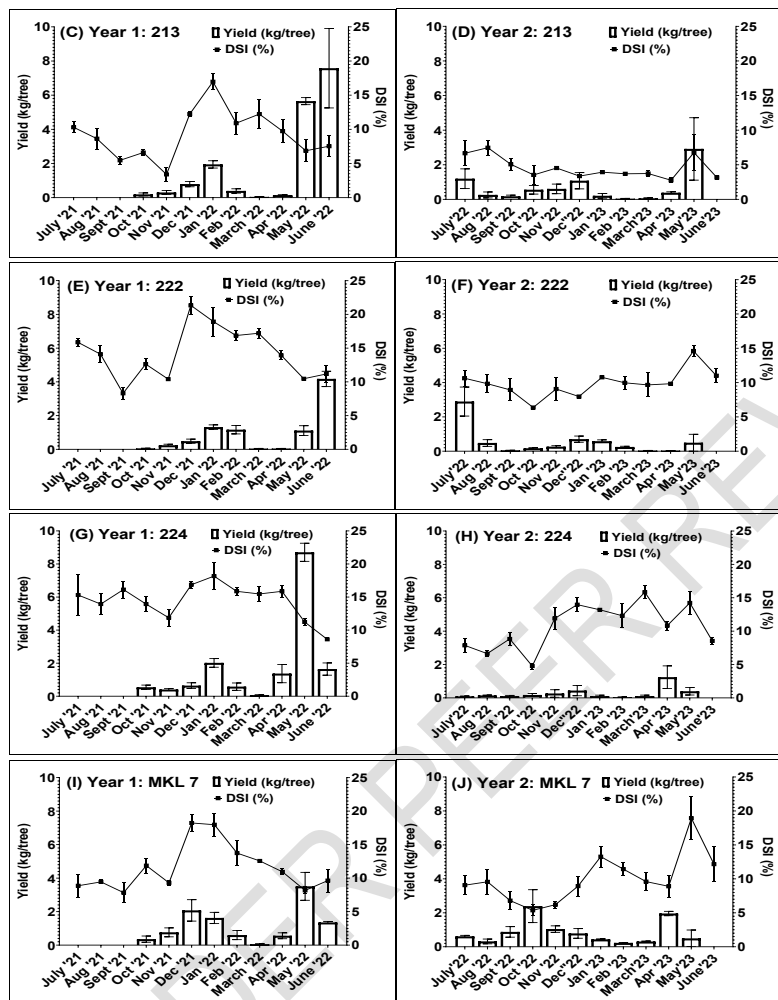
In Year 1 (July 2021–June 2022), clone 213 consistently demonstrated superior performance, maintaining the lowest disease severity index (DSI, 3.4–17.0%) while also achieving the highest yield (7.58 kg tree<sup>-1</sup> by June 2022). This indicates that clone 213 possesses strong resistance to *Hemileia vastatrix*, enabling it to sustain photosynthetic activity and allocate sufficient assimilates toward berry development despite infection pressure. Such performance supports earlier reports by Sanders (2019) that resistant genotypes can minimize yield losses from CLR. Clone 224 also recorded a high yield peak (8.71 kg tree<sup>-1</sup> in May 2022) despite moderate levels of rust severity (11.9–18.2%), suggesting a tolerance mechanism whereby yield is sustained despite disease stress. In contrast, clones 211 and 222, with higher rust severity (up to 19.5% and 21.3% DSI, respectively), produced substantially lower yields (4.71 and 4.17 kg tree<sup>-1</sup> at peak), consistent with the negative effects of rust on photosynthesis, assimilate supply and fruit development (Ribeyre & Avelino, 2012). The control clone, MKL 7, showed moderate rust infection (7.8–18.2% DSI) but remained consistently less productive, with its maximum yield reaching only 3.51 kg tree<sup>-1</sup>.

By Year 2 (July 2022–June 2023), yield declines across all clones, reflecting the biennial bearing nature of coffee and the cumulative effects of disease stress. Despite the overall reduction, clone 213 again maintained the lowest rust severity (2.8–6.8% DSI) and the highest yield (2.92 kg tree<sup>-1</sup> in May 2023), confirming its stable resistance and resilience across seasons. Meanwhile, clones 211 and 222 suffered severe yield losses by June 2023 might be due to high rust infection. Clone 224, though highly productive in Year 1, however, experienced a yield drop to 1.24 kg tree<sup>-1</sup> in April 2023, indicating unstable tolerance. Similarly, MKL 7 showed a transient peak yield of 2.39 kg tree<sup>-1</sup> in October 2022 but dropped to zero yield by June 2023.

Overall, these results confirm a negative association between CLR severity and yield, consistent with reports linking rust epidemics to reduced photosynthetic efficiency, carbohydrate depletion and impaired fruit development (Ribeyre & Avelino, 2012; Silva et al., 2021). Clone 213 emerges as a resilient genotype combining resistance with stable productivity, while clones 224, 211, and 222 illustrate varying degrees of susceptibility or tolerance, highlighting the importance of integrating genetic resistance into Liberica breeding and management strategies.

Commented [AJ6]: Provide more scientific reasons.





**Figure 1. Monthly progression of coffee leaf rust severity (disease severity index, DSI; solid lines with filled circles, left Y-axis) and fresh berry yield (bars; kg/tree, right Y-axis) in five *Coffea liberica* clones (211, 213, 222, 224, and control MKL 7) across two years (Year 1: July 2021–June 2022; Year 2: July 2022–June 2023). Figures A, C, E, G, I correspond to Year 1 and Figures B, D, F, H, J to Year 2.**

### 3.2 Clonal variability in mean yield and disease parameters

The mean values of fresh berry yield, disease incidence, and DSI confirmed strong clonal variability among the evaluated *C. liberica* clones (Table 1).

In Year 1 (July 2021–June 2022), clone 213 achieved the highest mean yield ( $1.420 \text{ kg tree}^{-1}$ ), with the lowest incidence (27.18%) and DSI (9.24%). This reflects strong resistance to CLR, which preserved photosynthetic capacity and enabled efficient assimilate partitioning toward fruiting. In contrast clone 222, with high incidence (37.58%) and DSI (14.27%), recorded the lowest yield ( $0.720 \text{ kg tree}^{-1}$ ), clearly reflecting susceptibility. Clone 211 showed similarly high disease levels

(40.61% incidence; 15.09% DSI) but a slightly higher yield (1.078 kg tree<sup>-1</sup>), indicating that high CLR levels consistently limits productivity. Interestingly, clone 224 maintained a relatively high yield (1.331 kg tree<sup>-1</sup>) despite high disease incidence (39.66%) and DSI (14.43%), suggesting tolerance, an ability to sustain yield despite substantial disease pressure. The control MKL 7, meanwhile, showed intermediate performance (0.908 kg tree<sup>-1</sup>; 33.20% incidence; 11.55% DSI), consistent with its role as a moderately productive but susceptible benchmark.

In Year 2 (July 2022–June 2023), overall yields declined across all clones, reflecting the combined effects of biennial bearing and cumulative disease stress. Clone 213 again achieved the highest mean yield (0.623 kg tree<sup>-1</sup>), with the lowest incidence (19.43%) and DSI (4.56%), confirming durable resistance and relative yield stability, despite a >50% reduction compared with Year 1. Clone 224, however, showed the steepest yield decline (from 1.331 to 0.259 kg tree<sup>-1</sup>), suggesting strong sensitivity to environmental and disease pressures. Clone 211 remained among the most susceptible (0.706 kg tree<sup>-1</sup>; 12.96% DSI), while MKL 7 moderate but maintained relatively stable yields across both years.

Seasonal patterns revealed that yield reductions were strongly influenced by biennial bearing, with disease severity closely tracking fruit load. In Year 1, heavier fruiting coincided with higher CLR severity, whereas in Year 2, reduced fruiting was associated with lower DSI values. The pronounced decline in clone 224 highlights its vulnerability not only to biennial effects but also to unfavorable climatic conditions such as drought or excessive rainfall, both of which are known to reduce coffee productivity.

Biennial bearing, characterized by alternating years of high and low fruiting due to resource reallocation (Picini, 1998), likely contributed to these fluctuations. High fruit loads have consistently been linked to increased CLR severity, as reproductive effort diverts assimilates away from defense, thereby weakening host resistance (Koutouleas, 2023; Merle et al., 2020). This reflects established physiological trade-offs: when resources are directed toward fruit development, assimilate depletion and nutritional imbalances reduce the plant's ability to regenerate leaves and maintain defense mechanisms, ultimately intensifying CLR impact on yield (Brinate et al., 2015; Meira et al., 2008; Pozza, 2008).

These findings indicate distinct host–pathogen interaction strategies among clones: resistance in clone 213 (low severity with stable yield), tolerance in clone 224 (moderate yield under disease but environmentally unstable), and susceptibility in clones 211 and 222 (high severity with reduced yield). This highlights the importance of integrating genetic resistance with agronomic practices to stabilize productivity under both biennial and climatic variability, providing a foundation for targeted *C. liberica* breeding and management strategies.

**Table 1. Mean fresh berry yield, disease incidence and disease severity index (DSI) of five *Coffea liberica* clones over two consecutive seasons (Year 1: July 2021–June 2022; Year 2: July 2022–June 2023).**

Clone	Fresh berry yield (kg tree <sup>-1</sup> )		Disease incidence (%)		Disease severity index (DSI, %)	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
211	1.078 abcA	0.706 abB	40.61 aA	38.37 aB	15.09 aA	12.96 aB
213	1.420 aA	0.623 abB	27.18 dA	19.43 cB	9.24 cA	4.56 cB
222	0.720 cA	0.496 abB	37.58 bA	30.14 bB	14.27 aA	9.89 bB
224	1.331 abA	0.259 bB	39.66 abA	33.14 bB	14.43 aA	10.74 bB
MKL 7	0.908 bcA	0.788 aA	33.20 cA	31.10 bB	11.55 bA	10.02 bB

Means followed by different lowercase letters within columns and uppercase letters within rows denote significant differences according to Tukey's test ( $p \leq 0.05$ ).

### 3.3 Disease–yield relationships and seasonal effects

Correlation analysis provided further insights into the relationship between disease pressure and yield (Table 2), showing that the impact of CLR on yield varied by both clone and season.

In Year 1 (July 2021–June 2022), no significant correlations were observed between yield and disease parameters (incidence or severity), indicating that yield was mainly driven by fruit load rather than disease. Clone 211, for example, showed negligible associations (INC:  $r = 0.27$ ; DSI:  $r = -0.03$ ), while clone 213 also displayed near-zero values (INC:  $r = 0.05$ ; DSI:  $r = -0.10$ ). Interestingly, MKL 7 even showed weak positive trends with both incidence and severity ( $r = 0.41$ ;  $r = 0.22$ ), further indicating that CLR did not constrain yield in this season of high fruiting.

In Year 2 (July 2022–June 2023), however, when overall yields declined due to biennial bearing and cumulative stress, correlations between disease and yield became more evident. Clone 211 showed weak negative correlations (INC:  $r = -0.23$ ; DSI:  $r = -0.36$ ), reflecting its susceptibility. Clone 213, however, showed moderate positive correlations (INC:  $r = 0.57$ ; DSI:  $r = 0.49$ ), indicating that higher yields coincided with higher CLR levels, possibly reflecting its resistance mechanisms that minimized yield losses despite infection. Clone 222 showed weak positive associations, while clone 224 remained largely unaffected by disease pressure. MKL 7 showed most notable response, which displayed a significant negative correlation with incidence ( $r = -0.60$ ,  $p < 0.05$ ), confirming its vulnerability to yield under elevated CLR pressure.

These contrasting seasonal patterns underscore that the relationship between CLR and yield is not uniform but instead shaped by host genotype  $\times$  environment  $\times$  pathogen interactions. The absence of significant correlations in Year 1 reflects the dominance of fruit load in regulating yield, while the stronger associations in Year 2 demonstrate how disease effects become more apparent when productivity declines. Such variability is consistent with reports that CLR epidemics are closely modulated by climatic drivers including rainfall, temperature, and relative humidity (Alvarado-Huamán et al., 2020; Avelino et al., 2015; Das et al., 2021; Rhiney et al., 2020). Epidemic development is particularly favoured when moderate temperatures (22–24 °C) coincide with high relative humidity (>80%), conditions known to optimize spore germination and infection (Das et al., 2021; Eskes and Da Costa, 1983; Rozo et al., 2012).

Overall, clone 213 consistently demonstrated resilience, combining low CLR severity with stable yield, making it the most promising candidate for commercial planting. In contrast, the susceptibility of clones 211 and 222 and the unstable tolerance of clone 224 emphasize the need to balance genetic resistance with yield potential in clonal selection and breeding strategies. These findings underscore the importance of integrating host resistance with adaptive management practices that account for climatic variability in CLR-prone environments.

**Table 2.** Pearson correlation coefficients ( $r$ ) between fresh berry yield and coffee leaf rust incidence (INC) and disease severity index (DSI) in five *Coffea liberica* clones across two seasons.

	Clone 211		Clone 213		Clone 222		Clone 224		MKL 7	
	INC	DSI	INC	DSI	INC	DSI	INC	DSI	INC	DSI
Yield Y1	0.27 <sup>ns</sup>	-0.03 <sup>ns</sup>	0.05 <sup>ns</sup>	-0.10 <sup>ns</sup>	0.08 <sup>ns</sup>	-0.11 <sup>ns</sup>	-0.15 <sup>ns</sup>	-0.37 <sup>ns</sup>	0.41 <sup>ns</sup>	0.22 <sup>ns</sup>
Yield Y2	-0.23 <sup>ns</sup>	-0.36 <sup>ns</sup>	0.57 <sup>ns</sup>	0.49 <sup>ns</sup>	0.36 <sup>ns</sup>	0.16 <sup>ns</sup>	0.08 <sup>ns</sup>	0.16 <sup>ns</sup>	-0.60*	-0.54 <sup>ns</sup>

ns = not significant ( $P > 0.05$ ); \* = significant ( $P < 0.05$ ). Correlation strength: 0.90–1.00 = very high, 0.70–0.89 = high, 0.50–0.69 = moderate, 0.30–0.49 = low, 0.00–0.29 = negligible.

#### 4. CONCLUSION

This study showed the impact of coffee leaf rust (CLR) on yield performance of newly developed *Coffea liberica* clones under Malaysian field conditions. Clone 213 consistently combined low rust severity with stable yields across two cropping cycles, making it the most promising candidate for sustainable cultivation. In contrast, clones 211 and 222 were highly susceptible, while clone 224, despite initial tolerance, showed strong environmental sensitivity. Correlation patterns indicated that CLR-driven yield losses varied with host resistance and environmental factors, with biennial bearing further amplifying seasonal fluctuations. These findings highlight the importance of integrating resistant clones with adaptive management practices to ensure stable productivity under rust pressure and climate variability.

## CONSENT

All authors declare that written consent is not applicable in this study.

## ETHICAL APPROVAL

All authors hereby declare ethical approval is not applicable in this study.

## REFERENCES

- Alvarado-Huamán, L., Borjas-Ventura, R., Castro-Cepero, V., García-Nieves, L., Jiménez-Dávalos, J., Julca-Otiniano, A., & Gómez-Pando, L. (2020). Dynamics of severity of coffee leaf rust (*Hemileia vastatrix*) on Coffee, in Chanchamayo (Junin-Peru). *Agronomía Mesoamericana*, 31(3), 517–529. <https://doi.org/10.15517/AM.V31I3.39726>
- Avelino, J., Cristancho, M., Georgiou, S., Imbach, P., Aguilar, L., Bornemann, G., Läderach, P., Anzueto, F., Hruska, A. J., & Morales, C. (2015). The coffee rust crises in Colombia and Central America (2008–2013): impacts, plausible causes and proposed solutions. *Food Security*, 7(2), 303–321. <https://doi.org/10.1007/s12571-015-0446-9>
- Avelino, J., Zelaya, H., Merlo, A., Pineda, A., Ordoñez, M., & Savary, S. (2006). The intensity of a coffee rust epidemic is dependent on production situations. *Ecological Modelling*, 197(3–4), 431–447. <https://doi.org/10.1016/j.ecolmodel.2006.03.013>
- Bebber, D. P., Castillo, Á. D., & Gurr, S. J. (2016). Modelling coffee leaf rust risk in Colombia with climate reanalysis data. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1709). <https://doi.org/10.1098/rstb.2015.0458>
- Bernardes, T., Moreira, M. A., Adami, M., Giarolla, A., & Rudorff, B. F. T. (2012). Monitoring biennial bearing effect on coffee yield using MODIS remote sensing imagery. *Remote Sensing*, 4(9), 2492–2509. <https://doi.org/10.3390/rs4092492>
- Brinat, S. V. B., Martins, L. D., Rodrigues, W. N., Colodetti, T. V., Cunha, V. V., Rosa, G. N. G. P., Junior, W. C. J., & Tomaz, M. A. (2015). Influence of copper sources on the management of leaf rust, growth and crop yield of Arabica coffee. *Journal of Food, Agriculture and Environment*, 13(2), 184–189.
- Brown, J. S., Whan, J. H., Kenny, M. K., & Merriman, P. R. (1995). The effect of coffee leaf rust on foliation and yield of coffee in Papua New Guinea. *Crop Protection*, 14(7), 589–592. [https://doi.org/10.1016/0261-2194\(95\)00040-2](https://doi.org/10.1016/0261-2194(95)00040-2)
- Bunn, C., Läderach, P., Guillermo, J., Jimenez, P., Montagnon, C., & Schilling, T. (2015). Multiclass classification of agro-ecological zones for Arabica coffee: an improved understanding of the impacts of climate change. *PLoS ONE*, 10(10), e0140490. <https://doi.org/10.1371/journal.pone.0140490>
- Cao, E. P., Constantino-Santos, D. M., Ramos, L. A. P., Santos, B. S., Quilang, J. P., & Mojica, R. M. (2014). Molecular and morphological differentiation among *Coffea* (Rubiaceae) varieties grown in the farms of Cavite Province, Philippines. *Philippine Science Letters*, 7(2), 387–397.
- Capucho, A. S., Zambolim, L., Duarte, H. S. S., & Vaz, G. R. O. (2011). Development and validation of a standard area diagram set to estimate severity of leaf rust in *Coffea arabica* and *C. canephora*. *Plant Pathology*, 60(6), 1144–1150. <https://doi.org/10.1111/j.1365-3059.2011.02472.x>
- Cerda, R., Avelino, J., Gary, C., Tixier, P., Lechevallier, E., & Allinne, C. (2017). Primary and secondary yield losses caused by pests and diseases: Assessment and modeling in coffee. *PLoS ONE*, 12(1), 1–17. <https://doi.org/10.1371/journal.pone.0169133>
- Costa, M. J. N., Zambolim, L., & Rodrigues, F. A. (2006). Effect of levels of coffee berry removals on the incidence of rust and on the level of nutrients, carbohydrates and reductor sugar. *Fitopatologia Brasileira*, 31(6), 564–571.
- Das, D. K., Shivanna, M. B., & Prakash, N. S. (2021). Vegetative vigour, yield and field tolerance to leaf rust in four F1 hybrids of coffee (*Coffea arabica* L.) in India. *Journal of Horticultural Sciences*, 16(2), 301–308. <https://doi.org/10.24154/JHS.V16I2.968>
- Davis, A. P., Gargiulo, R., Fay, M. F., Sarmu, D., & Haggard, J. (2020). Lost and found species of West Africa: *Coffea stenophylla* and *C. affinis*, the forgotten coffee crop. *Frontiers in Plant Science*, 11(616), 1–18. <https://doi.org/10.3389/fpls.2020.00616>
- Davis, A. P., & Rakotonasolo, F. (2021). Six new species of coffee (*Coffea*) from northern Madagascar. *Kew Bulletin*, 5974, 497–511. <https://doi.org/10.1007/S12225-021-09952-5>
- Djuikem, C., Grogard, F., Wafo, R. T., Touzeau, S., & Bowong, S. (2021). Modelling coffee leaf rust dynamics to control its spread. *Mathematical Modelling of Natural Phenomena*, 16. <https://doi.org/10.1051/mmnp/2021018>
- Esques, A. B., & Da Costa, W. M. (1983). 8. Characterization of incomplete resistance to *Hemileia vastatrix* in the Icatu coffee population. *Euphytica*, 32(2), 649–657. <https://doi.org/10.1007/BF00021478>
- Esques, A. B., & Toma-Braghini, M. (1981). Assessment methods for resistance to coffee leaf rust (*Hemileia vastatrix* Berk. & Br.). *Plant Protection Bulletin FAO*, 29(3/4), 56–66.
- Haile, M., & Kang, W. H. (2019). The role of microbes in coffee fermentation and their impact on coffee quality. *Journal of*

- Food Quality*, 1(4836709), 1–6. <https://doi.org/10.1155/2019/4836709>
- Hinnah, F. D., Sentelhas, P. C., Meira, C. A. A., & Paiva, R. N. (2018). Weather-based coffee leaf rust apparent infection rate modeling. *International Journal of Biometeorology*, 62(10), 1847–1860. <https://doi.org/10.1007/s00484-018-1587-2>
- ICO. (2022). Coffee Market Report. In *International Coffee Organization* (Issue June).
- Koutouleas, A. (2023). Coffee leaf rust: wreaking havoc in coffee production areas across the tropics. In *Plant Health Cases* (Issue May). The Author 2023. <https://doi.org/10.1079/planthealthcases.2023.0005>
- McCook, S. (2006). Global rust belt: *Hemileia vastatrix* and the ecological integration of world coffee production since 1850. *Journal of Global History*, 1(2), 177–195. <https://doi.org/10.1017/S174002280600012X>
- Meira, C. A. A., Rodrigues, L. H. A., & Moraes, S. A. (2008). Análise da epidemia da ferrugem do cafeeiro com árvore de decisão. *Tropical Plant Pathology*, 33(2), 114–124. <https://doi.org/10.1590/S1982-56762008000200005>
- Merle, I., Pico, J., Granados, E., Boudrot, A., Tixier, P., de Melo Virginio Filho, E., Cilas, C., & Avelino, J. (2020). Unraveling the complexity of coffee leaf rust behavior and development in different *Coffea arabica* agroecosystems. *Phytopathology*, 110(2), 418–427. <https://doi.org/10.1094/PHYTO-03-19-0094-R>
- Partelli, F. L., Oliveira, M. G., Covre, A. M., Vieira, H. D., Machado Dias, J. R., & Braun, H. (2018). Nutritional standards and nutritional diagnosis of the Conilon coffee plants in phenological growth stages. *Journal of Plant Nutrition*, 41(19), 2536–2546. <https://doi.org/10.1080/01904167.2018.1510513>
- Picini, A. G. (1998). *Desenvolvimento e teste de modelos agrometeorológicos para a estimativa de produtividade do cafeeiro (Coffea arabica L.) a partir do monitoramento da disponibilidade hídrica do solo*. Universidade de São Paulo.
- Pozza, E. A. A. (2008). Importância das doenças foliares do cafeeiro. Núcleo de estudos em fitopatologia. *Brasília: Sociedade Brasileira de Fitopatologia*, 1, 81–94.
- Rhiney, K., Knudson, C., & Guido, Z. (2020). Cultivating crisis: Coffee, smallholder vulnerability, and the uneven sociomaterial consequences of the leaf rust epidemic in Jamaica. *Annals of the American Association of Geographers*, 111(2), 440–458. <https://doi.org/10.1080/24694452.2020.1775543>
- Ribeyre, F., & Avelino, J. (2012). Impact of field pests and diseases on coffee quality. *Specialty Coffee: Managing Quality, January*, 151–176.
- Rozo, Y., Escobar, C., Gaitán, Á., & Cristancho, M. (2012). Aggressiveness and genetic diversity of *Hemileia vastatrix* during an epidemic in Colombia. *Journal of Phytopathology*, 160(11–12), 732–740. <https://doi.org/10.1111/jph.12024>
- Sanders, M. (2019). Breeding for coffee leaf rust resilience in *Coffea sp.* *Natural Sciences Education*, 48(1), 1–3. <https://doi.org/10.4195/nse2019.01.0102>
- Silva, M. D. C., Guerra-Guimarães, L., Diniz, I., Loureiro, A., Azinheira, H., Pereira, A. P., Tavares, S., Batista, D., & Várzea, V. (2022). An overview of the mechanisms involved in Coffee-*Hemileia vastatrix* interactions: Plant and pathogen perspectives. *Agronomy*, 12(2), 1–31. <https://doi.org/10.3390/agronomy12020326>
- Talhinhas, P., Batista, D., Diniz, I., Vieira, A., Silva, D. N., Loureiro, A., Tavares, S., Pereira, A. P., Azinheira, H. G., Guerra-Guimarães, L., Várzea, V., & Silva, M. do C. (2017). The coffee leaf rust pathogen *Hemileia vastatrix*: one and a half centuries around the tropics. *Molecular Plant Pathology*, 18(8), 1039–1051. <https://doi.org/10.1111/mpp.12512>
- Wahab, M. A. M. A., & Nor, N. A. A. M. (2016). Exploring the potential of coffee industry in Malaysia. *Economics and Social Science Research Centre*, 1016, 1–5.