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Original Article

Morphophysiological characteristics of *Hymenaea martiana* Hayne seeds in Northeastern Brazil are influenced by interannual environmental variations

Características morfofisiológicas de sementes de *Hymenaea martiana* Hayne no Nordeste do Brasil influenciadas pelas variações ambientais interanuais

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Abstract

Hymenaea martiana is of ecological, socioeconomic and folk medicine importance. However, information on how climatic conditions influence the production and quality of its seeds in natural populations is still limited. Influenced by interannual environmental variations. Considering the context of global environmental changes and the need to support collection, management, and conservation practices, this study aimed to analyze whether interannual variations in environmental conditions affect the physical and physiological quality of *H. martiana* seeds among different individuals of the remaining natural population of the Atlantic Forest in the municipality of Areia, Paraíba. Fruits were collected from 15 mother plants in 2021 and 2022, and the physical characteristics of the seeds, as well as characteristics related to emergence and initial seedling development, were analyzed. A completely randomized design was used, with a 2 × 15 factorial scheme (years and mother plants), with univariate and multivariate analyses being applied. The physical and physiological characteristics of *H. martiana* seeds are influenced by interannual environmental conditions and genetic variability among parent plants. Among the characteristics evaluated, final emergence was the most sensitive to environmental changes. Therefore, adopting strategies that consider these factors is essential to ensure the production of high-quality seeds, directly influencing the success of forest restoration, conservation, and sustainable use programs for this species.

Keywords: genetic diversity, seedling emergence, vigor, jatobá.

Resumo

Hymenaea martiana possui importância ecológica, socioeconômica e na medicina popular, no entanto, ainda são limitadas as informações sobre como as condições climáticas influenciam a produção e a qualidade das suas sementes em populações naturais. Considerando o contexto das mudanças ambientais globais e a necessidade de subsidiar práticas de coleta, manejo e conservação, este estudo teve como objetivo analisar se as variações interanuais nas condições ambientais afetam a qualidade física e fisiológica das sementes de *H. martiana*, entre diferentes indivíduos de uma população natural remanescente de Mata Atlântica no município de Areia, Paraíba. Os frutos foram coletados em 15 plantas matrizes nos anos de 2021 e 2022 e foram analisadas as características físicas das sementes, bem como as características relacionadas a emergência e desenvolvimento inicial das plântulas. O delineamento utilizado foi o inteiramente ao acaso, em esquema fatorial 2 x 15 (anos e plantas matrizes), sendo aplicadas análises uni e multivariadas. As características físicas e fisiológicas das sementes de *H. martiana* são influenciadas pelas condições ambientais interanuais e pela variabilidade genética entre as plantas matrizes. Dentre as características avaliadas, a emergência final foi a mais sensível as alterações ambientais. Logo, a adoção de estratégias que considerem esses fatores se torna primordiais para assegurar a produção de sementes de alta qualidade, influenciando diretamente no sucesso de programas de restauração florestal, conservação e uso sustentável dessa espécie.

Palavras-chave: diversidade genética, emergência de plântulas, vigor, jatobá.

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1. Introduction

Annual seed production plays a fundamental role in understanding natural forest regeneration and the effectiveness of management and conservation strategies. This process, however, is influenced by annual and seasonal variations in climate conditions (Souilla et al., 2024). According to the IPCC (2022), global climate change has caused a continuous rise in temperature, as well as intensification, a longer duration, and a greater frequency of extreme weather events.

Climatic factors such as temperature and water availability directly influence seed development and germination. Seed mass accumulation represents a critical phase characterized by the mobilization and accumulation of compounds such as proteins, carbohydrates, and lipids. Environmental changes at this stage can result in inadequate nutrient accumulation, directly impacting seed weight and physiological quality (Bailly and Gomez Roldan, 2023).

In this context, understanding the effects of climate change on plant reproduction becomes essential since seeds are the primary means of dispersal and perpetuation of species. Studies have shown that, in addition to the quantity of seeds produced, their physical and physiological qualities play crucial roles in the regeneration of natural populations, especially under conditions of increasing environmental stress (Goszka and Snell, 2020). However, studies evaluating the influence of environmental variables on the interannual variability of seed quality in native tropical species, such as those belonging to the genus *Hymenaea*, are still scarce.

Species of the genus *Hymenaea* stand out in reforestation projects aimed at recovering or restoring degraded areas (Guariz et al., 2021). Among them, *Hymenaea martiana* Hayne, popularly known as jatobá, occurs in the Caatinga, Cerrado, and Ombrophilous Forest biomes (Jardim Botânico do Rio de Janeiro, 2025). It is a tree that reaches between 8 and 18 m in height and is classified as a secondary plant, which is typical of Caatinga regions with humid floodplains and clayey soils (Lorenzi, 2009). In addition to its ecological value, this species has socioeconomic importance because its bark and resin are used in folk medicine (Silva et al., 2024), and the floury pulp that coats the seeds contains carbohydrates (glucose, xylose and xylitol) with biotechnological potential (Oliveira et al., 2019).

Despite its importance, information on how environmental conditions influence the production and quality of *H. martiana* seeds in natural populations is still limited. Considering the context of environmental change and the need to support collection, management, and conservation practices, the present study aimed to analyze whether interannual variations in environmental conditions affect the physical and physiological quality of *H. martiana* seeds among different individuals of a remnant natural population of the Atlantic Forest in the municipality of Areia, Paraíba, Brazil.

2. Materials and Methods

2.1. Study area and fruit collection

The fruits of *H. martiana* were collected from 15 mother plants in the municipality of Areia, Paraíba, Brazil, which is located in the Brejo Paraibano region (Figure 1). The region has a Köppen climate classification of "As," with high rainfall (exceeding 1,400 mm/year) and average temperatures ranging from 21 to 25 °C (Francisco and Santos, 2017; Arruda et al., 2022; Nascimento et al., 2022).

The harvests were carried out between November and January, corresponding to the 2021 and 2022 harvests. Although some of the harvests occurred in January of the following year, they were still part of the previous year's harvest, a period when the fruits were fully ripe and had fallen naturally from the trees. The same mother plants were evaluated in both experimental years. Selection was

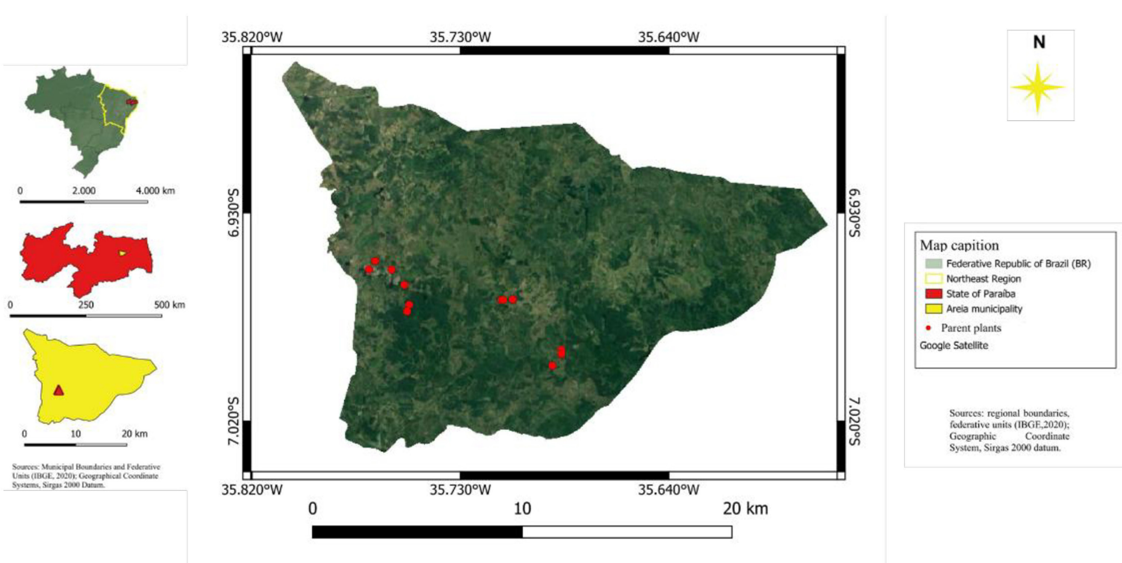

Figure 1. Locations of *Hymenaea martiana* mother plants in the municipality of Areia - PB.

based on good phytosanitary condition, and each plant was identified by visual marking with spray and georeferenced using GPS coordinates, ensuring the identification of the same trees in subsequent collections.

The meteorological data (temperature and rainfall) related to the fruit formation period were obtained from the Automatic Meteorological Station of the National Institute of Meteorology (INMET), located at the Center of Agricultural Sciences of the Federal University of Paraíba (CCA/UFPB), in Areia - PB (Figure 2).

The analyses were carried out at the Seed Analysis Laboratory (LAS) of the Department of Plant Science of the Center of Agricultural Sciences of the Federal University of Paraíba (DFCA-CCA/UFPB).

2.2. Experimental design

The experimental design used was completely randomized (CRD), with treatments distributed in a 2 × 15 factorial scheme, with two years of collection (2021 and 2022) and 15 mother plants, with four replicates per treatment.

2.3. Evaluated characteristics

2.3.1. Physical characterization of seeds

Prior to evaluation, the seeds were processed by manually removing the pulp with a serrated knife. To facilitate the extraction of the pulp residue remaining on the seeds, the seeds were immersed in water for six hours and then dried at room temperature. For each mother plant, 100 seeds were used to determine the length, width and thickness via a digital caliper (0.01 mm precision). A precision analytical balance (0.001 g) was used to obtain the weight.

The water content of the seeds was determined via the greenhouse method at 105 ± 3 °C for 24 h (Brasil, 2009a), with four replicates of 10 ± 0.5 grams of seeds for each mother plant, with the results expressed as a percentage.

2.3.2. Seedling emergence test

Owing to tegumentary dormancy, the seeds were scarified on the side opposite the hilum via iron sandpaper No. 120 (Silva et al., 2025). They were then asepsised in a sodium hypochlorite solution (2.5% commercial bleach) for three minutes (Brasil, 2009b). Sowing was carried out in plastic pots (30 cm in diameter and 22 cm in height) filled with medium-grain sand previously sterilized in an autoclave at 120 °C for 120 minutes (Brasil, 2009a). Four replicates of 25 seeds per mother plant were sown at a depth of 3.0 cm. The test was conducted in a greenhouse, where the average temperature obtained was 32 °C, with a relative humidity of 60%, as measured with a digital thermohygrometer. Manual irrigation was performed daily according to substrate moisture loss.

Emergence was evaluated daily until the 33rd day after sowing. The criterion used to consider seedling emergence was counting those with cotyledons completely above the substrate, with the results expressed as a percentage. In parallel with the emergence test, the percentage of the first emergence count was determined, with the seedlings that emerged 25 days after their installation being counted, and the results are expressed as a percentage.

To determine the emergence speed index, daily counts were carried out until the 33rd day after sowing, which were calculated by adding the number of seedlings that emerged daily, divided by the number of days elapsed between sowing and emergence, according to Maguire (1962). To obtain the average emergence time, evaluations were carried out daily until the 33rd day after sowing, with the results expressed in days (Edmond and Drapalla, 1958).

2.3.3. Initial seedling performance

At the end of the emergence test, the emerged seedlings were removed from the substrate to assess their length and dry mass. The lengths of the shoot (from the collar to the apical meristem) and the root system (from the collar to the tip of the main root) were measured using a ruler graduated in centimeters, and the results are expressed in cm.

The shoots and roots of each replicate were then separated with scissors and placed in previously labeled Kraft paper bags. These bags were then placed in a forced-air circulation oven at 65 °C for 72 hours to obtain the dry mass. After drying, the plants were weighed on an analytical balance with a precision of 0.001 g, and the results are expressed in g seedling^{-1}.

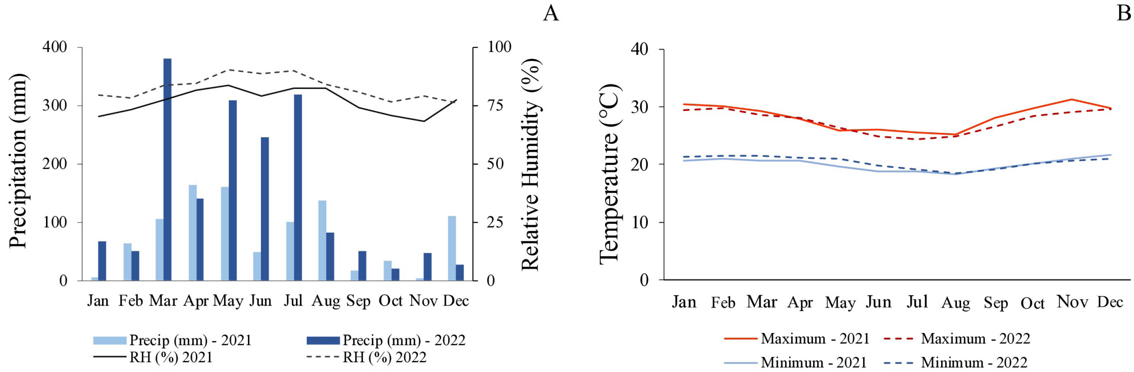

Figure 2. Meteorological data for the municipality of Areia - PB between 2021 and 2022. Precipitation and relative humidity (A) and maximum and minimum temperatures (B).

2.4. Statistical analysis

The data were subjected to the Shapiro–Wilk normality test and Bartlett's homogeneity of variance test. Once the assumptions were met, analysis of variance (ANOVA) was performed via the F test at the 1% and 5% significance levels. When a significant interaction between factors was identified, the interaction was unfolded. Mean comparisons were performed via the Scott–Knott test at 5% probability.

Principal component analysis (PCA) was subsequently performed to reduce data dimensionality and identify patterns of variability among parent plants, facilitating visualization of multivariate relationships. The analysis was based on eigenvalues and the variance explained by each component, considering only principal components with high explanatory power, according to the eigenvalue criterion greater than 1.

To assess the effect of collection year on the set of response variables, a multivariate analysis of variance (MANOVA) was applied via Pillai's statistic at the 5% significance level. Additionally, the effect size (partial η^2) was calculated and classified as small (<0.01), medium (0.01–0.06), or large (>0.14) according to Cohen's criteria to quantify the magnitude of the observed differences. The separation of environments was also assessed via linear discriminant analysis (LDA), which allows estimation of the accuracy of the classification of individuals into their respective groups. To compare the phenotypic characteristics of the seeds between the evaluated years, the data were standardized (z score), and the means for each group were calculated. Profile analysis was applied to assess differences in the response patterns between years, identifying variables with greater divergences between environments. This approach allows for the simultaneous comparison of multiple characteristics, highlighting those most sensitive to the conditions of each year.

The analyses were performed in R Core Team software version 4.4.2 (R Core Team, 2025) via the packages Scott-Knott (Jelihovschi et al., 2014), FactoMineR (Lê et al., 2008), car (Fox and Weisberg 2019), MASS (Venables and Ripley, 2002) effsize (Torchiano, 2020), ggplot2 (Wickham, 2016) and ggpubr (Kassambara, 2020).

3. Results

The interaction between the factors evaluated (years of collection and mother plants) was significant at the 1% probability level according to the F test for all 13 variables related to the physical and physiological characteristics of *H. martiana* seeds (Table 1), as was the significant effect of the individual factors.

Table 1. Summary of the analysis of variance for the physical characterization and physiological quality of *Hymenaea martiana* seeds collected in 2021 and 2022 from different mother plants of a natural population in Areia-PB.

Sources of Variation	Mean Squares [1]					
	DF	SL (mm)	SWi (mm)	ST (mm)	SWe (g)	WCS (%)
Years (F1)	1	28.92**	36.72**	20.80**	11.69**	68.92**
Mother plants (F2)	14	48.84**	7.16**	13.15**	6.20**	17.08**
F1 x F2	14	4.69**	3.45**	2.88**	1.58**	4.68**
Residue	90	0.36	0.65	0.39	0.07	0.50
CV (%)		2.10	3.70	3.80	4.70	5.50

Sources of Variation	Mean Squares [1]				
	DF	FEC (%)	EP (%)	ESI	MET (days)
Years (F1)	1	5018.10**	14148.40**	0.58**	168.08**
Mother plants (F2)	14	2852.20**	1022.00**	0.16**	42.51**
F1 x F2	14	530.70**	432.00**	0.12**	13.40**
Residue	90	99.30	173.80	0.02	0.83
CV (%)		29.40	21.80	23.10	3.20

Sources of Variation	Mean Squares [1]				
	DF	LAP (cm)	LRS (cm)	DMAP (g seedling^{-1})	RDM (g seedling^{-1})
Years (F1)	1	167.65**	43.07*	1.50**	0.13**
Mother plants (F2)	14	89.13**	44.21**	0.43**	0.10**
F1 x F2	14	30.88*	14.84**	0.14**	0.05**
Residue	90	4.38	4.89	0.01	0.01
CV (%)		11.00	12.80	11.20	21.40

[1]Significant effect at 1% (**), at 5% (*) and nonsignificant effect (ns) according to the F test.
Legend: degree of freedom (DF); coefficient of variation (CV); seed length (SL); seed width (SWi); seed thickness (ST); seed weight (SWe); water content of seeds (WCS); first emergence count (FEC); emergence percentage (EP); emergence speed index (ESI); mean emergence time (MET); length of aerial part (LAP); length of the root system (LRS); dry mass of aerial part (DMAP); and root dry mass (RDM).

Regarding physical dimensions, seed length showed a consistent pattern between years, with emphasis on mother plants M5 and M7, which exhibited the highest values in both collection years (Figure 3A). Width varied between mother plants and years. In 2021, the largest widths were recorded in seeds from mother plants M1, M5, M7, M11, and M12 (19.51 to 20.50 mm), while in 2022, mother plants M12 and M14 stood out, with average seed lengths of 20.99 and 21.58 mm, respectively (Figure 3B).

Seed thickness was also higher in 2022 for most matrices, except M4, which stood out in 2021 (Figure 3C). In 2021, mother plants were grouped into four classes, with M3, M7, and M11 having the thickest seeds. In 2022, seven groups were formed, with M1 and M11 plants having the thickest seeds. Seed weight (Figure 3D) was greater in 2022 in the M7, M8, M9, M10, M11, M12, and M15 matrices, whereas in 2021, only M5 had heavier seeds. In the 2021 collection, four groups were formed, with an emphasis on M1, M5, and M7, whereas in 2022, six groups were formed, with averages ranging from 3.76 to 6.79 g, in which the heaviest seeds were obtained from matrix plants M7 and M11. The seed moisture content (Figure 3E) was generally greater in 2022 for 10 of the 15 mother plants evaluated, with values ranging from 11.99 to 13.52% in 2022, whereas in 2021, it

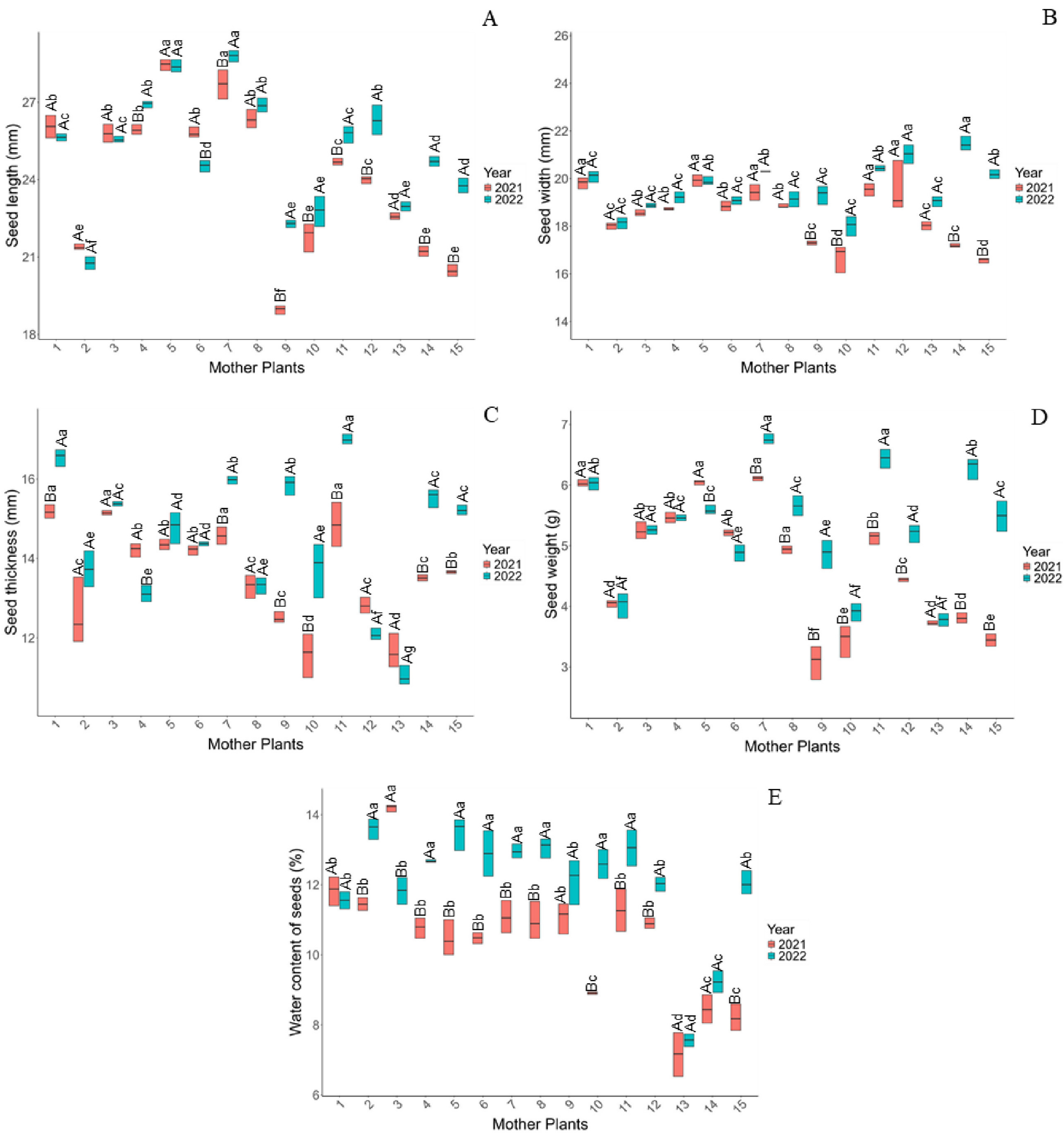

Figure 3. Physical characterization of *Hymenaea martiana* seeds collected in 2021 and 2022 from different mother plants of a natural population in Areia, Paraíba. Lowercase letters indicate significant differences between mother plants, and uppercase letters indicate significant differences between 2021 and 2022 (Scott–Knott test, p ≤ 0.05).

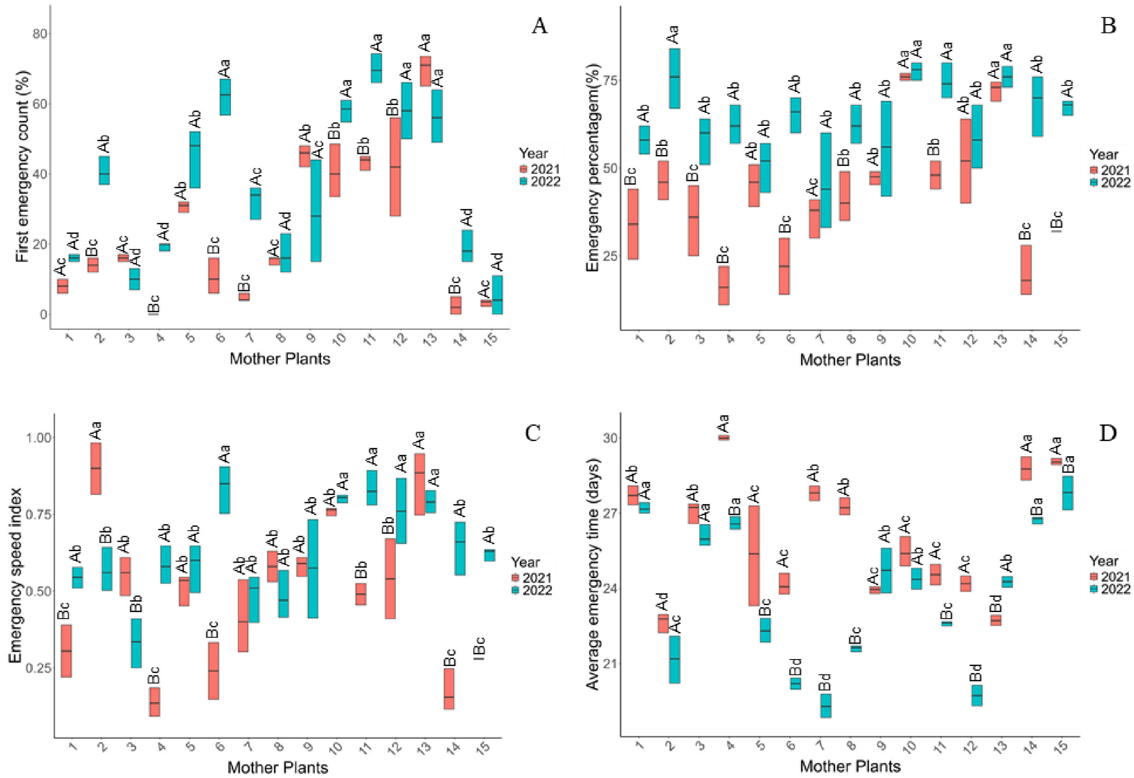

Figure 4. Physiological quality of *Hymenaea martiana* seeds collected in 2021 and 2022 from different mother plants of a natural population in Areia, Paraíba. Lowercase letters indicate significant differences between mother plants, and uppercase letters indicate significant differences between 2021 and 2022 (Scott–Knott test, $p \leq 0.05$).

ranged from 8.26 to 11.45%, reflecting the possible influence of annual rainfall on seed maturation.

With respect to the first emergence count (Figure 4A), seeds from the mother plants M2, M4, M6, M7, M10, M11, M12, and M14 produced seedlings at a lower percentage in 2021, ranging from 0-42%. In 2022, seeds from these mother plants produced seedlings with values ranging from 18 to 58%. In 2021, the mother plants were grouped into three distinct groups: the first consisting of only one mother plant (M13), the second consisting of five mother plants, and the third consisting of nine. In 2022, four groups were formed, with five mother plants in the first group, two each in the second and third groups, and six in the fourth group.

Final seedling emergence from *H. martiana* seeds (Figure 4B) was significantly greater in 2022 for nine mother plants, whereas for the other plants, there was no difference between collection years. In 2021, the mother plants were grouped into three distinct groups, whereas in 2022, only two groups were formed. Mother plants M10 and M13 stood out in both collection years, with the highest percentages of seedling emergence from their seeds.

Considering seed vigor, as assessed by the emergence speed index (Figure 4C), seeds from seven mother plants yielded greater values in 2022. Only seeds from M2 and M3 mothers presented a relatively high index when they were collected in 2021. Seeds from M10 and M13 remained among the best performers in both years, whereas seeds from M2 stood out in 2021, and those from M6 stood out in 2022. The seeds of most of the mother plants evaluated produced seedlings that required longer emergence when collected in 2021. In that year, the mother plants were grouped into four groups, with M2 and M13 having the lowest averages. In 2022, four groups were also formed, with M6, M7, and M12 having the lowest average seedling emergence times from their seeds (Figure 4D).

When the initial performance of the seedlings was evaluated, it was observed that seeds from seven mother plants resulted in seedlings whose shoot length was greater in 2022. Only seedlings from the seeds of the mother plant M9 obtained a relatively high average value in 2021. The mother plants were grouped into two and three distinct groups in the years 2021 and 2022, respectively, with seeds from M11, M12 and M13 standing out for originating seedlings with the greatest lengths in both years (Figure 5A).

With respect to root system length (Figure 5B), only mother plants that originated from M4, M12, or M14 seeds had relatively high average length in 2022. In both periods evaluated, the mother plants formed three groups. In 2021, the seeds from M9 and M13 resulted in seedlings with greater root lengths, whereas in 2022, the seeds from the M12 mother plant stood out because the average number of seedlings that originated from these plants was greater.

With respect to shoot dry mass, seeds from nine of the 15 mother plants produced seedlings with the highest mass accumulation in 2022, whereas seedlings from M9 and M13 seeds obtained the highest values in 2021. The mother plants were grouped into five classes in 2021, with M8, M9, and M13 standing out as having the highest averages for seedlings produced from their seeds. In 2022, the greatest shoot dry mass accumulation was observed in seedlings produced from M7 and M12 seeds (Figure 5C). With respect to root dry mass (Figure 5D), the highest average value in 2021 occurred in seedlings that originated from M1 seeds. In contrast, the seeds from the mother plants M5, M7, M11, M12, M14, and M15 produced the highest average number of seedlings in 2022. These results indicate that the 2022 collection favored greater accumulation of biomass in seedlings.

In the principal component analysis (PCA), the first two components explained 68.2% of the variance (Figure 6).

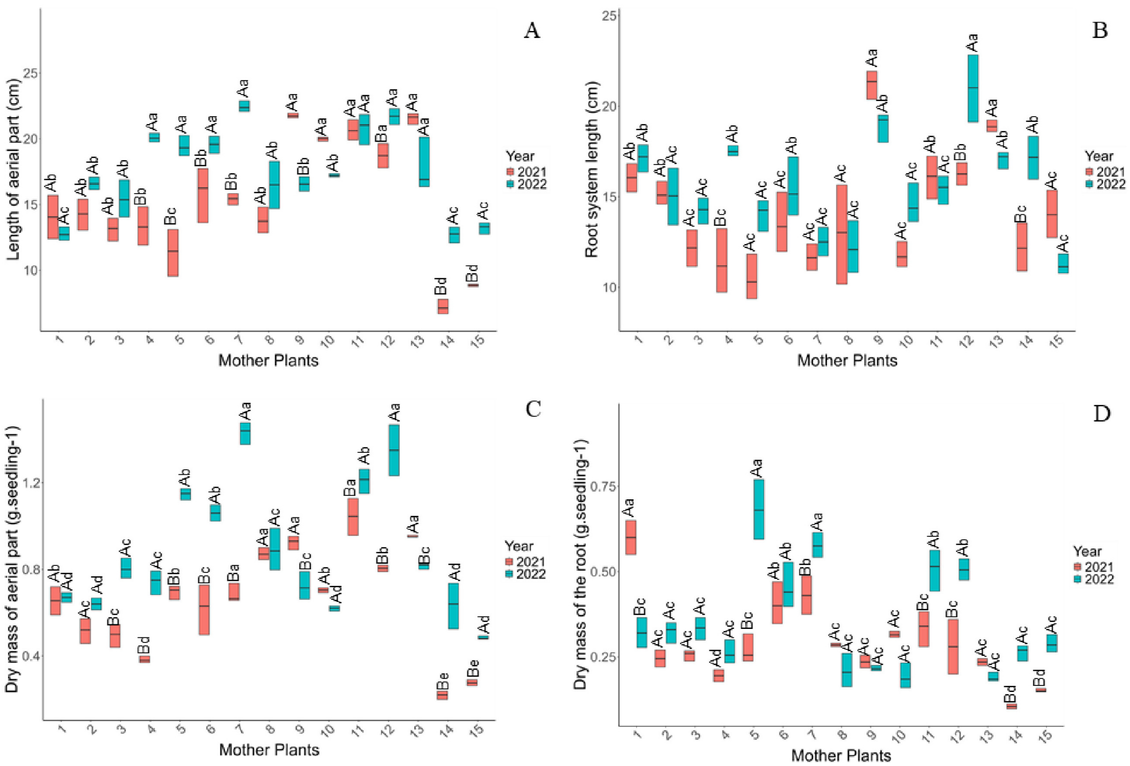

Figure 5. Initial growth of *Hymenaea martiana* seedlings collected in 2021 and 2022 from different mother plants of a natural population in Areia, Paraíba. Lowercase letters indicate significant differences between mother plants, and uppercase letters indicate significant differences between 2021 and 2022 (Scott–Knott test, $p \leq 0.05$).

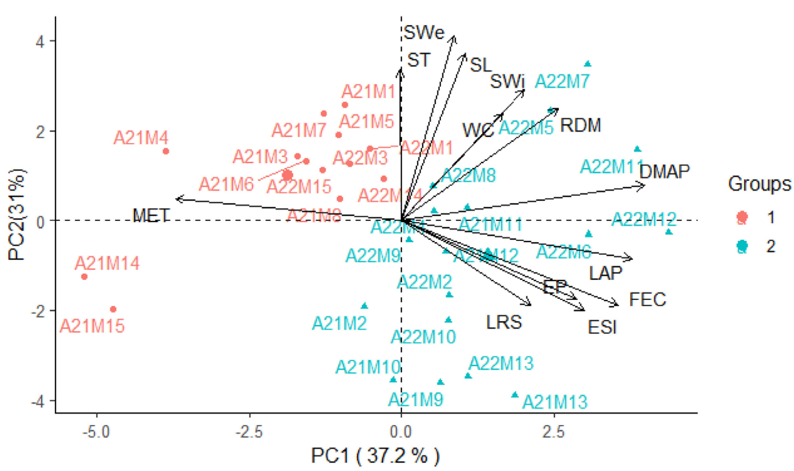

Figure 6. Biplot principal component analysis for the first two components of the physical and physiological characteristics of *Hymenaea martiana* seeds.

PC1 was strongly associated with the physiological variables of emergence and initial development (shoot dry mass, shoot length, first count, and mean emergence time), while PC2 was related to seed dimensions (weight, length, and thickness).

Based on these variables, the mother plants were grouped into four distinct sets. Group 1 (red), composed primarily of 2021 seeds, was associated with heavier and thicker seeds, but with slower-emerging seedlings. Group 2 (green), which included eight mother plants from both years, stood out for its better physiological performance, with higher values for final emergence, emergence speed, and shoot and root length. Group 3 (blue), composed only of M14 and M15 (2021), showed delayed seedling emergence due to high mean emergence times. Group 4 (purple), composed exclusively of 2022 seeds, was associated with higher shoot and root dry matter, reflecting greater initial seedling development.

According to the multivariate analysis of variance (MANOVA), there was a significant effect of collection year on the set of variables related to the physical characteristics of the seeds and their physiological quality (Pillai: 0.763; F: 3.98; $p < 0.01$). This result confirms that the environmental conditions of the two years evaluated jointly impacted the analyzed characteristics of the seeds.

Effect size analyses (Figure 7A) according to the criteria proposed by Cohen's d indicate that the effects were classified as large ($\eta^2 > 0.14$), only the length of the seed and root system, as well as the dry mass of the roots, had a medium magnitude effect. Linear discriminant analysis (LDA) achieved 96.7% accuracy in classifying collection years, reinforcing the existence of distinct morphophysiological patterns across years. The variables with the highest discriminant capacity were the emergence speed index, seed weight, shoot dry mass, and seed thickness, length, and width, with coefficients of 4.38, 1.25, 0.72, 0.63, 0.48, and 0.32, respectively (Figure 7B). The highest discriminant coefficient was observed for the emergence speed index, demonstrating that this variable is particularly sensitive to environmental conditions and, therefore, is a good indicator for differentiating the years evaluated.

The variables with the greatest absolute difference in the standardized mean profiles between the collection years are shown in Table 2. The variables final emergence, seed width, water content, and shoot dry mass presented relatively high values in the 2022 collection, whereas the average emergence time presented relatively high values in 2021. This behavior reinforces the influence of factors such as the higher rainfall and relative humidity observed in 2022, which can impact the physiological quality of the seeds.

4. Discussion

The results of this study demonstrated that the physical and physiological characteristics of *H. martiana* seeds

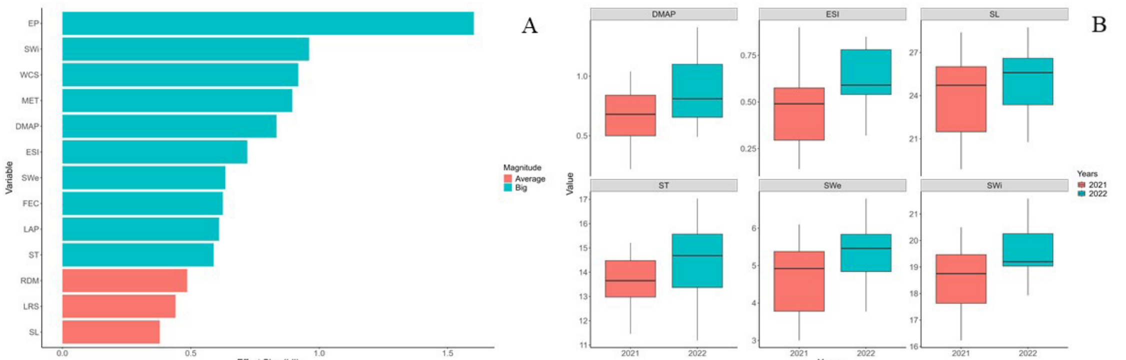

Figure 7. Effect sizes per variable according to Cohen's d criterion (A) and distribution of the most discriminant variables in linear discriminant analysis (B).

Table 2. Standardized average profiles of variables between collection years for variables with the largest absolute differences.

Variable	Years of collection		Difference
	2021	2022	
Emergence percentage	-0.628	0.628	1.255
Seed width	-0.438	0.438	0.876
Water content of seeds	-0.422	0.422	0.844
Mean emergence time	0.413	-0.413	-0.827
dry mass of aerial part	-0.390	0.390	0.779

are influenced by interannual environmental conditions (2021 and 2022) and by genetic variability among parent plants. This behavior highlights the species' sensitivity to interannual environmental variations and demonstrates the importance of selecting parent plants with superior traits to ensure seed quality.

The physical characteristics of the seeds (length, width, thickness, and weight) varied significantly between the years of collection and the mother plants. In 2022, most of the mother plants presented higher values, probably due to the greater water availability recorded that year (rainfall of 1742 mm), a condition that favored seed development. This behavior is consistent with the findings of Gomes et al. (2023), who reported that *Anadenanthera colubrina* var. cebil (Griseb.) Altschu reported a reduction in seed weight in years with lower precipitation, indicating the direct effect of climatic conditions on the physical and physiological quality of the seeds.

The higher water content observed in seeds in 2022 (11.99 to 13.52%) than in 2021 2021 (8.26 to 11.45%) may be associated with differences in climatic conditions between the years evaluated. From a technological perspective, this variation influences post-harvest strategies, since seeds with higher moisture content may requirerying procedures, but they also have greater potential for immediate use. Although the observed values are within the expected range for orthodox seeds (Matilla, 2022), the contrast between years reinforces the influence of water availability on seed composition. According to Gavranović Markić et al. (2024), there is a positive correlation between seed moisture and precipitation during the ripening period, which corroborates the results obtained, indicating that wetter conditions favor water accumulation in seeds.

In terms of physical characteristics, the physiological quality of *H. martiana* seeds was greater in 2022 than in the other years, indicating that the physiological quality seeds is strongly influenced by environmental conditions during maturation. In this study, it was observed that temperature and precipitation in 2022, during the seed formation period, may have been important factors in the interaction of the synthesis of compounds essential for germination, resulting in greater vigor and emergence rates. According to Penfield and MacGregor (2017), the developmental environment influences not only physical attributes but also physiological aspects that directly affect the germination performance of progeny.

Environmental conditions during seed development can directly influence seed quality, either by limiting dry matter accumulation or by restricting the ability of a plant to synthesize the compounds necessary for seed formation (Goszka and Snell, 2020). Furthermore, environmental stimuli affect gene expression, promoting the activation of enzymes and isoenzymes that participate in the digestion of endosperm reserves and the degradation of tegument components, processes that are fundamental for radicle protrusion (Bailly & Gomez Roldan, 2023).

The integrated study of these environmental factors is essential to understanding the ecology of *H. martiana* seeds, especially because most Brazilian forest seeds are still collected from natural populations, where there is wide intra- and interpopulation genetic variability (Menegatti et al., 2019). Temperature and precipitation, therefore, not only modulate seed development but also influence subsequent ecological processes, such as germination and seedling establishment in tropical species (Fontúrbel et al., 2021).

The presence of genetic variability among the mother plants was evident, especially in the mother plants M10, M11, and M13, whose seed performance was superior in terms of seedling emergence and initial development. Previous studies corroborate this variation. Lima et al. (2014) reported significant differences in the physiological quality of *Poincianella pyramidalis* (Tul.) L. P. Queiroz seeds from 28 mother plants from a single collection area.

Therefore, it is increasingly essential to understand the different ecophysiological aspects of forest species, such as *H. martiana*, with an emphasis on selecting mother plants on the basis of seed physiological quality and genetic diversity. This approach can inform forest conservation programs in different biomes, providing adequate input for the formulation of public policies aimed at environmental conservation (Pimenta et al., 2023).

Principal component analysis (PCA) (Figure 6) allowed us to distinguish well-defined groups, with the first component associated with physiological variables related to vigor and emergence, and the second with the physical dimensions of the seeds. In addition to helping select the descriptors that best represent population diversity, the data generated from these methods can provide important information for the maintenance of genetic resources (Gomes et al., 2022). Based on these results, seeds from the mother plants M2, M9, M10, and M13 stood out for their greater initial vigor, making them potential mother plants of interest for conservation and breeding.

Linear discrimination analysis (LDA) (Figure 7) reinforces the robustness of the results, allowing for highly accurate (96.7%) separation of seed lots from different years. As discussed by Rede et al. (2025), this method assumes a multivariate normal distribution for each group, enabling reliable probability estimates. The emergence speed index, seed weight, shoot dry mass, and thickness were the most discriminative variables, demonstrating that physiological and physical attributes are equally important in differentiating lots.

The absolute differences in the standardized mean profiles indicated that in 2022, the seeds performed better in terms of final emergence, width, water content, and shoot dry mass. These patterns suggest that more favorable environmental conditions, especially greater water availability, contribute to the formation of seeds with greater physiological vigor. These results have direct implications for strategies for collecting, conserving, and producing *H. martiana* seedlings, reinforcing the importance of sample planning and selection of parent plants in restoration programs for degraded areas, particularly under climate change scenarios (Beveridge et al., 2024).

Thus, the results demonstrate that the physical and physiological qualities of *H. martiana* seeds are directly affected by interactions between genetic and environmental factors. This reinforces the need to plan collection in more favorable years, especially those with higher rainfall, considering projected changes in climate regimes (IPCC, 2022). In this context, the selection of mother plants with superior characteristics constitutes a strategic measure for restoration, sustainable management, and conservation programs of native species (Atkinson et al., 2021).

The results obtained in this study can contribute to the planning of ecological restoration actions aligned with public policies such as the National Plan for the Recovery of Native Vegetation (PLANAVEG) (Brasil, 2017), reinforcing the importance of considering intraspecific variability in forest restoration strategies. Understanding this intraspecific genetic variability is fundamental for assessing the resilience of tree species to environmental change and for planning long-term conservation programs (Kesić et al., 2021).

5. Conclusions

The physical and physiological characteristics of *H. martiana* seeds are influenced by interannual environmental conditions and genetic variability among parent plants. Among the characteristics evaluated, the emergence speed index was the most sensitive to environmental changes. Therefore, adopting strategies that consider these factors is essential to ensure the production of high-quality seeds, directly influencing the success of forest restoration, conservation, and sustainable use programs for this species.

Data Availability Statement

The research data are only available upon request to the corresponding author.

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