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Analysis of the multidimensional characteristics of *Tabernaemontana heterophylla* seeds

Análise das características multidimensionais de sementes de *Tabernaemontana heterophylla*

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ABSTRACT

The analysis of *Tabernaemontana heterophylla* seeds entails morphological characterization and the study of genetic variability between batches. This knowledge is fundamental for evolutionary biology and agronomic and conservation practices. Crop productivity, species preservation, reforestation, and post-harvest processing can all benefit from understanding and considering seed size. This work aimed to determine the multidimensional characteristics and mass of the seeds using multivariate cluster analysis. We investigated multidimensional characteristics by measuring the dimensions and mass of the seeds and computing their physical attributes. Several statistical measures were used to assess the morphometric data, including the mean, amplitude, coefficient of variation, relative frequency, arithmetic mean, standard deviation, and confidence interval. In addition, grouping patterns and inter-variable dependencies were examined by multivariate cluster analysis using Ward's method. The results revealed significant variability in seed dimensions, indicating morphological unevenness in the seeds of this species. Euclidean distance analysis identified the formation of subclusters, implying distinct groupings based on seed size and mass. The finding highlights the significance of segregating lots with similar physical characteristics and defining representative properties for management practices. These variations reflect the genetic diversity required for adaptability and ecological resilience, ensuring forest ecosystems' survival and proper functioning. Alternatively, classifying and standardizing seed lots based on these physical traits can optimize post-harvest processing and increase agronomic productivity.

Index Terms: Morphology; physical properties; genetic variability.

RESUMO

A análise de sementes de *Tabernaemontana heterophylla* envolve a caracterização morfológica e o estudo da variabilidade genética entre lotes. Este conhecimento é fundamental para a biologia evolutiva e práticas agronômicas e conservacionistas. A produtividade das culturas, a preservação das espécies, a reflorestação e o processamento pós-colheita podem beneficiar da compreensão e da consideração do tamanho das sementes. Este trabalho teve como objetivo determinar as características multidimensionais e massa das sementes utilizando análise multivariada de agrupamento. Investigamos características multidimensionais medindo as dimensões e massa das sementes e computando seus atributos físicos. Diversas medidas estatísticas foram utilizadas para avaliar os dados morfométricos, incluindo média, amplitude, coeficiente de variação, frequência relativa, média aritmética, desvio padrão e intervalo de confiança. Além disso, padrões de agrupamento e dependências intervariáveis foram examinados por análise multivariada de cluster usando o método de Ward. Os resultados revelaram variabilidade significativa nas dimensões das sementes, indicando irregularidades morfológicas nas sementes desta espécie. A análise da distância euclidiana identificou a formação de subaglomerados, implicando agrupamentos distintos com base no tamanho e massa das sementes. A descoberta destaca a importância de segregar lotes com características físicas semelhantes e definir propriedades representativas para práticas de gestão. Estas variações refletem a diversidade genética necessária para a adaptabilidade e a resiliência ecológica, garantindo a sobrevivência e o bom funcionamento dos ecossistemas florestais. Alternativamente, a classificação e padronização de lotes de sementes com base nestas características físicas pode otimizar o processamento de pós-colheita e aumentar a produtividade agronômica.

Termos de Indexação: Morfologia; propriedades físicas; variabilidade genética.

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Introduction

Tabernaemontana heterophylla, a widely distributed tropical plant known for its medicinal properties, has aroused significant interest in botany and medicine. In addition to its therapeutic value, this plant exhibits remarkable morphological diversity, especially in the seeds, which may influence germination and adaptation to different tropical environments (Pinheiro et al., 2024a).

Exploring how these morphological and genetic variations impact the germination and environmental adaptation of *Tabernaemontana heterophylla* seeds, with a focus on the dimensional characteristics of the seeds, such as size and mass, would help to understand how these physical properties affect the plants' ability to survive and grow in different environmental conditions. This knowledge is essential for the conservation and sustainable usage of the species and for optimizing management practices such as storage and planting (Pinheiro et al., 2024b), boosting reproductive success, and using the plant medicinally. Thus, a thorough examination of the physical properties of *Tabernaemontana heterophylla* seeds advances morphological botany and has significant practical implications for ecology and medicine by improving automated systems.

Larger and heavier seeds generally contain more nutritional resources, which can improve germination rates and seedling resistance to environmental stresses. However, smaller seeds are more readily dispersed by the wind or animals, which helps the plant colonize new areas. Seed size indicates physiological quality in most species (Domic, Capriles, & Camilo, 2020). Smaller seeds have lower germination rates and vigor than medium and large seeds. Thus, seedling production strategies benefit from prior knowledge of seed size. An in-depth understanding of seeds' morphophysical and multidimensional characteristics is essential to advance our knowledge of plant reproductive biology and guide strategies for the conservation and management of natural resources and post-harvest stages, such as processing, drying, and storage (Pinheiro et al., 2023).

Tabernaemontana heterophylla's woody stem contains methanolic extracts. However, the extraction of indolic alkaloids, particularly those of the iboga variety, makes it economically significant. The extensive therapeutic potential of these indolic compounds has motivated in-depth studies to understand their chemical characteristics and biological activities better (Pinheiro et al., 2024a). The lack of detailed information on the physical properties of *Tabernaemontana heterophylla* seeds represents a significant gap. This information is crucial for developing more efficient storage, sowing, and processing methods. A comprehensive understanding of seeds' morphological, dimensional, and mass characteristics is essential for optimizing all post-harvest stages in large-scale operations (Araujo et al., 2022).

Knowledge of these aspects facilitates the implementation of more efficient agricultural practices and plays a crucial role in biodiversity conservation by highlighting the genetic variability in seed lot formation (Pinheiro & Ferreira, 2018). Maintaining this genetic variability in natural populations is essential for the species' adaptation to environmental changes, resistance to pests and diseases, and preserving unique plant characteristics (Lemos Filho et al., 2023).

Thus, the primary goal of this research was to determine the multidimensional characteristics and mass of the seeds using cluster analysis based on multivariate data. Cluster analysis allows for establishing homogeneous groups, revealing similarities and differences between seeds based on morphological traits and mass. This integrated approach aims to improve understanding of the relationships between the evaluated variables, improve data interpretation, and lead to a more comprehensive and effective characterization of *Tabernaemontana heterophylla* seeds.

Material and Methods

Study site and collection

The experimental work was carried out at the Forest Seed Laboratory of the Zoobotanical Park of the Federal University of Acre, located in Rio Branco, Acre. *Tabernaemontana heterophylla* seeds were harvested from a forest fragment on a private rural property in the Vila Acre area, situated on the outskirts of Rio Branco, Acre.

The seeds were collected while the fruit was still on the mother plant, dry, open, and physiologically ready for seed dispersal. The fruits were orange inside, with the aril partially covering the seeds (Figure 1i). The seeds were placed in a thermal box and transported to the laboratory while attached to the fruit. The aril was removed by soaking in water and rubbing it through a sieve, followed by natural drying on paper to remove excess water. We dried the seeds and refrigerated (16 °C) them for two days to maintain their integrity before measuring for size and mass.

Degree of humidity

To determine the degree of humidity, we used the oven methodology established in the Brazilian Rules for Seed Analysis (RAS) (Brasil, 2009). This methodology entailed exposing the seeds to temperatures of 105 ± 3 °C for 24 hours, with four repetitions, each using 5 g of seeds. The results were expressed as a percentage (%) of wet basis (b.u.), representing the seeds' water mass ratio to the total mass.

Thousand seed mass

The mass of a thousand seeds provides information about the seed size, maturity, and health. The Rules for Seed Analysis (Brasil, 2009) outlines the approach employed in this study, which consists of eight repetitions of 100 seeds counted by hand at random and weighed on a precision analytical scale (in grams). The variance, standard deviation, and coefficient of variation of the values obtained from the weighings were calculated as follows: Variance √= n (∑ x2) - (∑ x) 2 /n (n - 1), where: x = mass of each repetition and n = number of repetitions; Standard Deviation (S) = √variance; Coefficient of Variation (CV) = S/X x 100, where X = average mass of 100 seeds.

Morphometric evaluations or physical properties

In general, the quantity of forest seeds obtained is limited; hence, we adopted Pinheiro et al. (2024b) methodology — 99 of the 1,200 seeds generated after processing were chosen randomly and used for dimensional determinations. The current study's morphometric investigation used a larger sample of seeds than Ramashia et al. (2018). The seeds were measured and weighed according to Pinheiro et al. (2019). They were measured from the base to the apex for length, at the largest horizontal end for width, and the central median line for thickness (Figure 2) using a caliper with a precision of 0.01 mm. The measurements were determined according to the position of the hilum on the seeds. Thus, we ascertained the length from the hilum to the opposite base, the width in the median region with the largest amplitude, and the thickness at the apparent thinnest side (Figure 2). Where: Length L = longitudinal linear dimension (mm) and W and T = equatorial linear dimensions (mm).

The seeds' weight was determined on an analytical balance with a precision of 0.0001 g. After determining the three-dimensional measurements, the following physical properties were derived by mathematical calculations: Seed Volume Index = SVI – Pinheiro et al. (2023) Equation 1; Geometric Mean Diameter = GMD - Equation 2; Equivalent Mean Diameter = EMD - Equation 3; Arithmetic Mean Diameter = AMD - Equation 4 – Sahay and Singh (1994); Surface Area = SA Equation 5 – Sahay et al. (2005); Seed Sphericity = Ø Equation 6; Seed Volume = V Equation 8 – Mohsenin, (1986); Aspect Ratio = Ar Equation 7 – Varnamkhasti et al. (2008).

These properties were calculated according to the equations below:

$$\text{SVI} = \text{length x width x thickness} \quad (1)$$

$$GMD = Width \times Thickness \times Length^{1/3} \quad (2)$$

$$EMD = \left[lenght \frac{width \times thickness}{4} \right]^{1/3} \quad (3)$$

$$AMD = \frac{lenght + width + thickness}{3} \quad (4)$$

$$SA = \pi GMD^2 \quad (5)$$

$$\varnothing = \left[\sqrt[3]{\frac{Width \times Thickness \times Length}{Length}} \right] 100 \quad (6)$$

$$Ar = \left[\frac{width}{length} \right] 100 \quad (7)$$

$$V = \frac{\pi Width \times Thickness^2 \times Length^2}{6(2Length - Width \times Thickness)} \quad (8)$$

Data analysis

We conducted a statistical study using small samples, adhering to statistical principles and assumptions (Sokal & Rohlf, 1995). We took 99 seeds and divided them into three subsamples of 33 seeds, representing 8.25% of the batch. The classes were determined using statistical software.

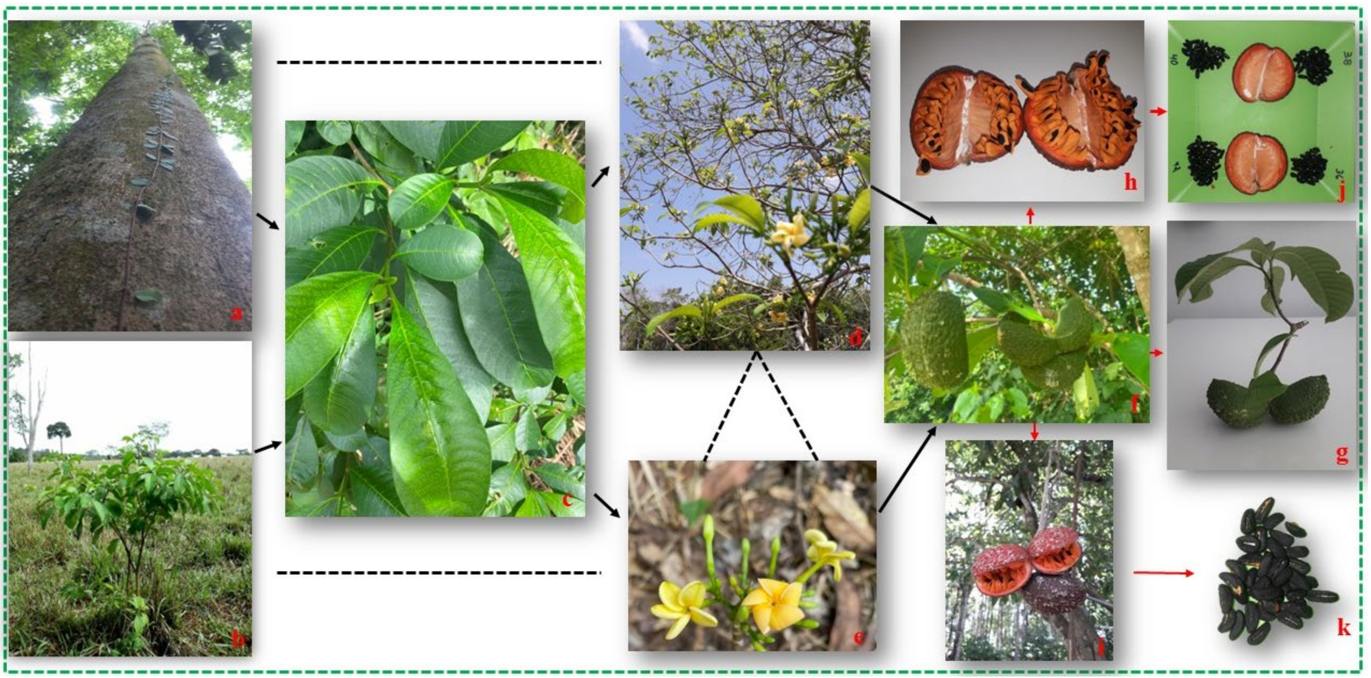

Figure 1: Different characteristics of the *Tabernaemontana heterophylla* plant during the reproductive phase. a - Plant size in a forest environment; b - Pasture environment; c - Leaves; d - Flowering; e - flowers; f - Green fruit on the plant; g - Green fruit collected; h - Opening of the fruit with seeds; i - Physiological maturity of the fruit on the plant; j - Seeds removed from the fruit, and k - Processed seeds.

Figure 2: Characteristics of the three-dimensional dimensions of *Tabernaemontana heterophylla* seeds: length a; width b; thickness c. Red lines show the position of the measurements.

The data on morphometric characteristics was examined using mean, range (maximum and minimum), coefficient of variation (CV), arithmetic mean, standard deviation, and confidence interval to determine the possible relationship between phenotypic variation and the variables analyzed.

A normality test was conducted for a specific distribution function with a known mean and variance. We assessed normality using the Lilliefors test (p-value) to determine whether a normal distribution well modeled the data set of random variables.

Statistical procedures

The three-dimensional characteristics and seed mass were subjected to multivariate cluster analysis utilizing Ward's method, Euclidean distance, and the standardized data matrix for each variable. The morphometric properties of each seed class were described using R Core Team® (2023) and BioEstat 5.3® software, which included the mean, standard deviation, coefficient of variation, minimum and maximum values, asymmetry, kurtosis, and confidence interval.

We used the original variables, length = X1, width = X2, thickness = X3, and seed mass = X4, to perform a principal component analysis for eigenvectors for seed dimensions and mass. The components were correlated using matrices, resulting in the establishment of components versus coefficients. The variables were designated as follows: length (components = Comp. 1, coefficients = Coef. X1), width (components = Comp. 2, coefficients = Coef. X2), thickness (components = Comp. 3, coefficients = Coef. X3), and mass (components = Comp. 4, coefficients = Coef. X4). We determined the total percentage of variance between the reported variables.

Results and Discussion

The seed properties of the examined plant species showed significant variation in shape, size, and mass. These distinct characteristics serve critical roles in the plant's reproductive and dispersal processes, reflecting specific adaptations to the environment in which it grows. However, the degree of humidity varied significantly (Table 1), suggesting that the loss in seed weight may occur throughout the phase of water content reduction, either during seed storage or the drying process. Seeds exposed to high humidity levels may show accelerated deterioration. Therefore, seed diversity can be critical to plant species' survival and reproductive success in diverse environments.

Table 1: Water content and mass of a thousand *Tabernaemontana heterophylla* seeds, representative for a batch. SD = standard deviation. CV = coefficient of variation.

Variables	Sample size	Average	SD	CV (%)
Humidity degree (%)	4	27.58	0.45	1.43
Mass of thousand seeds (g)	8	117.63	0.40	3.89

Seeds vary in shape, size, and mass due to their morphological properties, allowing assumptions regarding their genetic diversity. These studies enable the formation of homogeneous seed lots, which aid in selecting and preserving desirable propagation or cultivation traits. Table 2 displays the average values for seed physical properties, with coefficients of variation ranging from 5.55% to 28.72%. With an average value of 23.17% of oscillation between their dimensions, these coefficients of variation highlight the amplitude of variability in the seeds' physical attributes. Given the multiple criteria under analysis, this significant variation implies that the seeds exhibit remarkable morphological diversity.

The physical properties of seeds play a fundamental role in various aspects related to the formation of seed lots, especially in agricultural production and plant quality. Therefore, amplitude indicators such as Volume (V) and seed volume index (SVI) can help determine the dimensional direction for developing seed collection, sowing, and processing equipment. Identifying directional trends in both morphological dimensions can help guide equipment adaptation to the seeds' distinct qualities.

The seeds' geometric, arithmetic, and equivalent mean diameters are essential metrics for revealing the complexity of seed morphological variability. These measurements represent the heterogeneous or homogeneous ranges of seed shape and size and are intrinsically linked to the relative aspect of seed mass (Pinheiro et al., 2024b).

Table 2: Physical properties and fresh weight characterization of *Tabernaemontana heterophylla* seeds. In columns, L= Length; W = Width; T = Thickness; M = Mass; Seed Volume Index (SVI); Geometric Mean Diameter (GMD); Equivalent Mean Diameter (EMD); Arithmetic Mean Diameter (AMD); Surface Area (SA); Seed Volume (V); Ø = Sphericity; Ar = Aspect Ratio; CV = Coefficient of Variation; CI = Confidence Interval; SD= Standard Deviation.

Properties	Range	Mean ± SD	CV (%)	± 95% CI	Valor *p*
L (mm)	7.80 – 14.40	11.03 ± 1.36	12.35	10.76 – 11.29	ns
W (mm)	2.70 – 6.50	4.62 ± 0.75	16.18	4.46 – 4.76	ns
T (mm)	2.90 – 5.40	4.15 ± 0.50	12.13	4.04 – 4.24	ns
M (g)	0.08 – 0.27	0.12 ± 0.03	24.16	0.12 – 0.13	*
SVI	105.37 – 427.57	212.05 ± 59.86	28.72	200.72 – 224.30	*
GMD (mm)	4.72 – 7.53	5.92 ± 0.52	8.85	5.81 – 6.02	**
EMD (mm)	2.52 – 3.41	2.88 ± 0.16	5.55	2.48 – 2.91	*
AMD (mm)	5.33 – 8.47	6.50 ± 0.55	8.38	6.48 – 6.76	*
SA (mm^2)	70.09 – 178.30	110.99 ± 20.18	18.18	107.01 – 114.96	*
V (mm^3)	55.17 – 223.88	111,27 ± 31.34	28.17	105.09 – 117.44	*
Ø (%)	38.27 – 74.91	54.30 ± 6.75	12.44	52.96 – 55.62	ns
Ar	21.09 – 77.22	42.60 ± 9.41	22.09	40.74 – 44.45	*

*does not follow a normal distribution at the level of p < 0,05; ** p < 0,01; ^{ns} = not significant.

The coefficient of variation is a percentage indicator of the dispersion of the data from the average. A coefficient of variation of less than 5% in the diameter values may suggest exceptional consistency and homogeneity in a batch of seeds' length, width, and thickness parameters. The dimensions of the *Tabernaemontana heterophylla* seeds were consistent and uniform, with minimal variations across the different seeds in the batch, as evidenced by the coefficient of variation. This stability in diameters shows a significant homogeneity in the morphological characteristics of these seeds, indicating a more uniform and predictable sample in terms of its dimensions.

Seed sphericity is a parameter that indicates how closely the shape of a product resembles a sphere. This measurement quantitatively assesses a seed's regularity or tendency to approach a spherical shape. The more the seed resembles a complete sphere, the closer the sphericity value is to one (Pontes et al., 2018a). With a coefficient of variation of 18.18%, the seeds' surface area — vital to the drying and storage processes — showed good consistency in the water retention mechanisms. Larger seeds had a higher surface area, as demonstrated in Table 2. The average size of *Tabernaemontana heterophylla* seeds was 110.99 mm².

Seed conditioning is intrinsically linked to volume and surface area effects (Zareiforoush, Hosseinzadeh, & Adabi, 2011). The process directly influences water absorption during seed hydrolysis, affecting viability and germination. The seeds' surface area to volume ratio is an essential factor in the drying and soaking processes and the energy requirements for germination (Pontes et al., 2018b). In addition, the surface-to-volume ratio can characterize the effects of surface area on water absorption and loss rates in particulate materials (Mir, Bosco, & Sunooj, 2013).

The aspect ratio of seeds refers to the proportion between their linear dimensions, providing insight into their shape and elongation. The ratio is often expressed as the length divided by its width or length divided by its thickness. In this case, it encompasses the seeds' three linear dimensions distribution and allows for visualizing size variations outside normal standards (Araújo et al., 2022). Aspect ratio analysis helps understand variations in seed shape, particularly when results vary within the same batch, indicating significant variability in the size and shape of seeds of a species (Anandakumar et al., 2022). We observed a very high coefficient of variation (22.09%) for *Tabernaemontana heterophylla*, indicating that the seed batch may present considerable heterogeneity in its characteristics.

The results of the descriptive principal components revealed the eigenvector coefficients for the three-dimensional characteristics and seed mass. These coefficients represent the contribution of the original variables in the principal components (Components 1 to Components 4). The goal is to reduce and eliminate overlaps and select the most representative forms of the data through linear combinations of the original variables (Figure 3).

The coefficients shown in Figure 3 highlight the contribution of each original variable (X1) to the principal components (Comp. 1 to Comp. 4). Comp. 1 (-0.23) demonstrated that the original variable X1 had a moderate negative impact on Comp. 1. Thus, X1 and Comp. 1 are inversely related, and an increase in X1 is associated with a decrease in Comp. 1. The original variable X1 exerted a significant positive influence on Comp. 2 (0.84) and strongly contributed to the variance observed in this component. The original variable X1 exerted a slightly positive impact on Comp. 3 (0.14), suggesting a relatively minor contribution from

X1 to Comp. 3. Finally, in Comp. 4 (-0.45), the original variable X1 had a significant negative impact, indicating that X1 exerted a substantial negative influence throughout Comp. 4.

Regarding width, in Comp. 1 (-0.55), the original variable X2 negatively impacted Comp. 1. Thus, a drop in Comp. 1 correlated with an increase in X2. Even though the X2 variable exhibited only a moderately negative impact on Comp. 2 (-0.32), it still contributes to the variation observed in this component. In Comp. 3 (-0.58), the X2 variable exerted a substantial negative impact and is inversely related, being an important factor for the decrease in Comp. 3. In Comp. 4 (-0.49), the original variable X2 had a considerable negative impact throughout Comp. 4.

For thickness, it is evident that the original variable X3 had a considerable negative impact on Comp. 1 (-0.47). This suggests that X3 and Comp. 1 are inversely related, so an increase in X3 is associated with a decrease in Comp. 1. The X3 variable had a moderate negative impact throughout Comp. 2 (-0.35), contributing to the variation observed in this component. Comp. 3 (0.78) demonstrated that the X3 variable significantly positively impacts Comp. 3, and an increase in one promotes an increase in the other. For Comp. 4 (-0.16), the original variable X3 had a slightly negative impact, exerting a less pronounced negative influence than other variables.

The relationship based on the signs and magnitudes of the coefficients for principal data analysis revealed the seed mass coefficients. In Comp. 1 (-0.64), the original variable X4 significantly negatively impacts Comp. 1, suggesting that Comp. 1 tends to decrease when X4 increases. In Comp. 2 (0.23), the original variable X4 had a moderately positive impact on Comp. 2. X4 had a positive influence, albeit smaller than the other variables. In Comp. 3 (-0.13), the original variable X4 had a slight negative impact and, therefore, a relatively minor contribution to Comp. 3. Finally, in Comp. 4 (0.72), the original variable X4 had a substantial positive effect, indicating that throughout Comp. 4, X4 had a significant positive influence.

Figure 4 illustrates considerable variability in seed dimensions, indicating significant genetic diversity. The persistence of subclusters of seed agglomeration in samples of unequal sizes is evidence of this genetic variation. This characteristic implies that distinct groups or subgroups of seeds within the same sample exhibit comparable morphological characteristics, indicating the presence of various phenotypes or genetic variants within the batch of seeds under investigation. The formation of subclusters in samples with varying sizes implies that despite genetic diversity, certain morphological similarities or patterns can be identified and grouped (Nour et al., 2023).

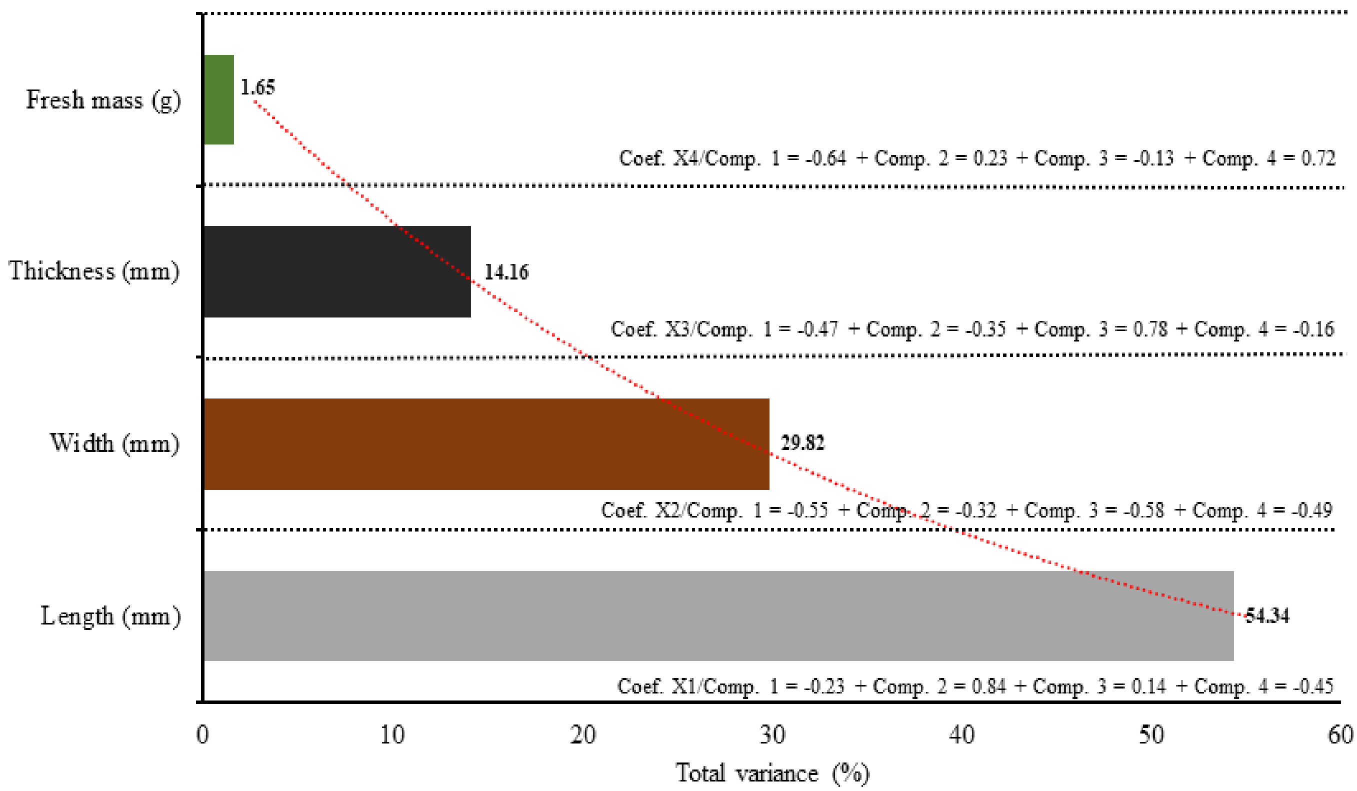

Figure 3: Results with determination of eigenvector coefficients for three-dimensional characteristics and seed mass of *Tabernaemontana heterophylla*. Comp. = components and Coef. = coefficients.

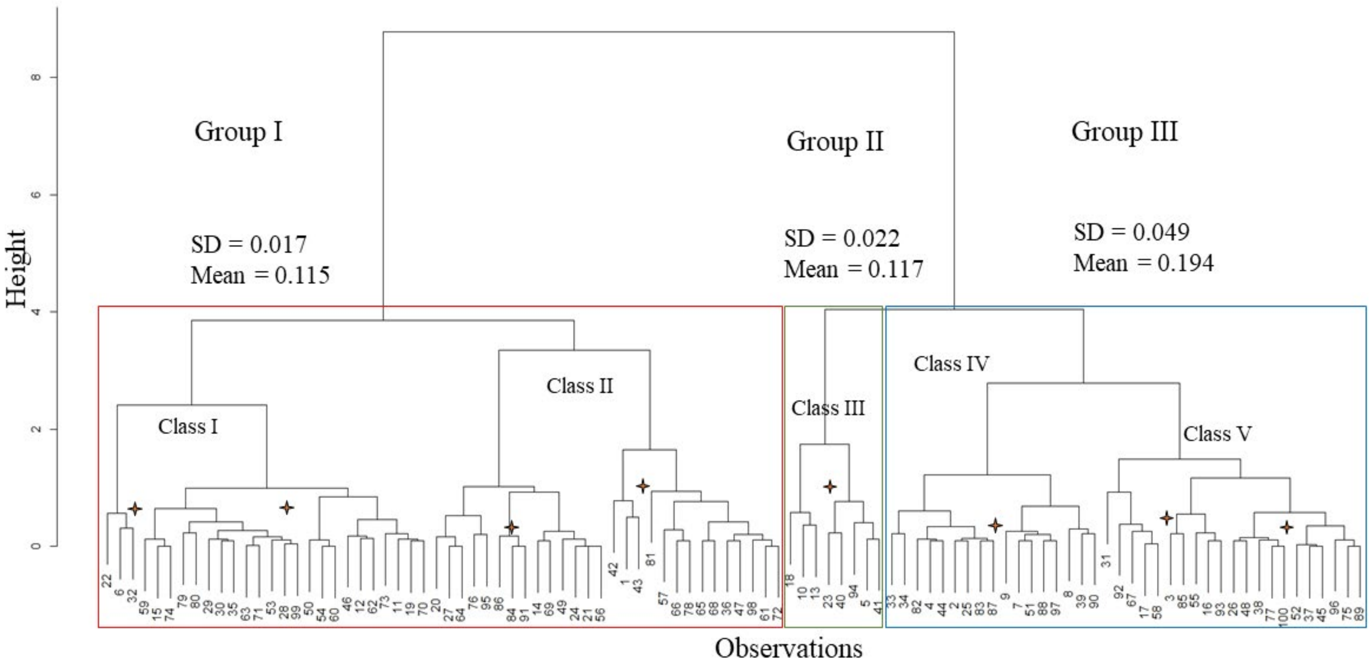

Figure 4: Dendrogram of the characteristics of three-dimensional physical properties and seed mass of *Tabernaemontana heterophylla* using the Ward method and Euclidean distance. The asterisks show the eight subsamples among the investigated classes with size variability. SD = standard deviation.

One hundred *Tabernaemontana heterophylla* seed dimensions and masses were subjected to cluster analysis using the seeds' four morphological characteristics (classes), quantitatively and qualitatively. The agglomerative cluster analysis revealed the formation of three primary clusters or groups. The first cluster represented group I, which comprised 46 samples collected from class I and II sites. The second cluster was more profound, with eight samples and a single class (III). Group III included 46 samples from class IV and V sites. Each primary class had notable subclasses corresponding to the sites marked with an asterisk (Figure 4). These results indicate significant seed shape and size heterogeneity within the seed batch of this species, yet these differences were not readily visible.

Table 3 provides estimates of the Pearson correlation coefficients (r) between multidimensional characteristics and seed mass and elucidates the association between the variables. The observed significant correlations highlight the statistical robustness of the relationships between the physical properties of the seeds and their corresponding mass. These results demonstrate the interdependence of the evaluated parameters, which contribute to a deeper understanding of the influence of these factors on seed mass variability in the context of the study on dimensional variability. The examined characteristics related to physical properties exhibited highly significant correlations ($p \leq 0.001$). Among these characteristics, correlations of smaller magnitude were particularly noteworthy, specifically those associated with length, width, and thickness, which were negative and non-significant. Table 3 provides more information about how these correlations differed in their capacity to distinguish between three-dimensional matrix correlations. It does, however, imply that seed shapes are independent of one another when there is no significant correlation between three-dimensional measures.

Furthermore, the geometric, equivalent, and apparent mean diameters, seed sphericity, and aspect ratio variables showed non-significant correlations ($p \geq 0.001$). The variables analyzed showed significant correlations, ranging from weak to strong, all above 0.39 ($p \leq 0.001$). The correlation between the equivalent mean diameter and sphericity (Ø %), as well as the negative estimates of the strong correlation (-0.74) between length and sphericity and moderate correlation (-0.65) between length and aspect ratio, were exceptions. This finding suggests a distinct and relevant relationship between these specific seed characteristics.

Table 3 shows no significant correlation between the multidimensional features of the seeds and their dimensions, as indicated by the low estimates of the correlation coefficients. These results suggest that variations in seed characteristics are intrinsic to the species. There is little to no correlation between the diversity in the multidimensional properties of the seeds and their physical dimensions (length, width, and thickness). This finding highlights the complexity and intrinsic diversity within the studied species by demonstrating that the many attributes of the seeds, evaluated in a multidimensional manner, are not directly related to their physical dimensions.

Table 3: Pearson correlation matrix (r) for physical property variables of *Tabernaemontana heterophylla* seeds. L= Length; W = Width; T = Thickness; M = Mass; Seed Volume Index (SVI); Geometric Mean Diameter (GMD); Equivalent Mean Diameter (EMD); Arithmetic Mean Diameter (AMD); Surface Area (SA); Seed Volume (V); Ø = Sphericity; Ar = Aspect Ratio.

(r)	L	W	T	M	SVI	GMD	EMD	AMD	SA	V	Ø	Ar
L (mm)	1	---	---	---	---	---	---	---	---	---	---	---
W (mm)	-0.08^{ns}	1	---	---	---	---	---	---	---	---	---	---
T (mm)	-0.06^{ns}	0.44*	1	---	---	---	---	---	---	---	---	---
M (g)	0.52*	0.70*	0.50*	1	---	---	---	---	---	---	---	---
SVI	0.42*	0.75*	0.69*	0.93*	1	---	---	---	---	---	---	---
GMD (mm)	0.39*	0.77*	0.71*	0.91*	0.99*	1	---	---	---	---	---	---
EMD (mm)	0.67*	0.59*	0.53*	0.92*	0.94*	0.93*	1	---	---	---	---	---
AMD (mm)	0.76*	0.51*	0.45*	0.89*	0.89*	0.88*	0.98*	1	---	---	---	---
SA (mm^2)	0.40*	0.77*	0.70*	0.92*	0.99*	0.99*	0.94*	0.89*	1	---	---	---
V (mm^3)	0.42*	0.75*	0.69*	0.93*	1.00*	0.99*	0.94*	0.89*	0.99	1	---	---
Ø (%)	-0.74*	0.65*	0.56*	0.11^{ns}	0.26^{ns}	0.30^{ns}	0.0^{ns}	-0.14^{ns}	0.28^{ns}	0.26^{ns}	1	---
Ar	-0.65*	0.78*	0.35^{ns}	0.19*	0.29^{ns}	0.33^{ns}	0.02^{ns}	-0.07^{ns}	0.31^{ns}	0.29^{ns}	0.94*	1

*significant ($p < 0.001$); ^{ns} not significant.

These analyses showed that this primary data could be fundamental to developing facilities related to seed processing, handling, storage, packaging, and transportation and that studies on seed size variations contribute to these processes (Asoiro et al., 2020; Oliveira et al., 2021; Pinheiro et al., 2023; Satpathy, Naik, & Jena, 2024). It is, therefore, vital to understand the degree of variation between seed sizes in the species researched to optimize stages and form uniform batches. Native species generally exhibit high heterogeneity regarding their three-dimensional biometric characteristics (Freire et al., 2024). Variations in seed size have also been reported in other legume studies (Araújo et al., 2014; Silva et al., 2024).

Seed size influences plant fitness, linking germination to seedling establishment and later life stages. This characteristic is fundamental to both evolutionary biology and agronomic and conservation practices. Understanding and considering seed size can lead to more effective reforestation, crop improvement, and species preservation techniques (Domic, Capriles, & Camilo, 2020; Zhang et al., 2023). Agronomically, seeds of different sizes can produce plants with varying vigor, health, and uniformity levels. Larger, well-formed seeds typically indicate high-quality production. They also assist in determining planting density and spacing and contribute to a more consistent germination rate, both of which are critical for the predictability and efficiency of agricultural production.

Ecologically, studying the advantages of various sized and shaped seeds for dispersal will help us better understand how plants adapt and survive in the environment (Santos et al., 2019, Gomes et al., 2023). Seed size can influence germination capacity and the successful establishment of seedlings. Larger seeds often have more nutritional reserves, which can help seedlings thrive in competitive environments. The genetic diversity of forest seeds is essential for preserving their original characteristics, promoting resilience to environmental changes, and ensuring the continuity of forest ecosystems. Conservation and management practices prioritizing retaining and promoting genetic diversity are fundamental to forest species' long-term sustainability and preservation.

The results of this study highlight the significance of striking a balance between genetic variability and the need for agronomic uniformity. While seed disuniformity and heterogeneity are advantageous for preserving genetic diversity, uniformity is necessary for efficient agronomic measures to optimize post-harvest processes and create homogeneous lots. Classification, selection, and improvement approaches can help achieve a balance that satisfies biological and agronomic requirements.

Conclusions

The analyses and various statistical explorations showed that *Tabernaemontana heterophylla* seeds exhibit form, size, and fresh mass heterogeneity. The multidimensional aspects of the seeds, when combined with the physical elements, can be utilized to classify *Tabernaemontana heterophylla* seeds, reflecting quality classes about the uniformity of forest species seed lots. These variations reflect the genetic diversity required for ecological adaptability and resilience, ensuring the survival and functioning of forest ecosystems.

Author Contribution

Conceptual idea: Pinheiro, R.M.; Ferreira, E. J. L.; Marques, R. A.; Methodology design: Pinheiro, R.M.; Barros, Q. S.; Data collection: Pinheiro, R.M.; Carvalho, H. P.; Silva, F. A. F.; Data analysis and interpretation: Pinheiro, R. M.; Ferreira, E. J. L.; Barros, Q. S and Writing and editing: Pinheiro, R. M.; Marques, R. A.; Carvalho, H. P.; Silva, F. A. F; Barros, Q. S.

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