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Seed and fruit size affect soaking and physiological seed quality in *Campomanesia adamantium*?

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ABSTRACT: The size of fruits and seeds can affect the seed germination process and aspects related to the vigor of the seedlings formed. Our aim was to characterize fruit and seed biometrics, evaluate the effect of seed size on soaking and the effect of seed size and temperature on the germination and vigor of *Campomanesia adamantium***.** The fruit was evaluated to determine longitudinal diameter, transverse diameter, fresh mass and empty, full and total seed quantities. The seeds were sorted into small, medium and large classes and then measured for length, width, thickness and mass. Seeds from each class were submitted to the germination test at 25 and 30 °C. The germination and vigor (first count, germination speed index, mean germination time and seedling length) data were evaluated by analysis of variance and a means test. Seeds from each size class were weighed repeatedly during soaking. The soaking data were fit to logistic and Peleg models and best fit curves with confidence bands were constructed to compare the effect of seed size. Fruit morphology showed high intraspecific variability. Germination was not affected by seed size or test temperature. Large seeds yielded taller seedlings while the 25 °C germination temperature produced the highest seedling growth rate. The small and medium seeds showed all three phases of the soaking process. Finally, soaking was initially slower for the large seeds than for the small and medium seeds.

Index terms: germination, native Cerrado vegetation, seed vigor, water absorption.

O tamanho da semente e do fruto afetam a embebição e a qualidade fisiológica de sementes de *Campomanesia adamantium*?

RESUMO: O tamanho de frutos e sementes pode afetar o processo de germinação de sementes e afetar aspectos relacionados ao vigor das plântulas formadas. Nosso objetivo foi caracterizar a biometria de frutos e sementes, avaliar o efeito do tamanho das sementes na embebição e o efeito do tamanho e da temperatura das sementes na germinação e vigor de *Campomanesia adamantium*. Os frutos foram avaliados para determinação do diâmetro longitudinal, diâmetro transversal, massa fresca e quantidade de sementes vazias, cheias e totais. As sementes foram classificadas em classes pequenas, médias e grandes e depois medidas quanto ao comprimento, largura, espessura e massa. Sementes de cada classe foram submetidas a testes de germinação a 25 e 30 °C. Os dados de germinação e vigor (primeira contagem, índice de velocidade de germinação, tempo médio de germinação e comprimento de plântulas) foram avaliados por análise de variância e teste de médias (Teste de Student-Newman-Keuls). Sementes de cada classe de tamanho foram pesadas repetidamente durante a embebição. Os dados de embebição foram ajustados aos modelos logístico e Peleg e curvas de melhor ajuste com intervalos de confiança foram construídas para comparar o efeito do tamanho das sementes. A morfologia dos frutos apresentou alta variabilidade intraespecífica. A germinação não foi afetada pelo tamanho das sementes ou pela temperatura do teste. Sementes grandes produziram mudas maiores, enquanto a temperatura de germinação de 25 °C produziu a maior taxa de crescimento de mudas. As sementes pequenas e médias apresentaram todas as três fases do processo de embebição. Finalmente, a embebição foi inicialmente mais lenta nas sementes grandes do que nas sementes pequenas e médias.

Termos para indexação: absorção de água, germinação, vegetação nativa do Cerrado, vigor de sementes.

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INTRODUCTION

Campomanesia adamantium is native to the Brazilian Cerrado and has many potential uses. It occurs naturally in the Midwest, Southeast and South regions of Brazil, belongs to the Myrtaceae family and is commonly called 'gabiroba' (Flora do Brasil, 2020). Not only is the fruit consumed in its natural state, the fruit and other parts of the plant are used to make ice cream, sweets, alcoholic drinks, pharmaceuticals and herbal medicines. Despite its great potential, information on the cultivation of this species is limited (Araújo and Souza, 2018; Leão-Araújo et al., 2019a). Plant breeding research sheds light on germination dynamics and the consequent dissemination of these species within natural environments.

Seed germination and seedling growth are critical phases of the plant life cycle and determine species distribution and abundance (Wulff, 1986). Rapid seedling emergence and development in the field can improve the probability of species survival (Marcos-Filho, 2015; Bagateli et al., 2019). Several ecological and evolutionary factors affect germination and seedling establishment (Marques and Oliveira, 2005) such as fruit and seed size (Surles, 1993; Oliveira et al., 2011; Dresch et al., 2013; Silva et al., 2014).

Seed size may be a consequence of evolution and is considered an adaptation to dispersal, the presence and duration of available moisture and seedling survival (Armstrong and Westoby, 1993; Murali, 1997). In general, larger seeds have well-formed embryos and greater reserves, which increase the probability of successful establishment (Haig and Westoby, 1991; Santos et al., 2009; Carvalho and Nakagawa, 2012). However, smaller seeds germinate faster than larger seeds (Murali, 1997), which can limit exposure to adverse conditions during this critical phase. In addition, Norden et al. (2009) related that the small seeds germinate faster, the results were interpreted in light of phylogenetic and biophysical constraints. So, the effect of seed size on plant species behavior during the initial development phase does not follow a single pattern (Cicek and Tilki, 2007).

Temperature also affects germination and emergence by altering the speed of water absorption and the speed of chemical reactions that mobilize or degrade stored reserves and synthesize several substances that affect seedling growth during germination (Bewley et al., 2013). The best germination temperature is one that optimizes germination speed and rate and can vary by species or even by cultivar (Marcos-Filho, 2015). Thus, studying the effect of temperature on germination sheds light on the initial success of a species in the field (Oliveira and Garcia, 2005).

Water uptake is a determining factor for germination speed and rate. Soaking occurs in three phases (Bewley and Black, 1978). Phase III is characterized by a resumption of embryonic growth and emergence of the primary root. However, the occurrence and duration of each phase is species specific (Marcos-Filho, 2015) and depends on several factor including seed size (Silva et al., 2018). Leão-Araújo et al. (2019b) concluded that the reparameterized Peleg model efficiently describes soaking in *C. adamantium* seeds and that phase II is short while phase III is not characterized by elevated water uptake. Therefore, studying the effect of *C. adamantium* seed size during soaking could assist the processes of seed collection and seedling propagation and shed light on the natural colonization of this species in the field.

The aim of the current study were (i) to characterize biometric aspects of *Campomanesia adamantium* fruit and seeds, (ii) to evaluate the effect of seed size on soaking, and (iii) evaluate the effect of seed size and temperature on seed germination and vigor.

MATERIAL AND METHODS

The fruit was harvested from 360 *Campomanesia adamantium* parent plants (Figure 1A) that were approximately 14 years old and located in Ipameri, GO, Brazil (17°43'19 '' S, 48°09'35 '' W, altitude 820 m). The climate of this region is classified, by the Köppen-Geiger classification, as Cwa-Mesothermal Wet, with an average annual rainfall of 1,490 mm and an average annual temperature of 25 °C· The flowers were marked at anthesis and the fruit collected 50 to 65 days after this stage (from October to December 2017). Only the marked fruits that had a yellow peel and soft consistency were harvested.

The fruit preselected for the study was free of any obvious signs of pest or disease damage. Biometric measurements and characterizations were performed on 100 randomly-chosen fruits. These were evaluated to determine longitudinal and transverse diameter (mm) (Figure 1B), using a digital caliper, fresh mass in g (Figure 1G), using a scale (precise to 0.0001g), counts of empty, full and total seeds, which were determined visually and by pressing the seeds between fingers to determine the presence of the endosperm and embryo.

The fruit was manually pulped, and the resulting pulp/seed mixture was fermented for 48 hours in a 25% ammonium hydroxide solution (Carmona et al., 1994). Afterwards, the seeds were washed in running water for five minutes and spread in a single layer on germination paper (28 x 38 cm) to surface-dry the tegument (30 minutes in a laboratory environment).

The seeds were then sorted into three size classes: small (S), medium (M) and large (L) (Figure 1H). One hundred seeds were randomly selected from each size class and measured to determine length, width and thickness (mm) (Figures 1C, 1D and 1E), using a digital caliper. The 10-seeds mass (mg) was also measured with 10 replications.

Position and dispersion measurements were obtained for the fruit: longitudinal diameter, transverse diameter, fresh mass, number of full, empty and total seeds, and the seeds: length, width, thickness and mass of 10 seeds. Graphs were also created to show the dispersion of these biometric and morphological variables.

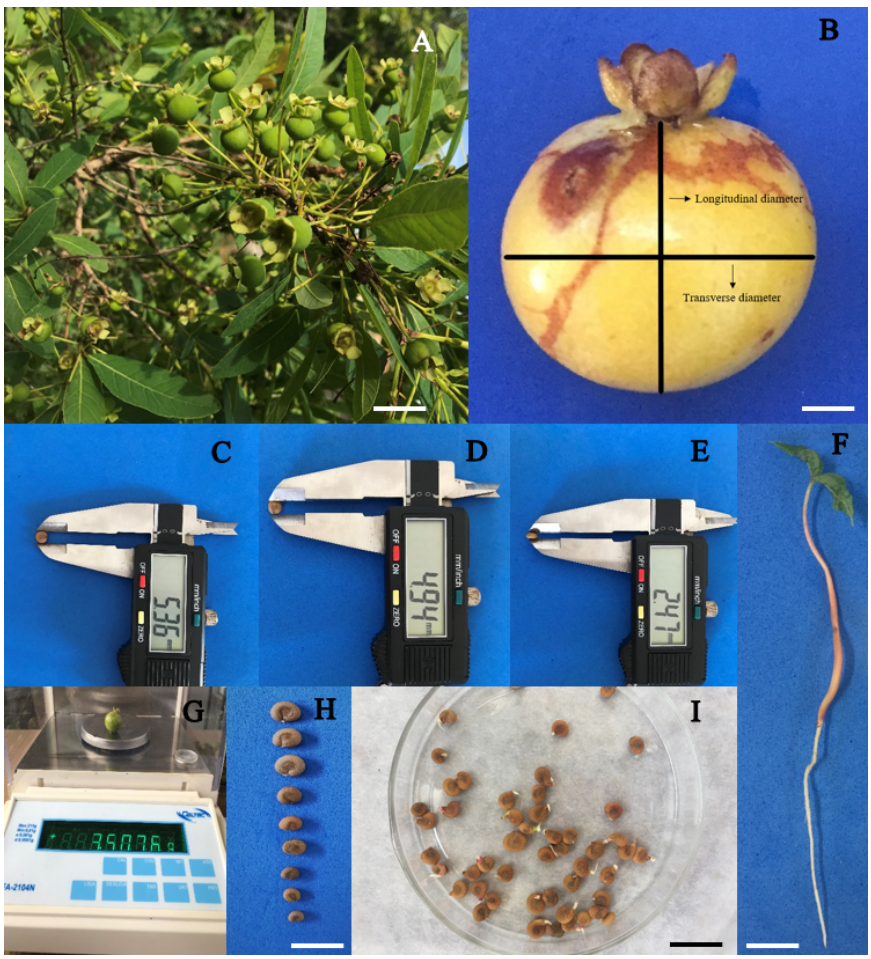

Figure 1. *Campomanesia adamantium* plant with fruit (A); Representation of the longitudinal and transverse diameters of *C. Adamantium* fruit (B); Length of a *C. adamantium* seed (C); Width of a *C. adamantium* seed (D); Thickness of a *C. adamantium* seed (E); Normal *C. adamantium* seedling (F); *C. adamantium* fruit weight (G); Large, medium and small *C. adamantium* seed classes (top to bottom, 3 seeds per class) (H); Root protrusion in *C. adamantium* seeds (I). Scale bars: A = 40 mm, B = 3.5 mm, F, H and I = 10 mm.

Physiological quality tests (described below) were performed on each size class to determine the effect of seed size and temperature on germination and vigor.

Germination test: four replications of 25 seeds per treatment were placed on two sheets of germination paper inside plastic germination boxes (Gerbox, 11 x 11 x 3.5 cm). A second sheet of paper was also placed on top of the seeds. The sheets of paper were previously moistened with distilled water to 2.5 times the mass of the dry paper. The Gerboxes were placed in germinators at either a constant 25 or 30 °C, with white light (~ 6500 K). The first (FC) and final germination counts (G) were performed at 20 and 42 days, respectively and expressed as percentages of normal plants. Normal seedlings were counted every three days and the germination speed index (GSI) was calculated according to Maguire (1962) and mean germination time (MGT), expressed in days, according to Labouriau and Valadares (1976).

Seedling length (SL): achieved using four replications of 10 seeds for each treatment, placed longitudinally in the upper third of two overlapping sheets of germination paper and covered with a third sheet, as in Nakagawa (1999). The germination paper was moistened using the same procedures described for the germination test. The rolls were then placed in a germination chamber at a constant 25 or 30 °C. After 42 days, the length of normal seedlings (Figure 1F) was measured with a digital caliper and expressed as cm.seedling^{-1}.

To determine the physiological potential of the seeds, by size class (S, M and L) and at 25 and 30 °C, experiments were set up using a completely randomized design, a 3 x 2 factorial scheme (seed size x temperature) and four replications. The normality of model residuals was evaluated using the Shapiro-Wilk test and homoscedasticity by the Bartlett test. Having satisfied all assumptions, G, FC, GSI, MGT and SL were submitted to ANOVA and the means compared by the SNK test (Student-Newman-Keuls), at the 5% significance level.

Before characterizing soaking of the three seed classes, seed moisture level were determined, using two replications of 20 seeds, drying in an oven for 24 hours at 105 ± 3 °C, weighing and then expressing the results as a percentage of wet weight (Brasil, 2009).

Soaking was performed on four replications of 50 seeds for each size class. The seeds were arranged in three sheets of rolled germination paper, which were wetted with deionized water until reaching three times the mass of the dry paper, and then placed in a germination chamber at a constant 25 °C. Seed mass and counts of seeds with primary roots were determined at regular intervals. Seed mass was measured at the start of the experiment and after 1, 2, 4, 6, 8, 22, 46, 60, 84, 108, 132 and 204 h. The seeds were weighed until 50% showed protrusion of the primary root (Figure 1I). Root protrusion data were expressed as percentages.

Before weighing, the seeds were dried superficially using sheets of germination paper. The percentage of water uptake at time (t) was calculated from mass (M), where M0 is the mass of the seeds at time 0:

$$f(t) = \left[\frac{Mt - M0}{M0} \right] x100$$

Preliminary tests were carried out and the logistic model was fit for S and M seeds, as proposed by Silva et al. (2018):

$$f(t) = a_1 \left[1 + \exp(-b_1 (t - c_1)) \right]^{-1} + \exp(b_2 (t - c_2)) + \varepsilon$$

Where *f(t)* is seed moisture content at time t, a_1 is the moisture content during equilibrium in phase II, b_1 is the rate of hydration, c_1 is the time delay between phases, a_2 would represent moisture content during equilibrium (stabilization) in phase III, but does not exist in this experiment, b_2 is the kinetic rate in phase III, c_2 marks the start time of phase III and is the random error term.

Large seeds were fit to the Peleg model (Peleg, 1988). The model was reparametrized as described by Silva et al. (2018):

$$f(t) = w_0 + t(k_1 + k_2 t)^{-1} + \varepsilon$$

Where *f(t)* is moisture content at time t, w_0, k_1, k_2 are the Peleg model parameters, representing initial moisture content (this parameter was not included in the present study because of the method used to model water accumulation),

the kinetic rate of hydration in phase I (h %$^{-1}$) and the Peleg capacity constant, respectively.

The parameters were estimated by the non-linear least squares method, using the Gauss-Newton algorithm. The degree of fit of the model was determined using the coefficient of determination (R^2), the adjusted coefficient of determination (R^2 *adj.*), and the Akaike information criterion (AIC):

$$R^2 = 1 - \frac{SSR}{SST}$$

$$R^2_{adj} = \frac{R^2(n-1) - p}{n - p - 1}$$

$$AIC = 2\left(p - \log L\left(\hat{\theta}\right)\right)$$

SSR is the residual sum of squares, *SST* is the total sum of squares, *p* is the number of model parameters, *n* is the number of observations and $L(\hat{\theta})$ is the maximum *p* of the likelihood function, assuming a normal distribution. Better fit is associated with higher R^2 and R^2 *adj*. values and lower AIC values.

Confidence bands were constructed (95%) to perform statistical comparisons among the soaking curves of the three seed sizes (Silva et al., 2018). The models were fit to the nls () function using the R environment for statistical computations. The maxcurv () function from the soilphysics software package (Silva and Lima, 2017) was used to determine the point of maximum curvature, which was used to delimit the soaking phases. The seedwater software package (Silva, 2019b) was used select models and the confbands() function (Silva, 2019a) was used to plot the 95% confidence bands.

RESULTS AND DISCUSSION

The longitudinal diameter of the fruit ranged from 13.07 to 32.12 mm, with a standard deviation of 4.12 mm, while the transverse diameter varied from 11.02 to 29.44 mm, with a standard deviation of 3.63 mm (Table 1). These values are higher than those found by Dresch et al. (2013), for fruit collected in Ponta Porã, MS, Brazil. These differences may be caused by the high intraspecific variability that exists among native species of the Cerrado, a region with high genetic diversity (Junqueira et al., 2010). According to Bellon et al. (2007), variations in fruit size may be more pronounced between different geographic regions, such as different states. Oliveira et al. (2011) found values similar to those of the present study, with mean longitudinal and transverse length of 19.4 and 18.3 mm, respectively. Oliveira et al. (2011) studied fruit harvested from a region (Triângulo Mineiro, Minas Gerais) near that of the present study (Ipameri, Goias), which may explain this similarity.

Table 1. Longitudinal diameter, transverse diameter, fresh mass, empty, full and total number of seeds of *Campomanesia adamantium* fruit.

	Longitudinal diameter	Transverse diameter	Fresh mass	Full seeds	Empty seeds	Total seeds
	mm		g	number		
Minimum	13.07	11.02	0.84	0	0	2
Maximum	32.12	29.44	8.43	7	4	8
Mean	20.45	18.17	3.31	3.18	1.99	5.17
Standard error	0.41	0.36	0.13	0.14	0.09	0.13
Standard deviation	4.12	3.63	1.28	1.38	0.91	1.33
CV (%)	20.16	19.99	38.84	43.65	46.00	25.79

The mean fresh fruit mass was 3.31 g, which was similar to that found by Dresch et al. (2013) for fruit classified as medium to large. Greater fruit development in the present study may be due to the high intraspecific variability of *C. adamantium*. The total number of seeds per fruit varied from two to eight, with two empty and three full seeds per fruit (i.e. 38 and 62% of total seeds per fruit, respectively). The percentage of empty seeds is important because it directly affects commercial success and sowing efficiency (ISTA, 1995).

The frequency distribution (Figure 2A) of the data shows that most fruit were grouped into the intermediate longitudinal diameter class (78%), (16.01 to 25.00 mm). Regarding transverse diameter, 87% of the fruit measured between13.01 and 22.00 mm (Figure 2B), while for fresh mass, 77% of the fruit measured from 2.01 to 5.00 g (Figure 2C).

Only 7% of the fruit did not contain empty seeds while 91% had two or three empty seeds (Figure 3). Empty seeds may be caused by several factors such as low pollen production in the male floral organs, high egg and embryo abortion rates, egg fertilization failures or absence of pollinating agents (Kosinski, 1987; Sousa and Hattemer, 2003). Fertilization failures in *C. adamantium* may be related to a lack of water during this process. Marcos-Filho (2015) reported that water is essential for pollen tube growth while Leão-Araújo et al. (2019c) concluded that the flowering stage in this species occurs during periods of drought.

It is essential to study non-destructive techniques, such as x-ray analysis, to characterize the occurrence of empty seeds in *C. adamantium*. An x-ray test was used on *Terminalia argentea* fruit to efficiently identify problems related to low germination such as empty seeds and embryonic abnormalities (Gomes et al., 2014). Therefore, evaluations of internal morphology are essential for selling seeds of native species and determining sowing quantities.

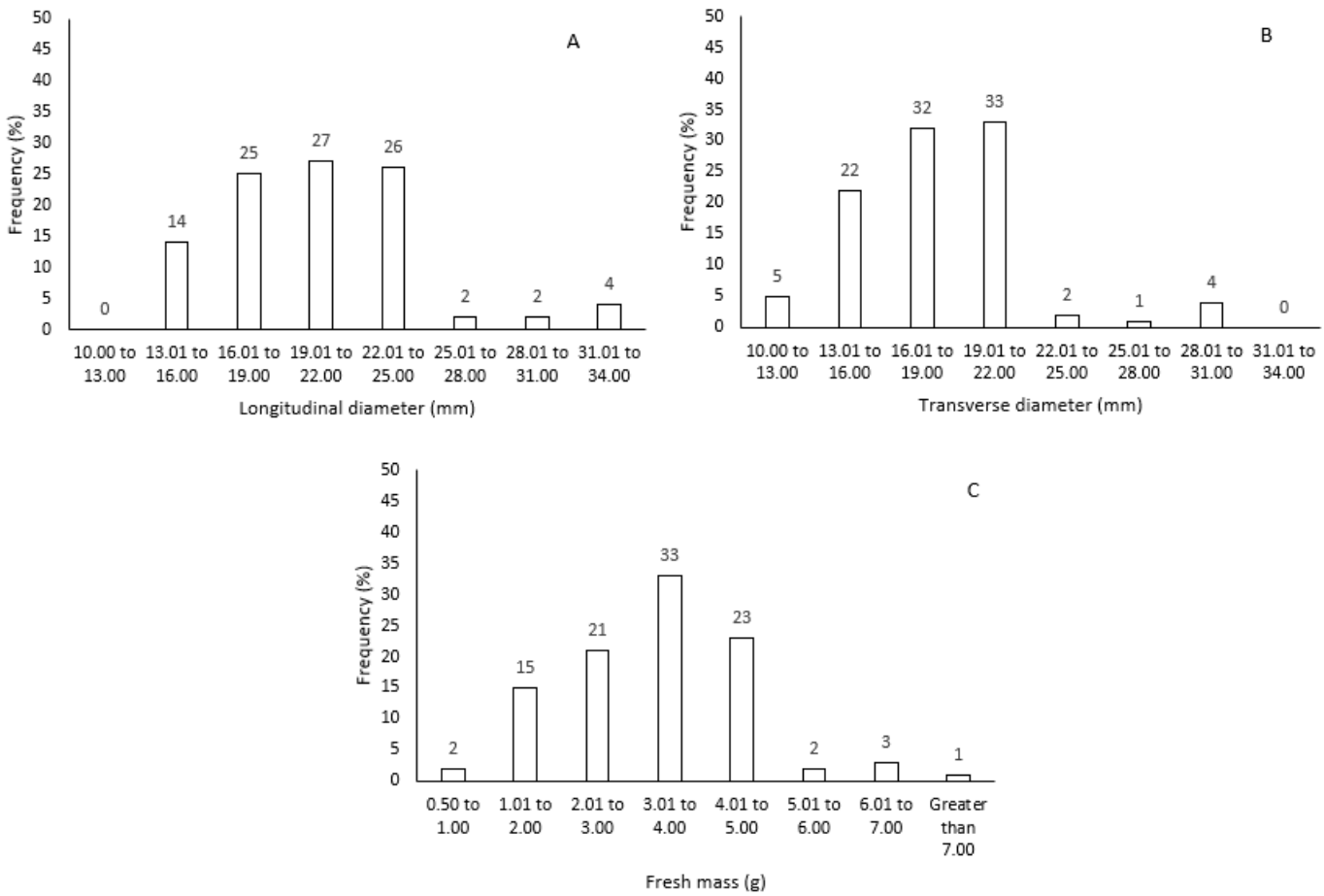

Figure 2. Frequency of longitudinal diameter (A), transverse diameter (B) and fresh mass (C) of *Campomanesia adamantium.*

The mean lengths of small, medium and large seeds were 4.31, 5.40 and 6.58 mm, respectively (Table 2). Dresch et al. (2013) found similar values for *C. adamantium* fruit classified into four groups: small, medium small, medium large and large. These authors reported mean seed lengths of 4.76 and 6.64 mm for seeds from small and large fruit, respectively.

The fresh mass of 10 small seeds ranged from 213 to 250 mg (Table 3). The fresh mass of medium seeds ranged from 357 to 402 mg while the mean mass of large seeds was 490 mg.

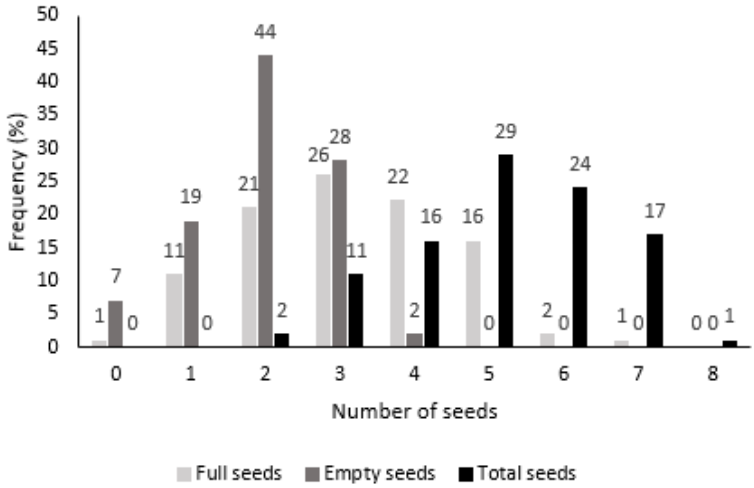

Figure 3. Frequency of full, empty and total numbers of seeds in *Campomanesia adamantium* fruit.

Table 2. Length (L), width (W) and thickness (T) of *Campomanesia adamantium* seeds separated into three size classes.

	Small seeds			Medium seeds			Large seeds		
	L	W	T	L	W	T	L	W	T
	mm								
Minimum	3.33	3.04	1.45	4.70	3.58	1.76	6.01	4.20	1.52
Maximum	4.92	4.45	3.21	5.97	5.91	3.63	8.08	6.23	3.09
Mean	4.31	3.64	2.31	5.40	4.54	2.43	6.58	5.13	2.45
Standard error	0.03	0.03	0.03	0.03	0.04	0.03	0.04	0.05	0.03
Standard deviation	0.34	0.32	0.28	0.31	0.38	0.29	0.44	0.47	0.32
CV (%)	8.01	8.91	12.55	5.74	8.42	12.02	6.65	9.18	13.05

Table 3. Fresh weight of 10 *Campomanesia adamantium* seeds separated into three size classes.

	Small seeds	Medium seeds	Large seeds
	mg		
Minimum	213	357	430
Maximum	250	402	548
Mean	232	389	490
Standard error	3.94	3.70	10.91
Standard deviation	12.46	34.51	34.51
CV (%)	5.37	7.04	7.05

The length of 87% of the small seeds fell between 4.01 and 5.00 mm, while 90% of the medium seeds fell between 5.01 and 6.00 mm and 83% of the large seeds were between 6.01 to 7.00 mm. The mean length of *C. adamantium* seeds found by Oliveira et al. (2011) was 6.00 mm, similar to that of the medium size seeds in the present study (Table 2 and Figure 4A).

Most of the small seeds (88%) were between 3.00 and 4.00 mm wide, while most medium (84%) and large seeds (70%) were between 4.01 and 5.00 mm and 4.51 and 5.50 mm wide, respectively (Figure 4B). The width histogram shows that most seeds, regardless of class, measured between 2.01 and 2.50 mm (Figure 3C).

Regarding the fresh mass of 10 small seeds, 90% weighed less than 250 mg (Figure 4D). The same percentage was obtained for small seeds weighing between 351 and 400 mg. Fifty percent of the large seeds weighed between 451 and 500 mg while 40% weighed between 501 and 550 mg. Similarly, Dresch et al. (2013) found a mean weight of 25.6 mg per seed for small seeds and 50.4 mg per seed for large seeds.

Physiological quality evaluations of the small, medium and large seeds (germination tests and seedling length at 25 and 30 °C) did not show significant interactions between these factors for any of the analyzed variables (Table 4). G was not affected by seed size or temperature. Similarly, Alves et al. (2005) concluded that the size of *Mimosa caesalpiniifolia* Benth seeds, derived from various sources, did not affect germination, however, vigor was directly related to seed size. Aguiar et al. (1996), also showed that size did not affect germination of *Caesalpinia echinata* Lam seeds. Temperature may not have influenced the germination of normal seedlings (G) because in the absence of other limiting factors, germination can occur within a relatively wide temperature range (Marcos-Filho, 2015).

The FC, GSI and MGT tests showed that vigor was not affected by seed size or temperature. These tests are all based on germination speed (Peske et al., 2012), which explains why they yielded similar results. GSI was also not

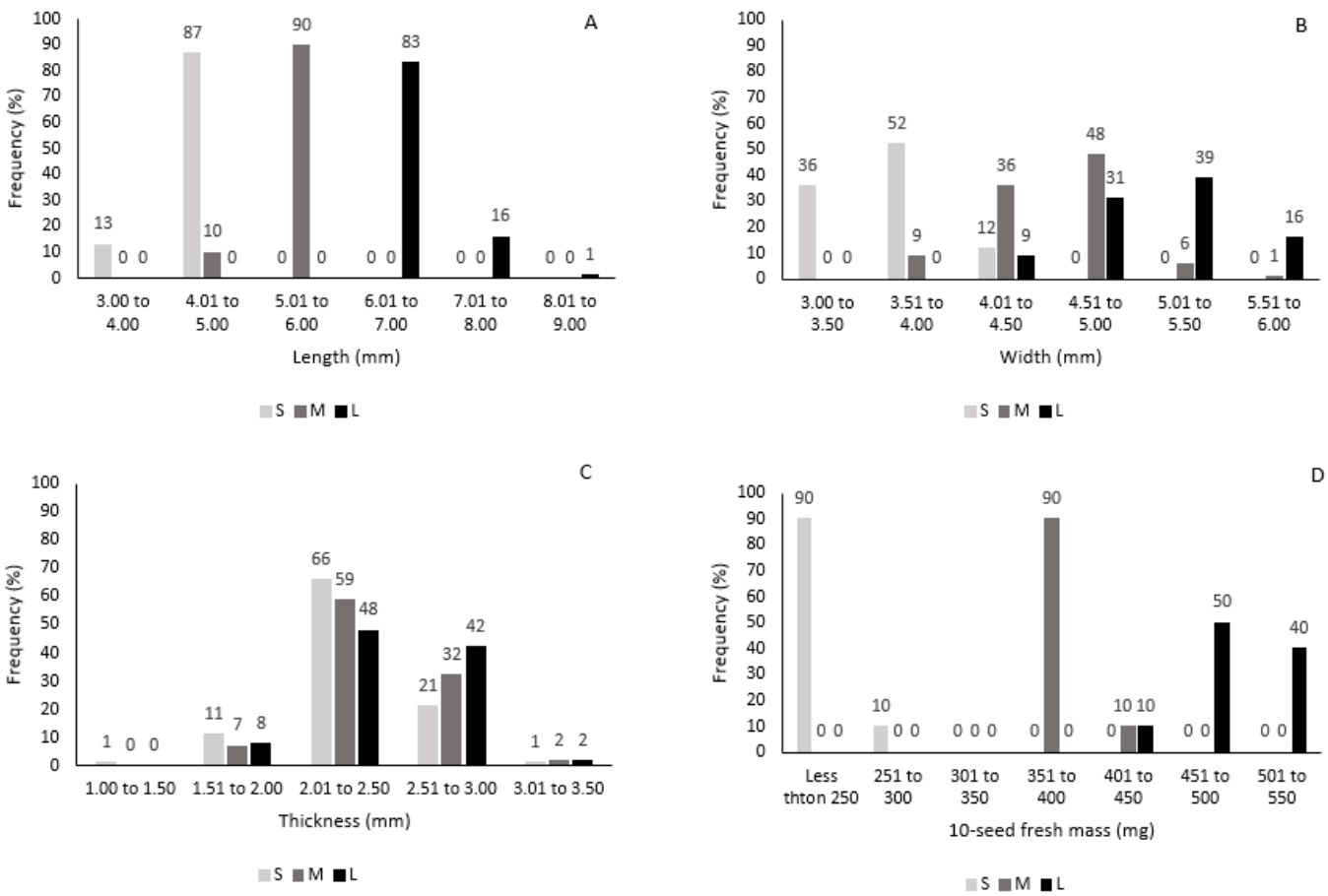

Figure 4. Frequency of length, width, thickness and fresh mass of 10 *Campomanesia adamantium* seeds.

Table 4. Physiological quality (FC: first germination count, G: germination, GSI: germination speed index, MGT: mean germination time and SL: seedling length) of three sizes of *Campomanesia adamantium* seeds germinated at two temperatures.

Seed size and temperature	FC	G	GSI	MGT	SL
	_____ % _____		_____	__ days __	__ mm__
Small	59 a	73 a	3.97 a	20.43 a	10.64 c
Medium	47 a	59 a	3.22 a	19.74 a	12.77 b
Large	56 a	67 a	3.65 a	19.69 a	15.53 a
25 °C	54 a	65 a	3.56 a	19.62 a	13.39 a
30 °C	54 a	67 a	3.66 a	20.29 a	12.57 b
p-Value (Size)	0.22318	0.05905	0.07272	0.71130	< 0.001
p-Value (Temperature)	0.95205	0.70279	0.69786	0.41436	0.01437
p-Value (Size x Temperature)	0.2701	0.33575	0.3853	0.91665	0.14038
CV (%)	24.88	15.91	16.89	9.95	5.67

Means compared by the Student-Newman-Keuls test.

affected by seed size in *Macadamia integrifolia* seeds (Rêgo et al., 1991) and *Acacia senegal* (L.) de Willd seeds (Ferreira and Torres, 2000).

Similarity in the seed vigor tests (FC, GSI and MGT) at 25 and 30 °C may be explained by Lamarca et al. (2011), who found that seeds of the *Eugenia* genus (Myrtaceae family) adequately germinate and form normal seedlings between 20 and 30 °C.

Evaluating continuity in seedling development by the SL test showed that seed size and temperature had a significant effect during growth. Large seeds were associated with longer seedlings while small seeds were associated with shorter seedlings. Alves et al. (2005) also reported that characteristics related to seedling size were efficient indicators of differences in the seed vigor of different sizes of *Mimosa caesalpiniifolia* seeds. Larger *Copaifera langsdorffii* seeds produced more vigorous seedlings, which benefited the establishment of seedlings in the field (Souza and Fagundes, 2014). Peske et al. (2012) reported that larger seeds normally produce larger seedlings. This may result from the greater reserves, larger embryos and better-formed embryos of these seeds (Surles, 1993; Carvalho and Nakagawa, 2012).

The seedlings grown at 25 °C were taller than those grown at 30 °C. Similar results were found for germination tests of several species of the Myrtaceae family (*Eugenia involucrata*, *E. pyriformis*, *Acca sellowiana* and *Campomanesia xanthocarpa*), showing that 25 °C may be the optimum germination temperature for these species (Gomes et al., 2016). Oliveira and Garcia (2005) showed that 25 °C is excellent for germinating *Syngonanthus elegantulus*, however, 30 °C produced better results for *S. elegans*. Temperature can affect seedling length because the germination process involves a sequence of chemical reactions that depend on specific enzymatic systems that have individual temperature requirements (Marcos-Filho, 2015). The efficiency of these reactions may determine the speed, uniformity, percentage and degree of seedling development.

R^2 and R^2 *adj*. values greater or equal to 90% (Table 5) show that the soaking of the small and medium seeds was efficiently modeled by the logistic model, adapted from Silva et al. (2018). Large seeds were fit to the reparametrized Peleg model (suggested by Silva et al., 2018), with R^2 and R^2 *adj*. values greater than 65%.

Overlapping confidence bands during the first 8 hours shows that the soaking curves of the S and M seeds were similar (Figure 5). This period of rapid soaking is characteristic of phase I, which generally lasts for eight to sixteen hours for cultivated species (Marcos-Filho, 2015). The water absorption rate of these seed classes drops significantly after 10 h, which is an indicator of phase II soaking (Bewley et al., 2013).

Table 5. Quality of fit criteria for models fit to soaking curves of three size classes of *Campomanesia adamantium* seeds.

Size	Model	R^2	R^2 adj.	AIC
S	Adapted Logistic	0.91	0.90	339.30
M	Adapted Logistic	0.98	0.98	224.09
L	Peleg	0.66	0.66	367.20

AIC: Akaike information criteria.

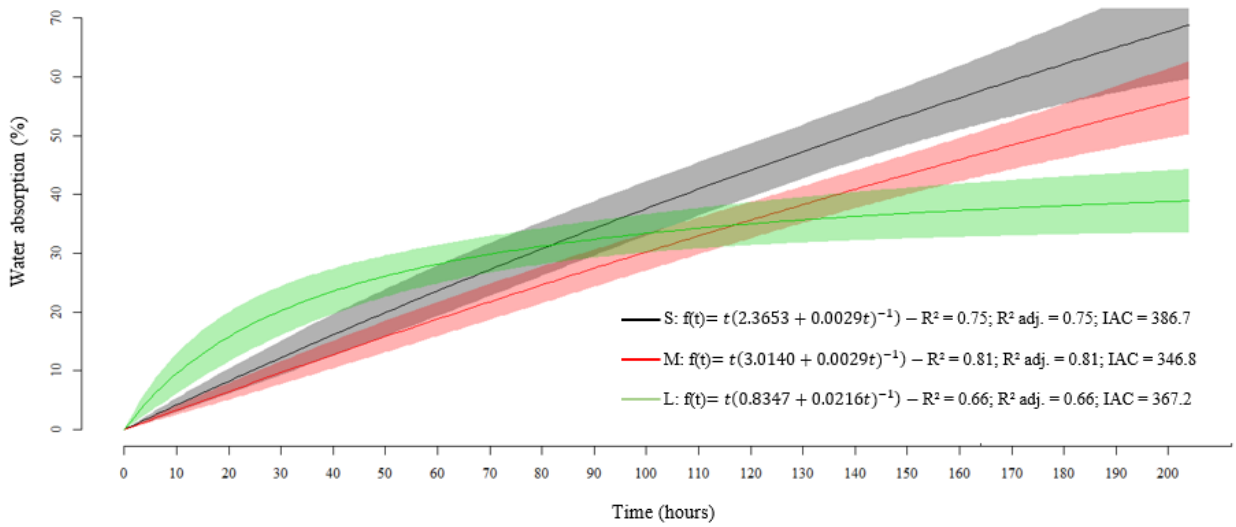

Figure 5. Adapted logistic model for small (S) and medium (M) seeds and the Peleg model for large (L) seeds, with 95% confidence bands for the soaking curves of three sizes of *Campomanesia adamantium* seeds.

After 40 h, the S and M seed curves do not overlap, indicating that water absorption differs between these classes. The small seed class reaches phase II more quickly than does the large seed class. According to Baalbaki et al. (2009), smaller seeds have a higher surface to volume ratio than larger seeds and consequently absorb water more quickly.

Primary root protrusion in all three size classes occurred 108 h after the start of soaking. Similar data were observed by Leão-Araújo et al. (2019b), who tested soaking in *C. adamantium* at three temperatures and observed root protrusion after approximately 100 h of soaking at 20 and 25 °C.

A resumption of embryonic growth, characterized by root protrusion (after 108 h), was accompanied by a resumption of rapid water absorption by the S and M seeds, which occurs because primary root emergence and seedling growth (Bewley et al., 2013) require greater water stores. Phase III justifies the use of the adapted logistic model, which considers an additional exponential term with two parameters.

The L seeds absorbed water more slowly than did the S and M seeds. This may occur because seed hydration occurs gradually and starts with the tissues closest to the surface, forming a "hydration front" as water progresses into the seed tissue (Marcos-Filho, 2015). The hydration rate in larger seeds is also slower because less tissue (per unit volume) is in contact with the wet substrate.

The L seed soaking curve did not show clear changes in water absorption rates that would indicate the three soaking phases (Bewley and Black, 1978). Only phase I and II can be easily characterized in this curve. The same was reported for this species (Leão-Araújo et al., 2019b), for pea and lentil seeds (Silva et al., 2018) and for sorghum seeds (Kashiri et al., 2010). These results probably occur because samples with more than one seed are evaluated and not individual seeds. In addition, these findings may be explained by Marcos-Filho (2015) who states that the beginning of one phase is not necessarily marked by the end of the previous phase and that two phases may occur simultaneously.

CONCLUSIONS

Fruit morphology may demonstrate great intraspecific variability.

Small and medium seeds presented all three phases of the soaking process while large seeds exhibited slower water absorption than did small and medium seeds.

Seed size and temperatures of 25 and 30 °C did not affect germination, however, 25 °C was associated with stronger seedling growth.

Large seeds produce taller seedlings than small and medium seeds.

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